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Preliminary comparison of scour depth estimation methods

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ABSTRACT: Bridge scour is a major cause of bridge collapse worldwide. Various approaches are available to estimate levels of scouring due to hydraulic loading. Such scour depth assessment methodologies typically employ a series of empirical and semi-empirical equations to estimate scour around a bridge element. This work examines three such methodologies, namely the Hydraulic Engineering Circular Number 18 method (HEC-18) 4th edition, the HEC-18 5th edition method and the Texas A&M University method (TAMU). The paper compares the results from these three calculation methods with field data from 23 bridge piers (eight bridges) located in the State of Maine (USA). The paper investigates the levels of conservatism in the estimates of scour depth calculated using these three methodologies. All three approaches tend to give conservative estimates of maximum scour depth, especially for low values of scour depth, when compared to the field dataset examined in this paper.

1 INTRODUCTION

1.1 *Background*

Scour is a complex problem for engineers which contributes to many bridge failures (e.g. Briaud et al. 2011, Maddison 2012, Prendergast & Gavin 2014, Ding et al. 2016, Ettema et al. 2017, Vardanega et al. 2021). Bridges form important lifelines and their performance during flood events is needed to keep communities connected. Network Rail reports that one bridge fails every 3.7 years due to scour in the United Kingdom (Network Rail 2015). Kallias & Imam (2016) presented a probabilistic analysis of local scour accounting for varying environmental conditions. Dikanski et al. (2017) presented a review on how climate change effects can be incorporated into bridge scour assessment procedures. Pregnolato et al. (2021) review scour management processes and conclude that risk-based approaches for scour assessment are desirable.

The collapse of the New York State Thruway bridge in 1987 occurred after a major flood and its failure cause was attributed to bridge pier scour (Briaud 2015a). Since then, scour assessment has received considerable attention (Briaud 2015a) and the first version of the Hydraulic Engineering Circular Number 18 (HEC-18) method to evaluate bridge scour was introduced (Briaud 2015a). The Texas A & M University method (TAMU) has also been proposed (Briaud 2015a, b).

The common issue with most scour estimation methodologies is that they have been designed based on results from flume tests conducted under laboratory conditions which may not be completely representative of the field environment (cf. Briaud 2015a, b, Qi et al. 2016). However, scour estimations using these methodologies are often conservative when compared to field measurements which may result in increased maintenance and construction costs (Abd El-Hady 2020). Therefore, the estimated level of conservatism for scour assessment methodologies is of practical interest and will be investigated in this paper by reviewing three scour estimation methodologies and comparing the calculated estimates of scour depth with a database of field measurements.

This preliminary study uses three scour assessment methodologies, referred to in this paper as: HEC-18 4th edition (Richardson & Davis 2001), HEC-18 5th edition (Arneson et al. 2012, Schuring et al. 2017) and TAMU (Briaud 2015a, b).

Qi et al. (2016) stated that HEC-18 4th edition is very accurate when used under laboratory conditions however it overpredicts field measurements. It is important to compare scour depth prediction methodologies to field data (see e.g. Hodgkins & Lombard 2002, Briaud 2015a, b, Qi et al. 2016) and also to benchmark scour estimation methods against each other (e.g. Zevenbergen 2010).

1.2 *Field Database (Hodgkins & Lombard 2002)*

In this paper the three scour assessment methodologies (HEC-18 4th edition, HEC-18 5th edition and TAMU) are used to assess scour for eight bridges (23 piers) located in the State of Maine (USA), for which scour depths were measured in the field between 1997 and 2001 and reported in Hodgkins & Lombard (2002) (the Pier IDs given in Table 1 were developed by the present authors in order to

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distinguish the individual piers in the subsequent analysis presented in Section 3).

Table 1. Bridge pier identification (all bridges in Maine, USA) (data from Hodgkins & Lombard 2002).

Bridge Name	Pier ID
Kenduskeag River at Bangor	A1
Kennebec River at Gardiner	B1, B2, B3, B4
Androscoggin River at Bethel	C1, C2
Penobscot River at Lincoln	D1, D2, D3, D4, D5, D6
Aroostook River at Ashland	E1, E2
St. John River at Van Buren	F1, F2, F3, F4
Austin Stream at Bingham	G1, G2
Saco River at Hiram	H1, H2

Hodgkins & Lombard (2002) stated that 'the predicted HEC-18 maximum pier-scour depths were compared to the observed maximum pier-scour depths' (Hodgkins & Lombard 2002, pg. 1) by using the equations in HEC-18, 4th edition which indicated that the prediction method was conservative. Hodgkins & Lombard (2002) explained that the measured pier scour depth is the maximum as the measurements were taken during 'the largest flow that occurred at the sites from 1997 through 2001′ (Hodgkins & Lombard 2002, pg. 12). All measurements took place in spring when maximum flows occur in the State of Maine due to snowmelt runoff.

All 23 piers were 'concrete mass piers' (Hodgkins & Lombard 2002, pg. 2). The choice of the eight bridges for the original study was based on a set of factors to ensure that bridge scour was likely. This choice includes the lack of unnatural material, the presence of erodible material (no bedrock and bridges not known for exposure to regular jams from ice or debris) (Hodgkins & Lombard 2002).

The collection of field data between 1997 to 2001 includes initial screenings with the help of the Maine Department of Transportation (MDOT) dive team and a team from the US Geological Survey. To establish baseflow conditions, graduated fiberglass rods and recording fathometers were mounted to a floating platform to take readings (Hodgkins & Lombard 2002). Additionally, bridge dimensions were determined by measuring tapes, through surveying and from MDOT bridge plans (Hodgkins & Lombard 2002). During high flows, rain gauges, precipitation data and real-time river flow information were utilized and observed data were determined through the 'concurrent ambient bed level method' (attributed by Hodgkins & Lombard 2002 to Landers & Mueller 1993, pg. 13). Table 2 presents a summary of the methods used to measure the relevant parameters for the scour assessment methodologies in the field.

1.3 *Study aims*

The study aims to: (1) compare results from the three pier scour assessment methods (i.e. HEC-18 4th edition, HEC-18 5th edition and TAMU methods) to the published field data from Hodgkins & Lombard (2002); (2) compute the difference between the assessed scour depth and the observed scour depth from the field and (3) compare the results of the three methods to identify possible reasons for the overestimation of maximum scour depth.

2 METHODOLOGY

2.1 *HEC-18*

The HEC-18 method for scour estimation in Hydraulic Engineering Circular No.18 is published by the Federal Highway Administration of the US Department of Transportation and it is now on its 5th edition, which was published in 2012 (Arneson et al. 2012, Schuring et al. 2017). According to Mueller (1996) HEC-18 is a useful method since it rarely underestimates bridge scour. The latest version of the method requires the following inputs to evaluate bridge scour on piers: pier length, pier width, approach velocity, skew angle, and depth of water flow (see Arneson et al. 2012 for further information on the method).

2.2 *TAMU*

The TAMU scour method was developed in the 1990s in Texas A&M University (TAMU) by Briaud and co-workers (Briaud, 2015a). The TAMU method explicitly accounts for soil properties in addition to geometry and flow velocity parameters (Briaud, 2015a, b). The TAMU scour method provides formulations to assess both the final scour depth and the maximum scour depth. The maximum scour depth was determined assuming the build-up of a constant velocity. The final scour depth accounts for the fact that velocities in a river are not constant and therefore the depth is calculated as an average value out of many velocities (Briaud 2015a). In this paper only the maximum scour depth equations were used.

2.3 *Comparison of HEC-18 4th edition, HEC-18 5th edition and TAMU*

The three scour depth assessment approaches reviewed in this work all require similar inputs. However, some differences in the methodologies are discussed below. The TAMU method can distinguish between low and high erodibility soils, accounting for soil properties in the critical velocity equation from (Briaud 2015b).

HEC-18 predicts the maximum scour depth based on flow velocity and geometric factors but not soil properties (Briaud 2015a): the scour estimation is

Table 2. Input parameters details. All input parameters taken from Hodgkins & Lombard (2002, pgs. 4 to 10) except pier spacing which was assumed [(1) = HEC-18 4th edition, (2) = HEC-18 5th edition and (3) = TAMU; D_{50} is the sieve size through which 50 percent of the material passes and D_{95} is the sieve size through which 95 percent of the material passes].

Input Parameter	Units	Relevant Methodology	Measurement Method	Factors affecting measurement accuracy	Type of flow
Flow velocity	m/s	(1), (2), (3)	Sounding weights (Columbous); velocity meter (price AA) hung from truckmounted crane with an expansible boom (pg. 12)	Multiple measurements near the pier across the upstream cross section to ensure maximum pier scour depth accuracy	High
Depth of flow	m	(1), (2), (3)	Sounding weights (Columbous); velocity meter (price AA) hung from truckmounted crane with an expansible boom; river-height measurements from a local datum (pg. 12)	Measured prior, during and after the depth and river flow measurements; snapshots of the flow conditions in the upstream and downstream channel and around the piers	High
Skew angle	Degrees	(1), (2), (3)	not applicable	not applicable	High
Pier width	m	(1), (2), (3)	Measuring tapes, surveying with an automatic level and rod, MDOT bridge plans (pg. 2)	Debris on the pier	Low
Pier length	m	(1), (2), (3)	Measuring tapes, surveying with an automatic level and rod, MDOT bridge plans	Debris on the pier	Low
Shape of pier nose	-	(1), (2), (3)	MDOT bridge plans (pg. 2)	From the bridge plans	Low
D_{50}	mm	(1), (3)	US BMH-60 bed-material sampler; Grid sampling & gravel template, MDOT divers (pg. 12)	Method depends on grain size	High
D_{95}	mm	(1)	US BMH-60 bed-material sampler; Grid sampling & gravel template, MDOT divers (method depends on grain size) (pg. 12)	Method depends on grain size	High
Pier spacing	m	(3)	not applicable	Sensitivity analysis (see Section 3)	not applicable

therefore the same for low and high erodibility soils using HEC-18 (all other factors being equal). The HEC-18 4th and 5th editions only differ by a single parameter (termed *k4* in the original source) which accounts for decrease in scour depth occurring from particle sizing variations. The parameter is removed from the 5th edition of HEC-18 (see Arneson et al. 2012).

2.4 *Input parameters*

Table 2 summarises the location of the input parameters required to calculate the maximum pier scour depth via the HEC-18 4th edition, HEC-18 5th edition and TAMU equations. Table 2 also explains how each parameter was measured in the field, and an indication of the accuracy of those measurements is also given based on the present authors review of the original study. All the parameters were provided by Hodgkins & Lombard (2002) and measurements of the grain sizes, the velocity, the depth of flow and the skew angle were all taken during high flows. Bridge dimensions were collected prior to any high flow event by using a variety of different methods including measuring tapes, surveying, and bridge plans. Pier spacing was the only parameter that was not available and was assumed as 10m in the analysis presented in this paper (note that pier spacing is only needed in the TAMU method).

3 ANALYSIS

Figure 1 compares the observed scour depth field data to the obtained values applying the HEC-18 4th edition method. Figure 1 indicates that HEC-18 4th edition method usually gives an overestimation of the measured scour (confirming the observation of Mueller 1996). One value (H1) is underpredicted by the method.

Figure 2 compares the observed scour field data to the predicted results from the HEC-18 5th edition. An overestimation of most of the field data is indicated on the plot. Two datapoints (H1 and F2) are underpredicted by the HEC-15 5th edition method.

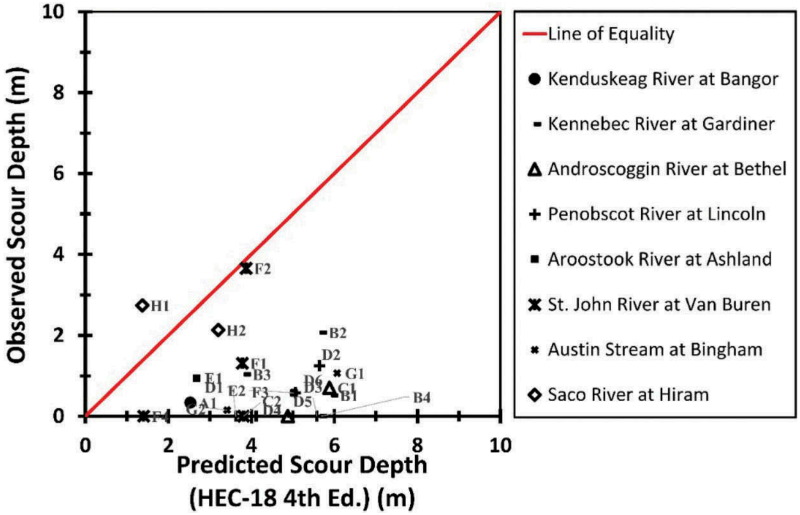

Figure 1. Observed field scour depths from Hodgkins & Lombard (2002) compared with predicted values using the HEC-18 4th edition method.

Figure 3 compares the observed scour field data from to the results for maximum pier scour from the TAMU method. The field scour depths are again overestimated by the method with pier H1 being the exception.

The TAMU methodology requires pier spacing (*S*) as an input which is not always available. Hodgkins & Lombard (2002) mentioned the use of bridge plans to determine the bridge dimensions. For this study, the bridge plans could not be sourced by the authors. The spacing calculation is used to estimate the influence factor to account for the effect of pier spacing on pier scour depth. Using constant spacing of 1, 3, 10 and 30m in the TAMU calculation for the 23 bridge piers and keeping all other parameters constant gives the results shown on Figure 5.

The variation in the maximum scour depth which is shown by Figure 4 shows that the less the spacing between piers, the greater the computed scour depth using the TAMU method. As spacing increases, the maximum scour depth stabilizes. In Figure 4 for instance, predictions using ‘*S* = 10m’ and ‘*S* = 30m’ are either the same or proximate in value.

Additionally, the critical velocity is also required to estimate maximum scour depth using the TAMU method. However, that the type of soil does not vary considerably across the database examined in this study, as all rivers were classed as low soil erodibility (Hodgkins & Lombard 2002, Arneson et al. 2012).

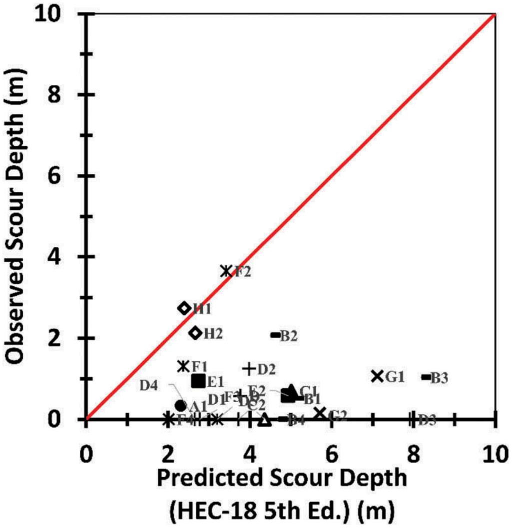

Figure 2. Comparison of observed field scour depths from Hodgkins & Lombard (2002) with values predicted using HEC-18 5th edition (legend as for Figure 1).

Figure 5 shows the difference between the estimated scour depths (for all three methods) and the measured field values plotted against the observed scour depth from the field. It can be tentatively concluded that all three methods struggle to estimate low values of scour as evidenced by the large scatter at low values shown on Figure 5 (although further data would be needed to confirm this hypothesis).

Figure 6 compares the observed scour data from Hodgkins & Lombard (2002) to the results calculated using all three scour estimation approaches. The three scour prediction methodologies reviewed in this paper appear to give similar results. The analysis of the three methods results tend to show an overestimation of scour depth, confirming the observations of Mueller (1996).

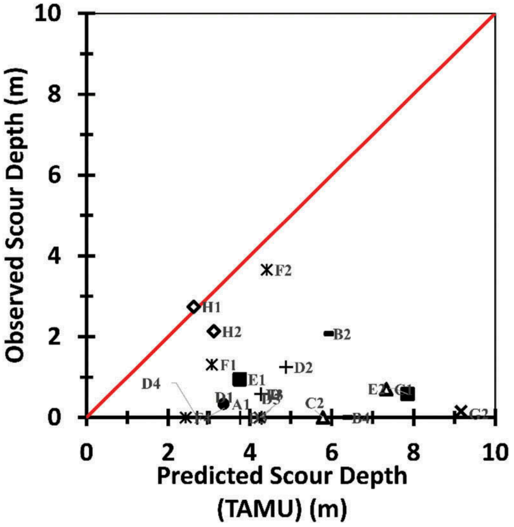

Figure 3. Comparison of observed field scour depths from Hodgkins & Lombard (2002) with values predicted using the TAMU method (legend as for Figure 1).

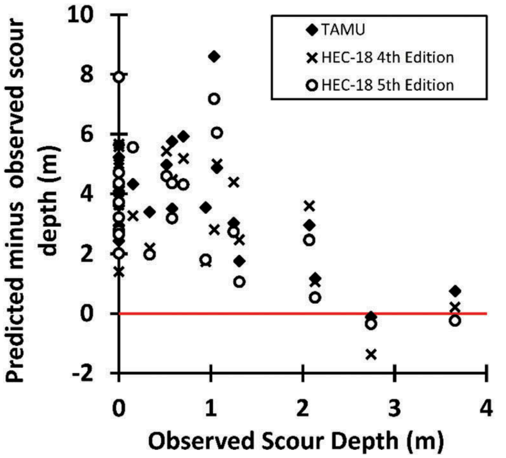

Figure 4. Predicted minus observed maximum scour value against observed field scour depths from Hodgkins & Lombard (2002).

4 DISCUSSION

As demonstrated by Figure 5, there is a general trend of overestimation of maximum pier scour depth. However, the sensitivity analysis performed for the spacing parameter reveals that the accuracy of a single parameter can considerably affect the results, and therefore further sensitivity studies with a larger database of scour measurements and a wider range of estimation methods is advocated for further work.

Future studies could also investigate the possible increase of maximum scour depth due to the rise in magnitude and intensity of future flood incidents because of climate change.

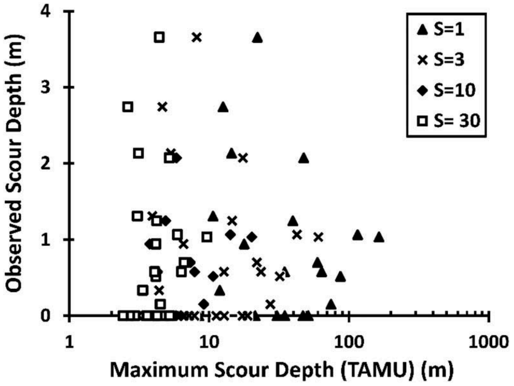

Figure 5. Effect of pier spacing in the TAMU calculation: observed field scour depths from Hodgkins & Lombard (2002).

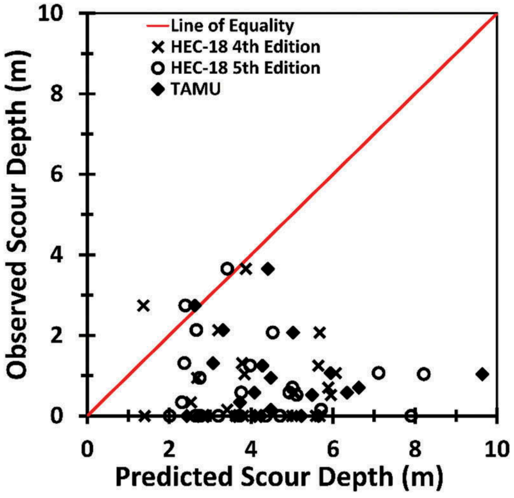

Figure 6. Comparison of observed field scour depths from Hodgkins &Lombard (2002) with predicted values from HEC-18 4th edition, HEC-18 5th edition and TAMU.

5 SUMMARY

The paper has reviewed three methods for scour assessment (HEC-18 4th edition, HEC-18 5th edition and TAMU) and shown that all generally overestimate the reported field scour measurements, which were retrieved from Hodgkins & Lombard (2002). Analysis of these and other methods with a larger dataset (e.g. Benedict & Caldwell 2014a, b) should be carried out, in particular to test the hypothesis that such assessment methods may not be suitable for estimating low scour values.

Overestimations of maximum scour depth while implying a degree of safety do not give an indication of actual field performance of bridge piers subjected to scouring effects. Therefore, conservative estimations will arguably lead to increased costs for the installation of scour countermeasures if specified for the assessed structures. However, it is acknowledged that some degree of conservatism is needed in this design context (cf. Zevenbergen 2010) and from an asset management perspective it would be useful to further quantify the general levels of conservatism with a wider range of scour assessment methodologies.

Changes to weather patterns and climate change effects may result in significant changes to the hydraulic loads on bridge structures (cf. Dikanski et al. 2017). Therefore, scour assessment methodologies should be examined further to determine the current level of conservatism in scour estimations and how this may change with increasing hydraulic demand.

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DATA AVAILABILITY

This study has produced no new experimental data.

REFERENCES

Abd El-Hady Rady, R. 2020. Prediction of local scour around bridge piers: artificial-intelligence-based modeling versus conventional regression methods. *Applied Water Science* 10 (2): [57].

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/hydrau-lics/pubs/hif12003.pdf> [22/02/2022]

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 PierScour Database (PSDb – 2014). US Geological Survey, Reston, VA, USA, Version 1.0. See https://pubs.usgs.gov/ds/0845/ [22/02/2022].

Briaud, J-L., Hurlebaus, S., Chang, K-A., Yao, C., Sharma, H., Yu, O-Y., Darby, C., Hunt, B.E. & Price, G. R. 2011. Realtime monitoring of bridge scour using remote monitoring technology. *Report 0-6060-1*. Texas, USA: Texas Transportation Institute. <http://tti.tamu.edu/documents/0-6060-1.pdf> [22/02/2022].

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].

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].

Dikanski, H., Boulent, I., Zanker-Hagen, A. & Avery, K. 2017. Climate change impacts on railway structure: bridge scour, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 170(5): 237–248.

Ding, Y., Yan, T., Yao, Q., Dong, X. & Wang, X. 2016. A new type of temperature-based sensor for monitoring of bridge scour. *Measurement* 78: 245–252.

Ettema, R., Constantinescu, G. & Melville, B. 2017. Flow-field complexity and design estimation of pier-scour depth: sixty years since Laursen and Toch. *Journal of Hydraulic Engineering* 143 (9): [03117006].

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>[22/02/2022].

Kallias, A.N. & Imam, B. 2016. Probabilistic assessment of local scour in bridge piers under changing environmental conditions, *Structure and Infrastructure Engineering* 12(9): 1228–1241.

Landers, M.N. & Mueller, D.S. 1993. Reference surfaces for bridge scour depths. In Shen, H.W. et al. (eds.), *Hydraulic Engineering 1993-Proceedings of the National Conference on Hydraulic Engineering*, July 25-30, San Francisco, CA: 2075–2080. New York, American Society of Civil Engineers.

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

Mueller, D.S. 1996. Local Scour at Bridge Piers in Nonuniform Sediment Under Dynamic Conditions. *Ph.D. thesis*, Colorado State University, Fort Collins, CO, USA.

Network Rail 2015. Climate Change Adaptation Report 2015. Available from: <https://www.networkrail.co.uk/wp-con-tent/uploads/2019/05/Climate-Change-Adaptation-Report-2015-FINAL.pdf> [22/02/2022].

Pregnolato, M., Vardanega, P.J., Limongelli, M.P., Giordano, P.F. & Prendergast, L.J. 2021. Risk-based scour management: A survey. In Yokota, H. & Frangopol, D.M. (eds.), *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Japan, 11-15 April 2021*: 693–701, The Netherlands, CRC Press/Balkema Taylor & Francis Group.

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): 2089–2105.

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/hydrau-lics/pubs/hec/hec18.pdf> [22/02/2022].

Schuring, J.R., Dresnack, R. & Golub, E. 2017. Design and Evaluation of Scour for Bridges Using HEC-18 (Volume 1 of 3), *Report no. FHWA-NJ-2017-011*. Available from: <https://rosap.ntl.bts.gov/view/dot/32878> [22/02/2022].

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.

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.