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Checking the Accuracy of Selected Formulae for both Clear Water and Live Bed Bridge Scour

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ABSTRACT

Due to severe scouring, many bridges failed worldwide. Therefore, the safety of the existing bridge (after contrition) mainly depends on the continuous monitoring of local scour at the substructure. However, the bridge's safety before construction mainly depends on the consideration of local scour estimation at the bridge substructure. Estimating the local scour at the bridge piers is usually done using the available formulae. Almost all the formulae used in estimating local scour at the bridge piers were derived from laboratory data. It is essential to test the performance of proposed local scour formulae using field data. In this study, the performance of selected bridge scours estimation formulae was validated and statistically tested using field data for existing bridges in Canada, Iraq (Kufa, Najaf), Pakistan, Bangladesh, and India. The validated formulae were HEC-18, Forehlich, and Johnson. The validation was conducted by comparing the predicted local scour depths obtained from applying the above-selected formulae with the local scour depths obtained from the field data. The comparison between them was presented using a scattergram. However, statistical tests were used to present the accuracy of the local scour predictions. The tests were conducted using three statistical indices, namely, Theil's coefficient (U), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE). Among the tested formulae, the Jonson formula gave satisfactory performance since the values of U, MAE, and RMSE were found to be 0.112, 1.351, and 1.650, respectively.

Keywords: Local scour, bridge pier, Kufa bridge, field data, scour formulae**.**

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التحقق من دقة صيغ المعادلات المحددة لكل من انجراف المياه النقية و الانجراف الحي للجسر

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الخلاصة

بسبب الانجراف الشديد ، فشل العديد من الجسور في جميع أنحاء العالم. لذلك ، تعتمد سلامة الجسر الحالي بشكل أساسي على المراقبة المستمرة للانجراف في البنية التحتية. ومع ذلك ، فإن سلامة الجسر قبل البناء ، تعتمد بشكل أساسي على النظر في تقدير الانجراف في البنية التحتية للجسر. عادة ما يتم تقدير الانجراف المحلي عند دعامة الجسر باستخدام الصيغ المتاحة. تم اشتقاق جميع الصيغ تقريبًا المستخدمة في تقدير الانجراف عند دعامة الجسر من البيانات المختبرية ومن الضروري اختبار أداء الصيغ المقترحة باستخدام البيانات الميدانية. في هذه الدراسة ، تم التحقق من صحة أداء معادلات تقدير انجراف الجسور المختارة واختبارها إحصائيًا باستخدام البيانات الميدانية للجسور المقامة في كندا والعراق (الكوفة والنجف) وباكستان وبنغلاديش والهند. كانت الصيغ التي تم التحقق من صحتها هي HEC-18 و Forehlich و Johnson. تم إجراء التحقق من خلال مقارنة أعماق الانجراف المحلي المتوقع الذي تم الحصول عليه من تطبيق الصيغ المختارة أعلاه مع أعماق الانجراف المحلي الذي تم الحصول عليه من البيانات الميدانية. تم عرض المقارنة بينهما باستخدام الشكل البياني. ومع ذلك ، تم استخدام الاختبارات الإحصائية لتقديم دقة التنبؤات المحلية. تم إجراء الاختبارات باستخدام ثلاثة مؤشرات إحصائية هي معامل ثيل (U) ومتوسط الخطأ المطلق (MAE) ومتوسط الخطأ التربيعي الجذر (RMSE). من بين الصيغ المختبرة أعطت صيغة Jonson أداءً مرضيًا حيث أن قيم U و MAE و RMSE كانت 0.112 و 1.351 و 1.650 على التوالي.

الكلمات الرئيسية: الانجراف المحلي، دعامة الجسر، جسر الكوفة، بيانات حقلية، صيغ معادلات الانجراف

1. INTRODUCTION

A hydraulics-related factor is responsible for roughly 60% of all bridge failures. Scour is the most common cause of bridge failure, accounting for one of the top three reasons globally **(Pruebas, 2020)**. The failure of the Sava bridge, in Croatia, the Malahide Viaduct bridge, in Ireland, and the Hintze Ribeiro Bridge, in Portugal, are some recent examples of bridge failures by scour in Europe. Scour is the most common cause of bridge failure in the United States. Data collected between 1989 and 2000 showed that only 53 bridges out of more than 500 failed due to human error, while the rest failed by scour. As a result of climate change, rainfall regimes and snow melting patterns will change and increase flooding frequency and intensity. Thus, the vulnerability of bridges to scouring will increase. In the next 20 years, and according to simulations conducted by the European Commission using climate change scenarios, roughly 20% of the bridges in Europe will be in great danger due to scouring. This number varies by country, but the largest dangers are expected in Austria (60%), Portugal (50%), Spain (42%), and Italy (39%) **(Pruebas, 2020)**.

Civil engineers are focusing on the bridges' structural design without paying any attention to hydraulic design. Scouring at the site of bridges should be considered at the design stage. Many formulae for estimating local scour at the bridge are available in the literature, and these formulae need to be checked for accuracy. However, most of these formulae were proposed based on laboratory work. The performance of these formulae needs to be assessed using field data.
From previous studies, the most often used and acknowledged local scour formulas or models were put to the test to see how accurate they were**(Mohamed et al., 2006)**.
Through the usage of dynamic color coding and visualization strategies, GIS techniques were employed to repair the Barboni Bridge and Al-Qadisiyah Bridge in Al-Muthanna Governorate, Iraq **(Aattan and Al-Bakri, 2020).** In a laboratory flume, a series of tests were conducted to determine the impact of the silt wire location on scour depth and scour area upstream of the weir site**(Al-Hassani and Mohammad, 2021).**
In this study, field data is used to assess the performance of the selected formula used for the estimation of local scour depth at bridges located around the world. The scour at Kufa bridge, Najaf Governorate in Iraq, was measured locally by using an M9 device for river survey works. Besides the data on bridges in India, Bangladesh, Pakistan, and Canada, the field data of the Kufa bridge was used for checking the accuracy of the formulae.

2. METHODOLOGY

2.1 The Case Study

The Kufa bridge is an essential old structure in the city of Najaf, Iraq. The bridge was built in the period (1954-1957). It consists of four openings separated by three single piers with a total length of 166 m. The width of each pier is two meters, and the space between any two successive piers or the pier and abutment is 44.5 m. In addition, field data for bridges in India, Bangladesh, Pakistan, and Canada were borrowed from the literature.

2.2. Field Measurements

In this study, the scour depth at the piers of the Kufa Bridge was measured locally using an M9 device. The surveyed cross-section of the Euphrates River at the location of the Kufa bridge is shown in **Fig. 1**. Section A-A was taken one meter from the pier nose towards downstream as shown in **Fig. 2**. From the surveyed section, the maximum scour depth was identified and then used with the other published field data on bridges scour in India, Bangladesh, Pakistan, and Canada for assessing selected formula for clear water scour prediction.

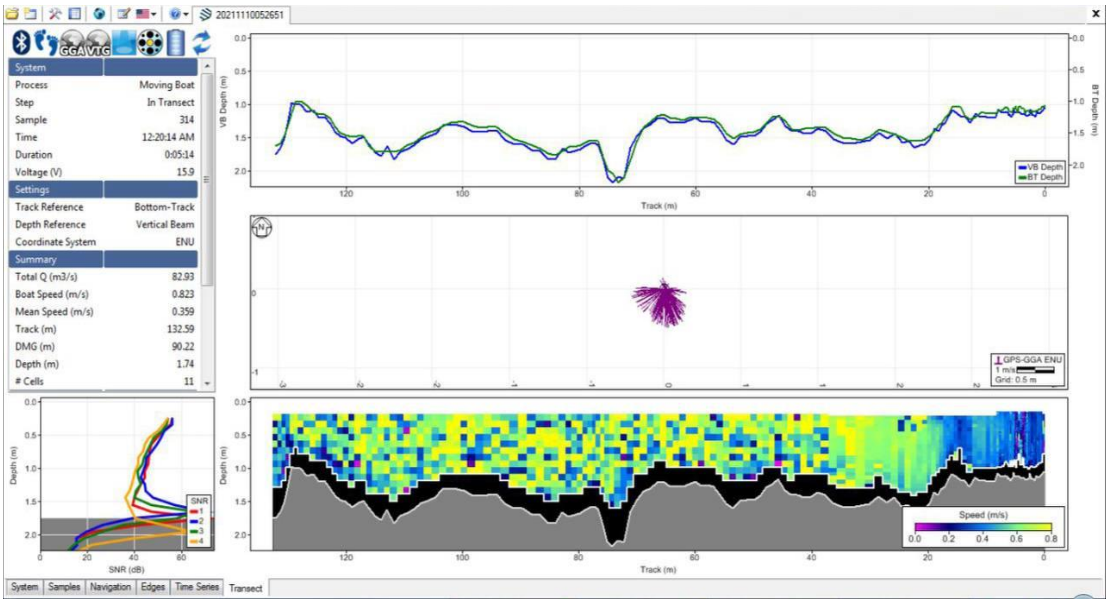


Figure 1. The recorded Kufa bridge profile by M9

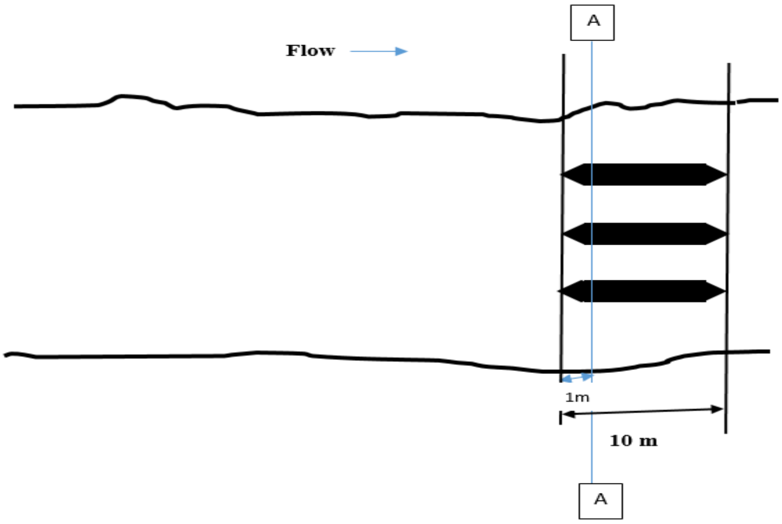


Figure 2. The site of the section in the Euphrates River

2.3 Selected Formulae for Estimation of Local Scour Depth

The following formula is selected for the estimation of local scour at the bridge pier:

2.3.1 HEC-18 pier scour formula

The HEC-18 pier scour formula (based on the Colorado State University, CSU formula)(Edition, 1991) is suggested for both live-bed, and clear-water pier scour. Maximum pier scour depths can be predicted using this formula. Simple pier substructure layouts and riverine flow scenarios in alluvial sand-bed channels are some of the most basic uses.

$$\frac{Y_s}{Y_1} = 2 * K_s * K_2 * K_3 * \left[\frac{b}{Y_1}\right]^{0.65} * Fr^{0.43} \quad (1)$$

Y_s is scour depth (m), K_s is a factor for the pier shape, K_2 factor for the angle of attack, K_3 factor for the type of scour (clear water or live bed), Y is the flow depth directly upstream of the pier (m), b is the pier width (m), and Fr is the Froude number.

2.3.2 Forehlich formula

The maximum relative depth of local live-bed scour at a bridge pier was calculated using a linear regression analysis of the measurement data collected on-site **(Forehlich, 1988).**

$$\frac{Y_s}{b} = 0.32 * K_s * Fr^{0.2} * \left[\frac{b_p}{b}\right]^{0.62} * \left[\frac{h}{b}\right]^{0.46} * \left[\frac{b}{d_{50}}\right]^{0.08} + 1 \quad (2)$$

Y_s is the scour depth (m), b is the width of the pier (m), b_p is the projected width of the pier (m), Y is the flow depth (m), Fr is the Froude number, and K_s is a factor for shape.

2.3.3 Johnson formula

In 1995, a formula was proposed for both live bed, and clear water scour based on field data **(Johnson, 1995)**.

$$Y_s = 1.35 * b^{0.7} * Y^{0.3} \quad (3)$$

where Y_s is scour depth (m), b is pier width (m), and Y is the flow depth (m)

3. RESULTS AND DISCUSSION

In this study, field data for bridges in Iraq, India, Bangladesh, Pakistan, and Canada were used to validate the selected scour estimation formulae. The data shown in **Table 1.** includes the name of the bridge, the geographical location of the bridge, year of measurement, approach velocity (v), the median size of the river bed material (d_{50}), water depth just upstream of the bridge site (y), and the pier width (b). The data showed that the values of the approached velocities ranged from 0.4 to 2.8 m/s, the d_{50} of the bed materials ranged from 0.2-0.5 mm, the water depths ranged from 1.3 to 8.2 m, and the piers width range from 1.5-9.15m.

Table 1. Selected data on bridges

Site	year	velocity (m/s)	d_{50} (mm)	y (m)	b (m)
Al Kufa bridge	2021	0.455	0.3	1.31	2
Shahdara railway bridge	1948	1.455	0.3	5.08	3.05
	1949	1.407	0.3	4.77	3.05
	1950	1.773	0.3	7.49	3.05
	1951	1.393	0.3	4.66	3.05
	1952	1.378	0.3	4.66	3.05
	1953	1.476	0.3	5.27	3.05
	1954	1.707	0.3	6.94	3.05
	1955	1.595	0.3	6.13	3.05
	1956	1.458	0.3	5.13	3.05
	1957	1.770	0.3	7.47	3.05
	1958	1.683	0.3	6.66	3.05
Barhamaputra bridge	1938	2.869	0.39	18.14	6.1
Par railway bridge	1941	2.116	0.33	10.67	3.96
Jhelum bridge	1938	1.509	0.32	5.64	6.1
Alexandra bridge	1938	1.710	0.37	6.52	3.05
Chenab bridge	1933	1.819	0.34	7.56	6.1
Chenab bridge	1932	1.849	0.34	7.74	7.62
Ravi bridge	1942	1.494	0.24	6.16	6.1
Sulej bridge	1929	1.533	0.32	5.61	6.1
Sulej brigde near adamwahan	1933	1.688	0.2	6.77	4.27
Chenab bridge at chund	1936	1.592	0.3	7.53	6.1
Beaver crossing	1962	1.465	0.5	7.05	1.83
Lacorey crossing	1962	1.366	0.5	6.12	1.52
Broad gauge railway bridge	1970	1.515	0.3	5.44	9.15
	1971	1.385	0.3	4.54	9.15

3.1 Determination of Scour Type (Clear Water or Live Bed) in Nonuniform Alluvial Bed

In nature and particularly in rivers, the sediment has nonuniform size distribution. It is usual to take the median size, d_{50}, as a representative size of sediment **(Subramanya, 2009)**. Clear water scour conditions usually exist when the flow intensity (mean approach velocity(v)/critical velocity(v_c)< 1). The clear water scour conditions exist for both uniform sediment and non-uniform sediment when flow intensity, $v/v_c<1$ or $[v-(v_a-v_c)]/v_c<1$ respectively**(Coleman and Melville, 2000**). The velocity (v_a) is called armor peak velocity, and it is equivalent to v_c in uniform sediment. The geometric standard deviation of the particle size distribution (g) for nonuniform sediment should be more than 1.3. Live bed scour exists when $v/v_a>1$. The following method can be used to determine whether the local scour type at the studied bridge in a nonuniform alluvial bed is clear water or live bed **(Coleman and Melville, 2000**).

1. The critical bed shear velocity, u_{*c} for d_{50} size from Shields diagram (for quartz sand in water at 20 ºC) for 0.1mm< d_{50} <1mm can be determined from the following equation
$u*c = 0.0115 + 0.0125d_{50}^{1.4}$ (4)

However, for 1mm< d_{50} < the following equation determines 100mm, the critical bed shear velocity

$u*c = 0.0305d_{50}^{0.5} - 0.0065d_{50}^{-1}$ (5)

2. The critical mean approach flow velocity(v_c**)** can be determined from the flowing logarithmic velocity distribution (for fully turbulent flow)

$\frac{v_c}{u*_c} = 5.75\ log(5.53\frac{y}{d_{50}})$ (6)

3. Thus, the armour peak velocity (v_a) (σ_g>1.3 only) can be determined by applying the following equations:
$d_{50a} = \frac{d_{max}}{1.8}$ (7)

However, $d_{max}=d_{90}=2d_{50}$ is valid for sediment particles with a grain size between 0.05 and 2 mm **(van Rijn, 1993)**.

The critical bed velocity for the armor layer(u_{*c_a}) for d_{50_a} size from the Shields diagram or (for quartz sand in water at 20°C) can be calculated for 0.1mm < d_{50_a} <1mm

$u*c_a = 0.0115 + 0.0125d_{50a}^{1.4}$ (8)

when the range of median sediment size 1mm <d_{50_a} <100mm, then u_{*c_a} is determined by

$u*c_a = 0.0305d_{50a}^{0.5} - 0.0065d_{50a}^{-1}$ (9)

4. The critical mean approach flow velocity, v_c can be determined from the flowing logarithmic velocity distribution (for fully turbulent flow)

$\frac{v_{ca}}{u_{ca}} = 5.75\ \log\left(5.53\ \frac{y}{d_{50a}}\right)$ (10)

5. The velocity that marks the transition from clear water to live bed conditions for nonuniform sediments, v_a can be calculated from

$va = 0.8 * vca$ (11)

To find the type of scour at each bridge included in the field data, Eq. (4) to (11) were applied. The results from the application of the equations are shown in **Table 2**. It is found that type of scour at the Kufa bridge is clear water type while the scour type at other bridges was live bed.

Table 2. Type of scour for non-uniform alluvial bed

Site	Fr	u^*_c	Vc	d_{50a}	u^*_{ca}	V_{ca}	V_a	V-(Va-Vc)/Vc	V/Va	type of scour
Al Kufa bridge	0.127	0.014	0.348	1.111	0.026	0.577	0.461	0.981	0.986	clear water scour
Shahdara railway bridge	0.206	0.014	0.395	0.333	0.014	0.402	0.321	3.869	4.526	live bed scour
	0.206	0.014	0.393	0.333	0.014	0.400	0.320	3.768	4.401	live bed scour
	0.207	0.014	0.408	0.333	0.014	0.416	0.332	4.528	5.334	live bed scour
	0.206	0.014	0.392	0.333	0.014	0.399	0.319	3.739	4.366	live bed scour
	0.204	0.014	0.392	0.333	0.014	0.399	0.319	3.701	4.319	live bed scour
	0.205	0.014	0.396	0.333	0.014	0.403	0.322	3.912	4.578	live bed scour
	0.207	0.014	0.406	0.333	0.014	0.413	0.330	4.394	5.170	live bed scour
	0.206	0.014	0.401	0.333	0.014	0.408	0.327	4.160	4.883	live bed scour
	0.206	0.014	0.395	0.333	0.014	0.402	0.322	3.875	4.533	live bed scour
	0.207	0.014	0.408	0.333	0.014	0.415	0.332	4.521	5.325	live bed scour
	0.208	0.014	0.404	0.333	0.014	0.411	0.329	4.349	5.115	live bed scour
Brahmaputra bridge	0.215	0.015	0.462	0.433	0.015	0.474	0.379	6.390	7.560	live bed scour
Par railway bridge	0.207	0.014	0.427	0.367	0.015	0.436	0.349	5.136	6.065	live bed scour

Jhelum bridge	0.203	0.014	0.403	0.356	0.014	0.410	0.328	3.932	4.596	live bed scour
Alexandra bridge	0.214	0.015	0.419	0.411	0.015	0.429	0.343	4.262	4.980	live bed scour
Chenab bridge	0.211	0.014	0.417	0.378	0.015	0.426	0.341	4.541	5.333	live bed scour
Chenab bridge	0.212	0.014	0.418	0.378	0.015	0.427	0.342	4.604	5.410	live bed scour
Ravi bridge	0.192	0.013	0.391	0.267	0.013	0.395	0.316	4.012	4.722	live bed scour
Sulej bridge	0.207	0.014	0.402	0.356	0.014	0.410	0.328	3.994	4.671	live bed scour
Sulej bridge near adamwahan	0.207	0.013	0.388	0.222	0.013	0.391	0.313	4.540	5.393	live bed scour
Chenab bridge at chund	0.185	0.014	0.409	0.333	0.014	0.416	0.333	4.083	4.788	live bed scour
Beaver crossing	0.176	0.016	0.457	0.556	0.017	0.473	0.379	3.379	3.869	live bed scour
Lacorey crossing	0.176	0.016	0.451	0.556	0.017	0.467	0.374	3.200	3.653	live bed scour
Broad gauge railway bridge	0.207	0.014	0.397	0.333	0.014	0.404	0.323	3.998	4.684	live bed scour
	0.208	0.014	0.391	0.333	0.014	0.398	0.318	3.729	4.354	live bed scour

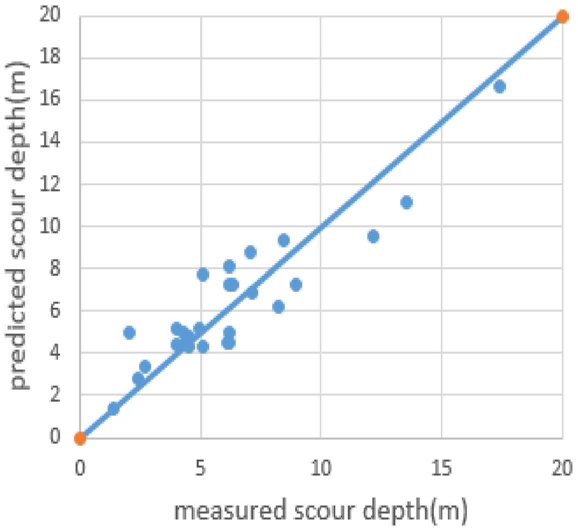
3.2 Validation of the Selected Formulae

Various parameters included in the field data were used as input into Equations (1) to (3). These parameters are pier width, water depth, the median size of bed material, and flow velocity. The results obtained from applying the selected formulae are shown in **Table 3**.

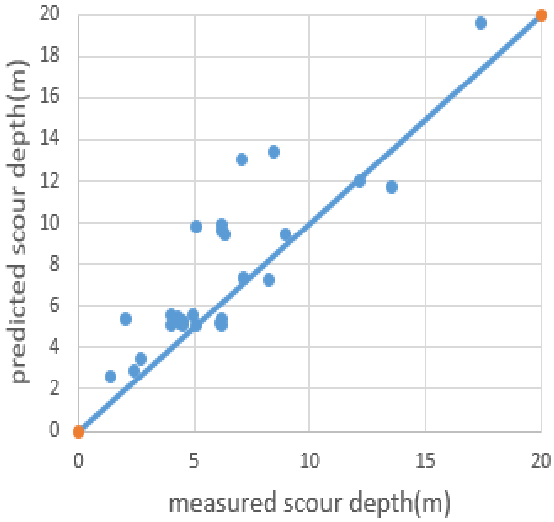
Table 3. Results obtained from the application of selected formulae

Site	Ks	K2	K3	Measured scour depth	Local scour depth (HEC 18)	Local scour depth (Forelich)	Local scour depth (Johnson)
Al Kufa bridge	0.9	1	1.1	1.38	1.406	2.635	2.378
Shahdara railway bridge	1.1	1	1.1	6.16	4.474	5.121	4.798
	1.1	1	1.1	4.03	4.372	5.061	4.709
	1.1	1	1.1	4.95	5.133	5.528	5.391
	1.1	1	1.1	4.54	4.340	5.040	4.676
	1.1	1	1.1	5.1	4.320	5.036	4.676
	1.1	1	1.1	6.15	4.525	5.155	4.852
	1.1	1	1.1	4.28	4.999	5.442	5.269
	1.1	1	1.1	4.54	4.775	5.307	5.077
	1.1	1	1.1	4.35	4.484	5.129	4.813
	1.1	1	1.1	4.01	5.127	5.524	5.387
	1.1	1	1.1	2.05	4.941	5.400	5.205
Barhamaputra bridge	1.1	1	1.1	13.57	11.163	11.745	11.420
Par railway bridge	1.1	1	1.1	7.17	6.885	7.362	7.197
Jhelum bridge	1.1	1	1.1	8.99	7.233	9.412	8.044
Alexandra bridge	1.1	1	1.1	6.19	4.961	5.351	5.172
Chenab bridge	1.1	1	1.1	6.16	8.154	9.902	8.783
Chenab bridge	1.1	1	1.1	12.14	9.520	12.036	10.335
Ravi bridge	1.1	1	1.1	6.19	7.287	9.591	8.259
Sulej bridge	1.1	1	1.1	6.31	7.277	9.416	8.031
Sulej bridge near adamwahan	1.1	1	1.1	8.21	6.171	7.281	6.619
Chenab bridge at chund	1.1	1	1.1	5.09	7.697	9.834	8.772
Beaver crossing	1.1	1	1.1	2.71	3.365	3.462	3.703
Lacorey crossing	1.1	1	1.1	2.42	2.840	2.883	3.116
Broad gauge railway bridge	1.1	1	1.1	8.43	9.384	13.378	10.568
	1.1	1	1.1	7.06	8.813	13.042	10.010

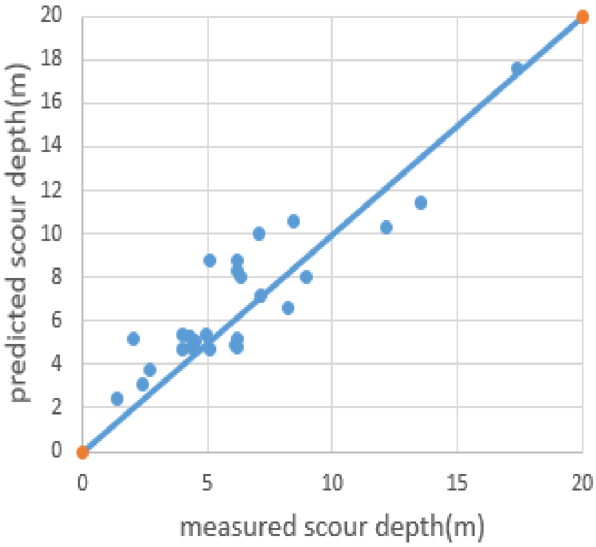
The field data used in the validation process was measured at the Kufa bridge, published by **(Qadar, 1981)**, and related to bridges in India, Bangladesh, Pakistan, and Canada. Scattergrams were plotted between the measured scour depth and the predicted scour depth **Fig. 3**.



a. Validation of HEC-18 Formula



b. Validation of Forehlich Formula



c. Validation of Johnson formula

Figure 3. Validation of the selected formulae

3.3 Statistical Tests

Statistical tests were used to evaluate the accuracy of scour predictions by the selected formulae. Statistical tests used were Theil's coefficient (U), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) **(Mohamed et al., 2006)**. It was found that Johnson's equation gave minimum errors between the measured and predicted scour values as shown in **Table 4**. The following formulae describe the above tests.

$$U = \frac{\left[\frac{1}{n}\sum_{i=1}^{i=n}(Y_{so}-Y_{sp})^2\right]^{\frac{1}{2}}}{\left[\frac{1}{n}\sum_{i=1}^{i=n}Y_{so}^2\right]^{\frac{1}{2}}+\left[\frac{1}{n}\sum_{i=1}^{i=n}Y_{sp}^2\right]^{\frac{1}{2}}} \quad (12)$$

where Y_{so} is the observed scour depth while Y_{sp} is the predicted scour depth, and n is the number of recorded cases.

Regardless of how data are defined, it is bounded to the intervals 0 and 1. A value of 0 indicates perfect prediction. A value of 1 corresponds to perfect inequality or negative proportionality between observed and predicted values.

The mean absolute error (MAE) and root mean square error can be calculated using the following tests

$$MAE = \frac{1}{n}\sum_{i=1}^{i=n}\left|Y_{so} - Y_{sp}\right| \quad (13)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}(Y_{so} - Y_{sp})^2} \quad (14)$$

Table 4. Summary of the statistical tests performed on the equations and models chosen

Scour Equation	Theil's Coefficient, U	Mean Absolute Error, MAE	Root Mean Square Error, RMSE
1. (HEC-18)	0.622	4.622	5.571
2. Forehlich	0.137	1.537	1.939
3. Johnson	0.112	1.351	1.650

4. CONCLUSIONS

It is essential to test their performance using field data for existing bridges located in different geographical regions worldwide. In this study, field data was used to validate three selected formulae that were widely used to estimate the local scour at bridges. The selected formula was proposed based on laboratory data. Field data on local scour at the Kufa bridge, Najaf, Iraq, was collected using an M9 device, while the other field data was related to bridges located in different geographical regions and was borrowed from the published literature. In the validation processes the predicted scour depths and that obtained from the field data were presented using scattergrams. In addition, statistical tests were also performed to confirm the accuracy of the predicted scour depths. The statistical indices used to test the performance of the selected formulae were Theil's coefficient (U), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE). Among the tested formula. It was found that the Johnson equation is the most accurate formula.

REFERENCES

Al-Hassani, N. Z., and Mohammad, T. A., 2021. Impact of the Weir Slit Location, the Flow Intensity and the Bed Sand on the Scouring Area and Depth at the Dam Upstream, *Journal of Engineering*, 27(5), pp. 49–62. DOI: 10.31026/j.eng.2021.05.04.

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., and Clopper, P. E., 2012. *Evaluating scour at bridges* (No. FHWA-HIF-12-003), National Highway Institute (US).

Froehlich, D. C., 1988. Analysis of onsite measurements of scour at piers, In *Hydraulic Engineering: Proceedings of the 1988 National Conference on Hydraulic Engineering*, pp. 534-539.

Johnson, P. A., 1995. Comparison of pier-scour equations using field data, *Journal of Hydraulic Engineering*, *121*(8), pp. 626-629.

Melville, B. W., and Coleman, S. E., 2000. *Bridge scour*, Water Resources Publication.

Mohamed, T. A., Pillai, S., Noor, M. J. M. M., Ghazali, A. H., Huat, B. K., and Yusuf, B., 2006. Validation of some bridge pier scour formulae and models using field data, *Journal of King Saud University-Engineering Sciences*, *19*(1), pp., 31-40.

Pruebas, 2020. Scour and its relation to the collapse of bridges. Technical Report, IDVA Engineering Company, Spain, Available at https://www.idvia.es/en/scour-and-its-relation-to-the-collapse-of-bridges-2>

Qadar A., 1981. The Vortex Scour Mechanism at Bridge Piers, *Proceedings of the Institution of Civil Engineers*, *71*(3), pp. 739-757.

Subramanya, K., 2009. *Flow in open channels.* McGraw-Hill Publishing Company, New Delhi, India.

Van Rijn, L. C., 1993. *Principles of sediment transport in rivers, estuaries and coastal seas* (Vol. 1006, pp. 11-3), Amsterdam: Aqua publications.

Wattan, S. A. A., and Al-Bakri, M., 2019. Development of Bridges Maintenance Management System based on Geographic Information System Techniques (Case study: AlMuthanna\Iraq), *Journal of Engineering*, 25(7), pp. 21–36, DOI: 10.31026/j.eng.2019.07.02.