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Comparison of maximum scour estimations using the HEC-18 method with field data from the USGS database

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Abstract. A-priori estimates of maximum scour depth are important for bridge engineers, managers and owners. HEC-18 is an established method which uses empirical equations to estimate bridge scour. This paper applies the HEC-18 methodology to compute maximum scour depth for 936 bridge piers for which field scour depth measurements are available from an online database from the United States Geological Survey (USGS). The results are in general agreement with past research efforts which suggest that the HEC-18 methodology tends to overestimate maximum bridge pier scour depth. The database is also categorized into various sub-sets to study the effect of different particle sizes and devices used to measure scour in the field.

Keywords: Bridge Scour; HEC-18; Databases

1 INTRODUCTION

The exposure of bridge foundations due to scour is a major reason for structural failure (e.g. Maddison 2012, Ettema *et al.* 2017). Bridges are important links between settlements, especially during emergencies; therefore, it is essential to maintain them to ensure continued operation. The accurate estimation of potential bridge scour remains a challenge for engineers because to measure scour is proven to be difficult during times of high flow due to challenges such as debris concentration and strong currents (cf. Arneson *et al.* 2012).

The HEC-18 is an established method to estimate scour depth (e.g. Arneson *et al.* 2012, Calappi *et al.* 2012, Briaud 2015). The method comprises a series of empirical equations calibrated with laboratory flume test data (e.g. Zevenbergen 2010, Briaud 2015, Qi *et al.* 2016). Despite being popular, the method is reported to give conservative estimates of field scour (Johnson 1995, Mueller and Wagner 2002, Zevenbergen 2010, Briaud *et al.* 2014, Qi *et al.* 2016).

A database of field scour depth measurements is available from the United States Geological Survey (USGS) (Benedict and Caldwell 2014a, b, USGS 2004). The USGS database provides a series of reports, which contain information on pier dimensions, soil characteristics and flow characteristics for the bridges of interest. The database includes data from measurements taken on 936 bridge piers for which data has been extracted using seven different measurement approaches (summarised in Table 1).

This paper aims to: (1) compare estimations from the HEC-18 maximum pier scour assessment methodology to the measured data available from USGS field database; (2) examine the accuracy of the HEC-18 estimations for different sub-sets of the database (as outlined below); and (3) compare the accuracy of the HEC-18 calculations undertaken with the field database measurements and with the findings from previous studies (Zevenbergen 2010, Qi *et al.* 2016).

Regarding aim (2), different subsets were used to study the consistency of the results across the dataset. The subsets studied relate to the river bed material particle size: (a) $D_{50} \leq 0.99$mm, (b) $0.99 < D_{50} \leq 9.99$mm, (c) $D_{50} > 9.99$mm; and the scour measurement device used: (d) fathometer soundings, (e) Bludworth fathometer, (f) Ground Penetrating Radar (GPR), (g) Acoustic Doppler Current Profiler (ADCP) and (h) 'Scour depth based on ambient bed' from a nearby station (USGS 2004).

Table 1. Description of measuring devices used to take the scour depth measurement for the 936 piers.

Measuring Method	Description	Source
GPR	Ground penetrating radar with dual 80-MHz antennae that transmit electromagnetic pulses into the subsurface	Butch (1991), Mueller *et al.* (1994), Wilson (1995)
Sounding Fathometer	Soundings with a lead weight producing discrete sound noise of the cross section in combination with "Eagle Model Mach 1 Graph recording" fathometer producing continuous soundings	Norman (1975), Butch (1991), Wilson (1995), Atkins and Hedgecock (1996), Hayes (1996), Holnbeck (2011)
Bludworth fathometer	In combination with ultrasonic devices	Jarrett and Boyle (1986)
ADCP	Using a portable acoustic doppler current profiler	Holnbeck (2011), Benedict and Caldwell (2014a, b)
Ambient Bed	'Scour depth based on ambient bed' from a nearby station	USGS (2004)

2 METHODOLOGY

This paper uses the HEC-18 method to assess maximum pier scour for 936 bridge piers using the USGS database (Benedict and Caldwell 2014a, b, USGS 2004). In this paper, the HEC-18 framework (Arneson *et al.* 2012) was used, however the 'armouring coefficient' (K_4) was not applied to Eq. 1 because of the assumption of a uniform riverbed material size (see Eq. 1); moreover, the relevant equation for the K_4 coefficient has been said to be unreliable according to Zevenbergen (2010). More details on the input parameters used in this work are detailed by Gavriel *et al.* (2022) and Gavriel *et al.* (2023). Gavriel *et al.* (2023) present a 'one-at-a-time' sensitivity study to investigate the relative influence of some key input parameters for the HEC-18 framework. Eq. 1 is taken from Arneson *et al.* (2012, p. 7.3) along with the definitions of the equation terms:

$$y_s = 2.0 y_1 K_1 K_2 K_3 \left(\frac{a}{y_1}\right)^{0.65} Fr_1{}^{0.43} \tag{1}$$

where: y_s is the 'scour depth', y_1 is the 'flow depth directly upstream of the pier', K_1 is the 'correction factor of the pier nose shape', K_2 is 'the correction factor for angle of attack of flow', K_3 is the 'correction factor for bed condition', α is the 'pier width', L is the pier length and Fr_1 is the 'Froude number directly upstream of the pier'(Arneson *et al.* 2012, p. 7.3).

The pier length (L) was not available for 33% (309/936) of the database. To carry out the analysis presented in Tables 2 to 4, the unknown L inputs were calculated as a ratio of the pier width, α i.e. using $L = 11.7\alpha$. 11.7 is the average of the 627 known L/α values.

3 RESULTS

Fig. 1a shows the results from the HEC-18 analysis using the USGS database (Benedict and Caldwell 2014a, b, USGS 2004). The plot confirms the general findings of Johnson (1995), Mueller and Wagner (2002), Zevenbergen (2010), Briaud *et al.* (2014) and Qi *et al.* (2016) who reported that HEC-18 overestimates scour depth. In particular, 89.6% of the analysed dataset is overestimated by HEC-18. A detailed analysis of the findings is summarized in Table 2. However, the results do not align with the observations of Zevenbergen (2010) and Qi *et al.* (2016) who both reported that ≈70% of their studied datapoints lie within ± 30% from the line of equality. Only 13.2% of the predictions lie within the ± 30% boundaries for the dataset examined in this paper.

Fig. 1a shows 22.1% of the data points concentrated within the ± 50% bounds (see Table 2). Additionally, 548/936 (≈ 60% of the database) points correspond to scour depth estimations < 2m. Fig. 1b shows all scour depth estimations < 2m. In this case, 83.6% of the points are overestimated by HEC-18. The percentage of predictions within the ± 30% bounds is 15.9% (87/548) (Table 3), which is slightly larger than the percentage of all the data with the ± 30% bounds (13.2%) (124/936) (Table 2). When considering the ± 50% bounds, 23.9% (131/548) of the database lies in this region (Table 3).

Figs. 2a and 2b show the same data presented on Figs. 1a and 1b but with factor 1.3 and 1.5 bounds drawn. For the USGS dataset, only 10.8% of the data lie within the factor 1.3 bounds, whereas 14.4% of the points lie within the 1.5 factor bounds (Figure 2a). For the scour depth < 2m, 13.3% of the dataset lies within a factor of 1.3 whereas 16.6% lies within a factor of 1.5. The full results of this analysis are presented in Table 4.

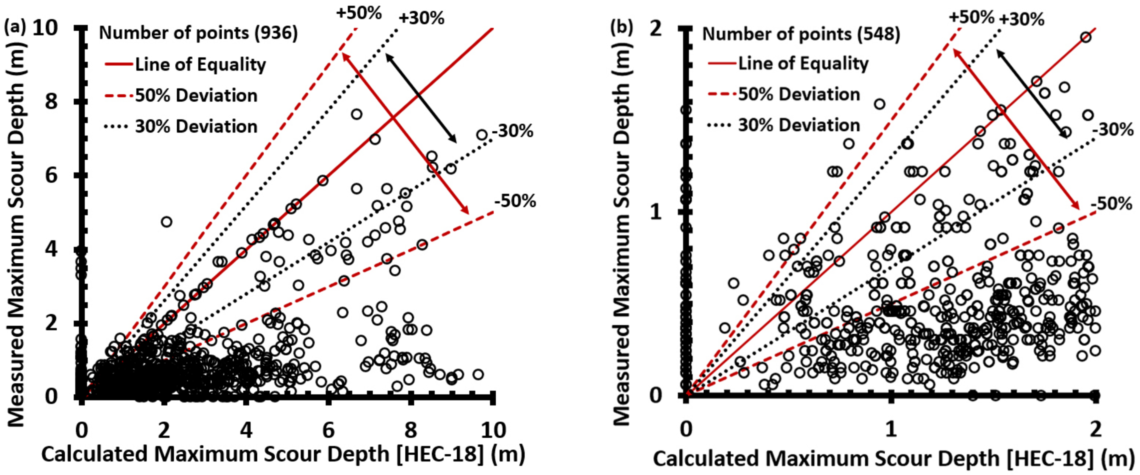

Figure 1. (a) Comparison of observed field scour depths from the USGS database with calculated values from the HEC-18 5th edition for $y = x \pm 0.3x$ and $y = x \pm 0.5x$ bounds (plot adapted from Gavriel *et al.* 2023) (b) comparison of observed field scour depths < 2m from USGS data with calculated values from the HEC-18 5th edition for $y = x \pm 0.3x$ and $y = x \pm 0.5x$ bounds.

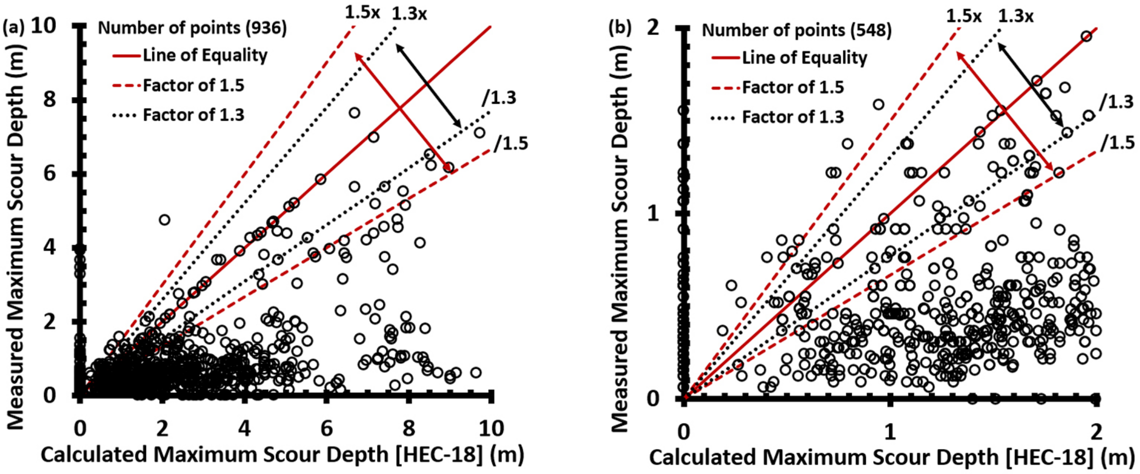

Figure 2. (a) Comparison of observed field scour depths from the USGS database with calculated values from the HEC-18 5th edition for $y = 1.3x$; $y = x/1.3$; $y = 1.5x$ and $y = x/1.5$ bounds (b) comparison of observed field scour depths < 2m from USGS data with calculated values from the HEC-18 (5th edition) for $y = 1.3x$; $y = x/1.3$; $y = 1.5x$ and $y = x/1.5$ bounds.

4 DISCUSSION

For 309 datapoints L was unknown. To assess if the assumption of $L = 11.7\alpha$ is acceptable (Fig. 3b), scour depth for $L = 5.85\alpha$ (half of 11.7) (Fig. 3c) and scour depth for $L = 23.4\alpha$ (double 11.7) (Fig. 3d) were calculated for all the database records with unknown L values. The calculated scour depths for the unknown L values (Fig. 3b,c,d) are compared against the results calculated for the given L values (Fig 3a) in Fig. 3. For pier scour depth for $L = 5.85\alpha$ (Fig. 3c), 27.8% (86/309) of the datapoints lie within the ± 50% bounds, for $L = 11.7\alpha$ (Fig. 3b), 27.8% (86/309) of the datapoints lie within the ± 50% bounds and for the $L = 23.4\alpha$ (Fig. 3d), 26.5% (82/309) lie within the ± 50% bounds, whereas for the known L (Fig 3a), 19.3% (121/627) of the datapoints lie within the ± 50% bounds. For about 75% of the database the value of the estimated scour depth remains the same, regardless of the value of L. Therefore it is reasonable to assume $L = 11.7\alpha$ for the unknown L values for the dataset studied in this paper. When L changes between $L=5.85\alpha$ to $L=23.4\alpha$ (Fig. 3b and d) the scour depth remains unchanged for 90.9% (281/309) of the database. For the 9.1% (28/309) of the database for which scour depth changes when L changes, scour depth increases by 37% on average, when L increases from $L = 5.85\alpha$ to $L = 11.7\alpha$ and 44% on average when L increases from $L = 11.7\alpha$ to $L = 23.4\alpha$.

Table 2. Statistical analysis of the USGS database against HEC-18 estimations of maximum scour depth. In 16 cases, the estimated scour depth was equal to the observed scour depth to two decimal points: these 16 cases have been added to the overestimated values to calculate the percentages shown (*n* = number of datapoints).

Subset	Total		Underestimated		Overestimated		within ± 30%		within ± 50%	
	n	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)
All data	936	100	97	10.4	839	89.6	124	13.2	207	22.1
Bed material gradation										
$D_{50} \leq 0.99$mm	436	46.6	60	6.5	376	40.2	91	9.7	152	16.2
$0.99 < D_{50} \leq 9.99$mm	148	15.8	6	0.6	142	15.1	16	1.7	24	2.6
$D_{50} > 9.99$mm	352	37.6	31	3.3	321	34.3	17	1.8	31	3.3
Scour measurement technique										
GRP	16	1.7	2	0.2	14	1.5	1	0.1	1	0.1
Fathometer Soundings	624	66.7	82	8.9	542	58.0	81	8.6	141	15.1
Bludworth Fathometer	63	6.7	1	0.1	62	6.6	2	0.2	4	0.4
ADCP	17	1.8	5	0.5	12	1.3	9	1.0	12	1.3
Ambient Bed	28	3.0	0	0.0	28	3.0	0	0.0	0	0.0
Not specified	188	20.1	7	0.7	181	19.2	31	3.3	49	5.2

D_{50} = soil sieve size through which 50% of the material can pass

Table 2 shows the summary statistical analysis of the different categories in terms of percentage over and underestimated datapoints and percentage of datapoints which lie within the ± 30% and ± 50% bounds. To explore possible trends, the data is categorized in terms of particle size and in terms of the measuring devices used to take the readings in the field. Table 3 summarises the statistical analysis of the different categories for scour depth less than 2m to investigate whether HEC-18 is more accurate for lower scour depth values. In terms of overestimation, in all cases with the exception of the GPR (1/3) (33.3%) and ADCP (0%), more than 80% of the datapoints are overestimated by the HEC-18 calculations presented in this paper.

There is, however, a difference in the percentage of datapoints lying within the ±30% boundaries depending on the subcategory. For the scour depths which are below 2m (Table 3), a higher percentage of datapoints lie within the ± 30% and ± 50% bounds, in comparison to Table 2 which represent all 936 scour depths in the database. When considering the all the 936 datapoints (Table 2), 34.9% (152/436) of the datapoints with $D_{50} \leq 0.99$mm lie within the ± 50% bounds, whereas a similar percentage of 34.2% (100/292) is found for the 548 datapoints for scour depth < 2m and with $D_{50} \leq 0.99$mm (Table 3). The percentage of datapoints which lie within the ± 50% bounds for the $0.99 < D_{50} \leq 9.99$mm subset decreases from 16.2% (24/148) (Table 2) to 13.1% (8/61) (Table 3).

Table 3. Statistical analysis of the USGS database against HEC-18 estimations of maximum scour depth less than 2m. In four cases, the estimated scour depth was equal to the observed scour depth to two decimal points: these four cases have been added to the overestimated values to calculate the percentages shown.

Subset	Total		Underestimated		Overestimated		within ± 30%		within ± 50%	
	n	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)
Scour depth < 2m	548	100	90	16.4	458	83.6	87	15.9	131	23.9
Bed material gradation										
$D_{50} \leq 0.99$mm	292	53.3	56	10.2	236	43.1	63	11.5	100	18.2
$0.99 < D_{50} \leq 9.99$mm	61	11.1	5	0.9	56	10.2	14	2.6	8	1.5
$D_{50} > 9.99$mm	195	35.6	29	5.3	166	30.3	10	1.8	23	4.2
Scour measurement technique										
GRP	3	0.5	2	0.4	1	0.2	0	0.0	1	0.2
Fathometer Soundings	461	84.2	80	14.5	381	69.6	78	14.3	118	21.6
Bludworth Fathometer	24	4.4	1	0.2	23	4.2	0	0.0	3	0.5
ADCP	2	0.4	2	0.4	0	0.0	0	0.0	0	0.0
Ambient Bed	3	0.5	0	0.0	3	0.5	0	0.0	0	0.0
Not specified	55	10.0	5	0.9	50	9.1	9	1.6	9	1.6

Table 4. Statistical analysis of the USGS database against HEC-18 estimations of maximum scour depth: number of points within factor 1.3 and 1.5 bounds given in the table.

	All data (*n* = 936)				Scour depth < 2m (*n* = 548)			
Subset	within factor 1.3		within factor 1.5		within factor 1.3		within factor 1.5	
	n	(%)	*n*	(%)	*n*	(%)	*n*	(%)
Total	101	10.8	135	14.4	73	13.3	91	16.6
Bed material gradation								
$D_{50} \leq 0.99$mm	75	8.0	98	10.5	56	10.2	66	12.0
$0.99 < D_{50} \leq 9.99$mm	11	1.2	17	1.8	9	1.6	14	2.6
$D_{50} > 9.99$mm	15	1.6	20	2.1	8	1.5	11	2.0
Scour measurement technique								
GRP	0	0.0	1	0.1	0	0.0	1	0.2
Fathometer Soundings	70	7.5	86	9.2	67	12.2	81	14.7
Buldwidth Fathometer	2	0.2	2	0.2	2	0.4	2	0.4
ADCP	8	0.9	10	1.1	0	0.0	0	0.0
Ambient Bed	0	0.0	0	0.0	0	0.0	0	0.0
Not specified	21	2.2	36	3.8	4	0.7	7	1.3

HEC-18 appears to be more accurate for scour depth estimations for lower particle size, i.e. as the particle size increases, the accuracy of the result decreases. In Table 2, the percentage of data points within the ±30% bounds decreases from 20.9% (91/436) for the $0 < D_{50} \leq 0.99$mm category to 4.8% (17/352) for the $D_{50} > 9.99$mm category. Similarly in Table 3, the percentage of points lying between the ± 30% bounds decreases from 21.6% (63/292) to 5.1% (10/195) for $D_{50} < 0.99$mm and $D_{50} > 9.99$mm respectively.

In terms of scour depth measurement, fathometer soundings are the most prevalent measuring technique in the database. The percentage of datapoints which lie within the ± 30% bounds for fathometer soundings increases for scour depth < 2m (cf. Tables 2 and 3). This increase also occurs for the ± 50% bounds with respect to the fathometer soundings sub-category. The scour depth measurement technique was unknown for about 20.1% of the scour datapoints in the database.

Table 5 summarises the number of points which lie within the different bounds studied in this paper. Table 5 shows that for the categories listed in the table, more points lie within the ± 30% and ± 50% bounds in comparison to the 1.3 factor and 1.5 factor bounds respectively, as would be expected.

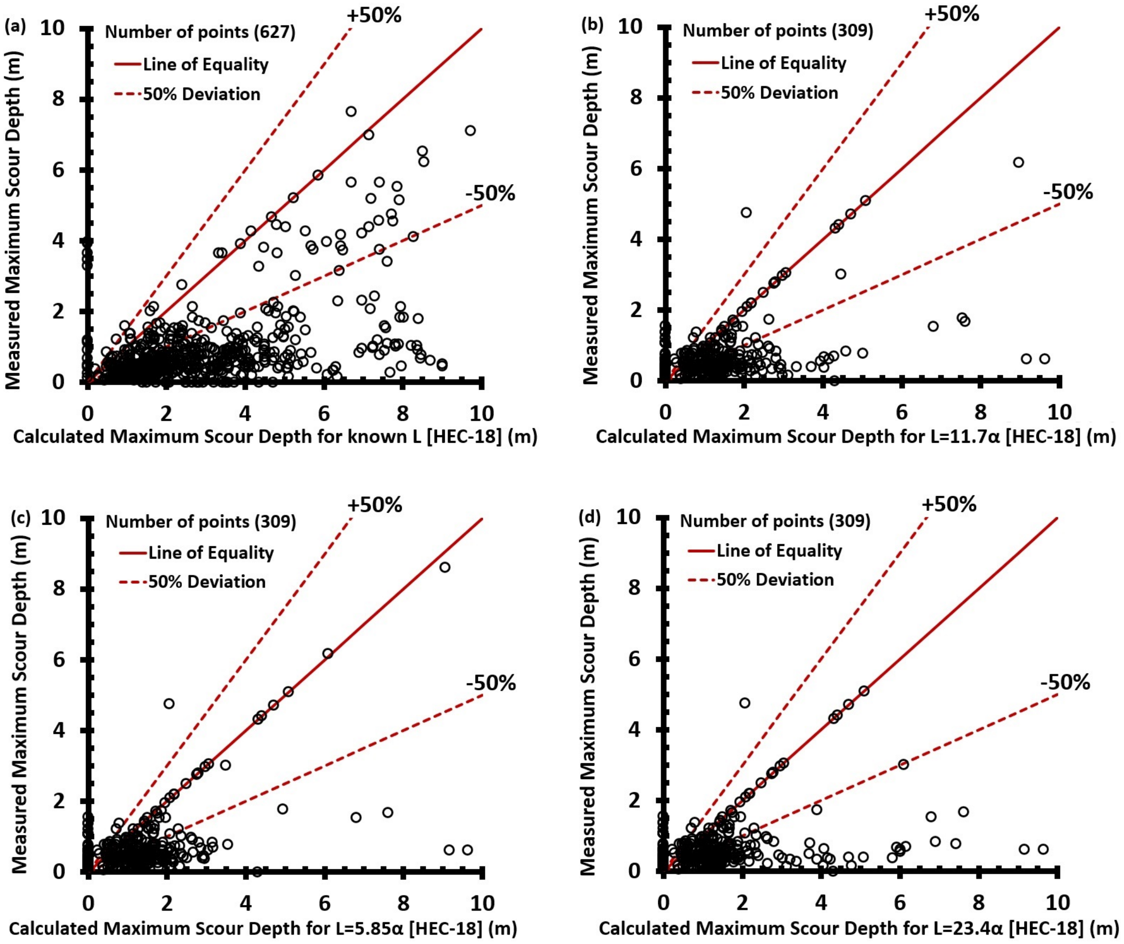

Figure 3. Comparison of observed field scour depths from the USGS database with calculated values from the HEC-18 5th edition for (a) known *L*; (b) *L=5.85α*;(c) *L=11.7α*; (d) *L=23.4α*

Table 5. Summary of points within the boundaries for each of the categories proposed.

Category	*n*	(%)
All data (n = 936)		
Factor of 1.3	101	10.8
±30%	124	13.2
Factor of 1.5	135	14.4
±50%	207	22.1
Scour Depth < 2m (n = 548)		
Factor of 1.3	73	13.3
±30%	87	15.9
Factor of 1.5	91	16.6
±50%	131	23.9

5 SUMMARY AND CONCLUSIONS

The paper compared the HEC-18 predictions of scour depth with measured bridge pier scour depth for over 936 field data available from the USGS database. The findings of other researchers who reported that HEC-18 overestimates maximum field scour measurements were confirmed. The paper observed that HEC-18 is more accurate when estimating scour depth < 2m (cf. Table 5). The results were split into subcategories in terms of particle size and the scour measuring devices used. It was concluded that the greater the particle size the less accuracy of the HEC-18 estimations for the data considered here. The preliminary findings presented in this paper should be further tested with more detailed statistical analyses and other datasets.

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