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Validation of Some Bridge Pier Scour Formulae and Models Using Field Data

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Abstract. Estimation of maximum local scour at the pier site is necessary for safety and economy of the designed bridge. Numerous formulae are available for predicting maximum local scour depth at the pier site. Almost all of these formulae were developed based on laboratory data. Validation of these formulae using field data is necessary to recommend the formulae with a reasonable estimation. In this study, four formulae were selected for validation process using field data recorded from bridges subjected to scour in Pakistan, Canada and India and the data obtained from Qadar [7]. The selected formulae which were used for validation process had been proposed by Colorado State University (CSU), Melville and Sutherland, Jain and Fisher, and Lauren and Toch. Three statistical tests were carried out to determine the formulae equation with minimum prediction errors. They were mean absolute error (MAE), root mean square error (RMSE), and Theil's Coefficient (TC). The statistical tests showed that error in the prediction of maximum local scour depth using CSU formula was minimum compared to the errors in the prediction of the other three formulae. For CSU formula, the computed values of MAE, RMSE and TC were found to be 0.11, 0.93 and 1.24 respectively.

***Keywords**:* Bridge, Local scour, Field data, Formulae, Validation.

Introduction

Many bridges failed around the world because of extreme scour around pier and abutment. For example, during the spring floods of 1987, 17 bridges in New York and New England, USA were damaged or destroyed by scour. In 1985, floods in Pennsylvania, Virginia, USA destroyed 73 bridges. A total number of 383 bridges failed in the USA alone in the year 1973 [1]. The failure of bridges due to scour will result in economical loss and may also result in the losses of human life. In an extensive study of bridge failures in the United States, it reported that damage to bridges and highways from major regional floods in 1964 and 1972 amounted to about $100,000,000 per event [2]. The failure of bridges in

Malaysia due to scour problems during flood is not published, so there is no local record to be used in this study.

An accurate prediction of scour depth at piers is essential for the safe design of the bridge foundation. As a result, an intensive research was conducted over the past three decades in order to develop reliable relationships for estimating maximum scour depth and also to reduce the impact of local scour on the bridge substructure. Numerous formulae for estimating maximum local scour at pier site have been developed by many researchers and the development of these formulae were based on data collected from physical models with conditions different from that existed in the prototype. So, the use of these formulae in the field is uncertain because of simplified conditions in the laboratory. For example, studies employed laboratory flumes, which were rectangular in cross section and had smooth fixed walls were different from natural channels which are non-rectangular with mobile banks and overbank flow occurring frequently at the design flow rate and the lateral flow distribution in non-uniform.

Validation of the proposed formulae using field data is necessary to improve the prediction of maximum local scour at bridge piers. This may decrease unnecessary expenses for scour counter measures, making the bridge design process more efficient. This will also lead to a greater accuracy of bridge scour prediction and increased confidence in bridge design, thus increasing public safety of users. Coleman and Melville [3] presented an evaluation on the failure of three bridges in New Zealand. Johnson [4] made a comparison of pier scour formulae using field data. Koopaei and Valentine [5] compared between the local scour data collected from self-formed laboratory channels with predicted local scour depth computed using some formulae for estimating local scour at pier site. They concluded that most of the formulae overpredicted the maximum local scour depth. Johnson [6] developed safety factors that are direct reflection of the allowable level of risk using a probabilistic approach.

In this study, field data for recorded local scour depth for bridges located in Pakistan, Canada and India were used to validate four selected formulae for estimating local scour at bridge sites. Statistical methods were used to recommend the formula with minimum errors in its prediction.

Bridge Pier Scour Formulae and Models

Many formulae and models are available for predicting maximum local scour depth at a pier site. Almost all the local scour formulae and models were developed based on the laboratory data. This is because the local scour is a very complex phenomenon which has resulted from the interaction between the flow around a bridge pier and the erodible bed surrounding it. Based on this, only very limited attempts were successful to model the scour computationally. However, the formulae and models derived from these attempts are usually applied by the civil engineers to evaluate conditions. The conditions included estimating the depth of local scour for newly designed bridges and for existing bridges experiencing local scour problems. So, the validation of the local scour formulae and models by using field data is necessary to find the uncertainty associated with the application of these equations to field conditions. Four of the more commonly used and cited local scour formulae or models were tested to determine their accuracy. The Federal Highway Administration's Hydraulic Engineering Circular No. 18 (HEC-18) [1] recommends the use of the Colorado State University (CSU), which is described below [8]:

$$\frac{d_s}{y} = 2.0 K_1 K_2 \left(\frac{b}{y}\right)^{0.65} Fr_1^{0.43} \quad (1)$$

where d_s is scour depth, y is flow depth at the upstream of the pier, K_1 is correction factor for pier nose shape, K_2 is correction factor for angle of attack flow, b is the pier width, and Fr_1 is the Froude number at upstream of the pier. K_1 and K_2 are obtained from Table 1.

Table 1. Values of K_1 and K_2 for different pier types [8]

Type of pier	K_1	Angle of flow attack	L/b=4	L/b =8	L/b=12
Square nose	1.1	0^o	1.0	1.0	1.0
Round nose	1.0	15^o	1.5	2.0	2.5
Circular cylinder	1.0	30^o	2.0	2.5	3.0
Sharp nose	0.9	45^o	2.3	3.3	4.3
Group cylinders	1.0	90^o	2.5	3.9	5.0

L = pier length

It is recommended in HEC-18 that the limiting value of d_s/y is 2.4 for $Fr_1 \leq 0.8$ and 3.0 for $Fr_1 > 0.8$. Melville and Sutherland [9] developed a scour model based on extensive laboratory experimentation. The model is described below:

$$d_s = K_l K_d K_y K_a K_s b \quad (2)$$

where K_l = flow intensity factor
K_d = sediment size factor
K_y = flow-depth factor
K_a = pier-alignment factor
K_s = pier-shape factor
d_s, and b are as defined before

K_l is a function of the approach velocity relative to the critical velocity and K_d is a function of the sediment gradation expressed as the geometric standard deviation. Values of all K factors are obtained from equations or graphs provided by Melville and

Sutherland [9]. Lauren and Toch developed design curves that were described by Neil [10] in the form of mathematical formula.

The formula for estimating the local scour as described by Johnson [4] is:

$$d_s = 1.35 b^{0.7} y^{0.3} \quad (3)$$

where d_s is the maximum predicted local scour depth, b is the width of the bridge pier, and y is the flow depth.

Jain and Fisher (1979) as cited in Johnson [4] developed a set of equations based on laboratory experiments.

For $\left(Fr_1 - Fr_c\right) > 0.2$

$$d_s = 2.0 b \left(Fr_1 - Fr_c\right)^{0.25} \left(y/b\right)^{0.5} \quad (4)$$

where Fr_c is critical Froude Number and d_s, Fr_1, y and b are as defined before.

For $\left(Fr_1 - Fr_c\right) < 0$

$$d_s = 1.85 b \left(Fr_c\right)^{0.25} \left(y/b\right)^{0.3} \quad (5)$$

For $0 < \left(Fr_1 - Fr_c\right) < 0.2$, the larger of the two scour depths computed from the above equations is used.

Validation and Testing of Selected Bridge Pier Scour Formulae and Models

In this study, some of the more commonly used and cited scour formulae and models for predicting local scour at pier site were validated using field data. The formulae and models were Colorado State University (CSU), Melville and Sutherland, Jain and Fisher, and Lauren and Toch. The field data used for the validation process were collected from bridges which had experienced local scour in three countries, namely Canada, India and Pakistan, and this data was used by Qadar [7]. The computed local scour depths obtained from the application of the selected four formulae and models to the three bridges mentioned earlier are shown in Table 2. A comparison between the recorded field data and the computed scour depths are shown in Figs. 1, 2, 3 and 4. Statistical tests were conducted to evaluate the accuracy of the prediction obtained from the four formulae and models used in estimating local scour depth at bridge pier. The tests are the Theil's coefficient (U), mean absolute error (MAE), and root mean square error (RMSE). Mathematically, Theil's coefficient, mean absolute error, and the root mean square error are in the forms shown in Eqs. (6), (7) and (8) respectively.

Table 2. Comparison of measured and computed local scour depths [11]

Year	Bridge location	(Q) m^3/s	Discharge per unit width (q) m^2/sec	Normal scour depth (D*) m	Pier Width (b) m	Mean approach velocity (u) m/s	Froude number (Fr)	Observed Scour depth $(d_s)_o$ m	Scour depth applying CSU formula $(d_s)_c$ m	Scour depth applying M & S formula $(d_s)_c$ m	Scour depth applying J & F formula $(d_s)_c$ m	Scour depth applying L & T formula $(d_s)_c$ m
1948	Pakistan	2437	7.39	5.08	3.05	1.43	0.203	11.24	8.75	11.58	10.41	9.88
1949	Pakistan	1474	6.71	4.77	3.05	1.38	0.202	8.8	8.36	11.17	10.03	9.48
1950	Pakistan	5469	13.28	7.49	3.05	1.75	0.205	12.44	11.71	14.67	13.38	12.88
1951	Pakistan	1247	6.49	4.66	3.05	1.38	0.205	9.2	8.24	11.02	9.88	9.34
1952	Pakistan	1587	6.42	4.66	3.05	1.36	0.201	9.76	8.21	11.02	9.89	9.34
1953	Pakistan	2352	7.78	5.27	3.05	1.46	0.203	11.42	8.99	11.83	10.67	10.12
1954	Pakistan	4874	11.58	6.94	3.05	1.68	0.204	11.22	11.04	13.98	12.72	12.21
1955	Pakistan	7085	9.78	6.13	3.05	1.58	0.204	10.67	10.06	12.95	11.74	11.21
1956	Pakistan	2465	7.48	5.13	3.05	1.43	0.202	9.48	8.81	11.65	10.49	9.94
1957	Pakistan	5441	13.22	7.47	3.05	1.75	0.205	11.48	11.69	14.64	13.36	12.86
1958	Pakistan	4308	11.21	6.66	3.05	1.65	0.205	8.71	10.71	13.63	12.38	11.86
1962	Canada	567	10.33	7.05	1.83	1.46	0.175	9.76	9.83	11.44	11.26	10.75
1962	Canada	510	8.36	6.12	1.52	1.35	0.175	8.54	8.46	9.77	9.69	9.24
1970	India	3364	8.24	5.44	9.15	1.52	0.208	13.87	13.2	20.44	17.13	16.01

CSU = Colorado State University
M&S = Melville and Sutherland
J&F = Jain and Fisher
L&T = Lauren and Toch

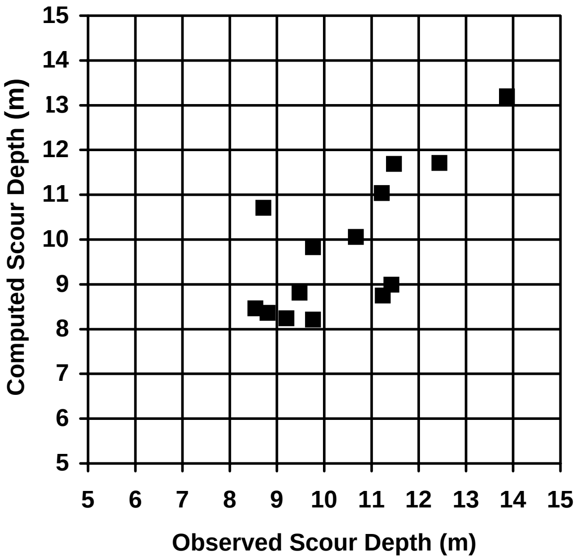

Fig. 1. Comparison of measured and computed scour depths using CSU formula.

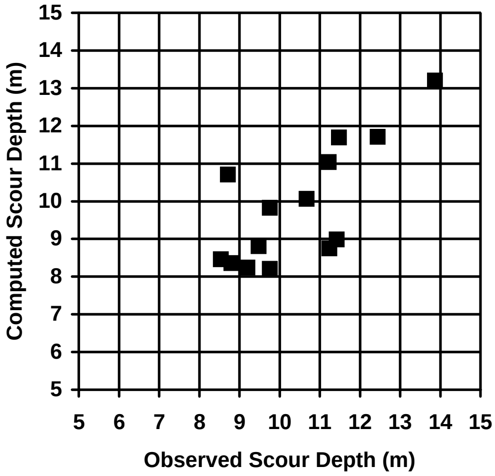

Fig. 2. Comparison of measured and computed scour depths using Melville and Sutherland formula.

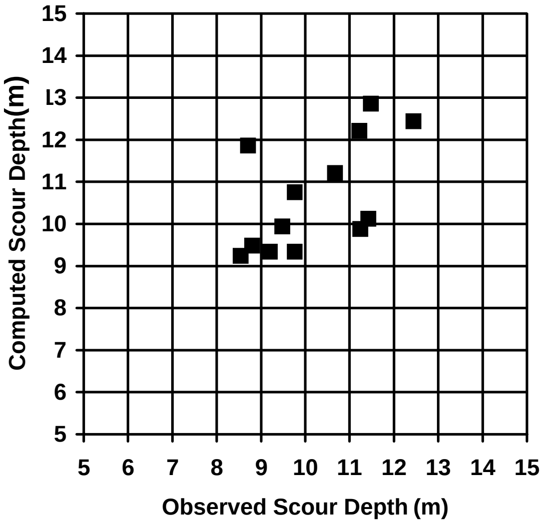

Fig. 3. Comparisonof measured and computed scour depths using Lauren and Toch formula.

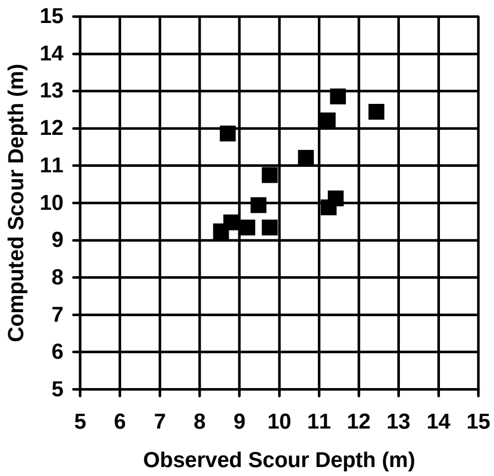

Fig. 4. Comparison of measured and computed scour depths using Jain and Fisher formula.

$$U = \frac{\left[\sum (d_s)_c - (d_s)_o\right]^{\frac{1}{2}}}{\left[\sum_{i=1}^{n} (d_s)_o\right]^{\frac{1}{2}}} \tag{6}$$

where U is Theil's coefficient (U = 0 for model of perfect prediction and U = 1 for unsuccessful model), $(d_s)_o$ is the measured scour depth in meters, $(d_s)_c$ is the corresponding predicted scour depth in meters obtained from the application of the selected scour formulae and models.

$$MAE = \sum_{i=1}^{n} |e_i| / n \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n}} \tag{8}$$

where *e* is the error in the predicted scour depth for *i* event of the record from the application of the formula or model, and n is number of records.

Evaluation of the output obtained from the application of Eqs. (6), (7) and (8) on the four selected formulae and models was made and smaller values were obtained. These indicate accurate prediction. Table 3 shows the average values obtained from the statistical tests

Table 3. Summary of the statistical tests conducted on the selected formulae and models [11]

Scour equation and model	**Theil's Coefficient, U**	**Mean Absolute Error, MAE**	**Root Mean Square Error, RMSE**
1. Colorado State University, CSU	0.11	0.93	1.24
2. Melville and Sutherland, M & S	0.28	2.43	2.88
3. Jain and Fisher, J & F	0.15	1.40	1.62
4. Laursen and Toch, L & T	0.12	1.04	1.29

Discussion

In this study, four selected formulae and models were validated. The selected formulae were Colorado State University (CSU), Melville and Sutherland, Jain and Fisher, and Lauren and Toch. The selected formulae have the advantage of containing most of the variables governing the local scouring phenomenon. These variables are pier width, pier length, water depth, velocity of the flowing water, pier alignment and pier shape. For example, formulae proposed by Jain [12] and Raudkivi and Ettema [13] were based on laboratory data related to a clear water scour at cylindrical pier model. But, Melville [14] proposed a model for computing scour at bridge foundation (both bridge pier and abutment). However, the model is considered as a complicated one. On the contrary, the model proposed by Shen [15] is too simplified because it is considering only one variable, namely the pier width. Raudkivi [16] gave figures for finding the scour depth based on shear velocity and mean velocity ratio while the objective of the present study is to validate the available proposed local scour formulae at the site of bridge pier.

The validation process was conducted using field data of three bridges located in Canada, India and Pakistan. The same field data was used by Qadar [7]. The comparison between the measured scoured depths and computed scour depths using Colorado State University formula showed that they are in agreement. The maximum and minimum errors between the measured and computed scour depths were found to be 3.15 m and 0.14 m respectively. But, the other three formulae showed lower degree of accuracy and this is also confirmed by using three different statistical tests namely, Theil's coefficient, U, mean absolute error, MAE, and root mean square error, RMSE. Table 3 shows the computed values of the above three statistical tests. The validation process and the statistical tests showed that the Colorado State University Formula is the best among the four selected formulae, followed by Laursen and Toch, Jain and Fisher and Melville and Sutherland formulae. From Fig. 1, it is seen that the scour depths predicted for the various flows by the Colorado State University formula are scattered around the line of perfect agreement, while the predicted values by other formulae are clearly over-predicted as shown in Figs. 2, 3 and 4. For example, the scour depths predicted using Melville and Sutherland formula are over estimated and the mean absolute error was found to be 2.43 and Theil's coefficient is 0.28 and the maximum error was found to be 6.9 m. The output from the selected formulae mostly overpredicted the scour depths compared with the recorded depths and the difference can be attributed to the fact that these formulae were obtained from experiments carried out in laboratory flumes with fixed walls while in real case the channel section has different site conditions. Normally, the entire cross-section of the channel at bridge site is mobile. Due to the shortage of the field data, Koopaei and Valentine [5] validated selected formulae for estimating local scour depth using experimental data of self-formed flume. They used the experimental data to validate selected scour formulae. They justified this by considering the data collected from self-formed channel equivalent to field data. They concluded that most of the validated formulae overpredict the local scour depth. They proposed an empirical formula which can estimate the local scour depth with reasonable accuracy.

Conclusions

Four selected formulae and models for estimating local scour at bridge piers were validated using field data. Statistical tests were also conducted to investigate the accuracy of the output from the validated formulae. Within the limited available field data, validation process revealed that Colorado State University formula is more accurate among the other three tested formulae.

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التحقق من دقة بعض ا عادلات والنماذج ا ستخدمة حساب ا ت ا وقعي لدعامات ا سور باستخدام معطيات موقعية

ثامر أ د مد، وأس بليه، ومكت جهوري مكت مد نور، وعبدا ليم غزا ،
و كي هت، وبدر النساء يوسف

قسم الهندسة المدنية، كلية الهندسة، جامعة بترا الماليزية، ٤٣٤٠٠ سالنكور، ماليزيا

(قدِّم للنشر في ٢٠٠٥/٠١/٠٥م؛ وقبل للنشر في ٢٠٠٦/٠٩/٢٦م)

ملخص البحث. إن تقدير أكبر حت موقعي عند دعامات الجسور مهم لسلامة اقتصادية الجسور عند التصميم. استخدمت معادلات كثيرة لتقدير الحت الموقعي عند موقع الجسور، لكن معظم هذه المعادلات تم التوصل إليها باستخدام معادلات مختبرية وعليه فإن التحقق من دقة هذة المعادلات باستخدام معطيات موقعية مهم لاقتراح معادلات ذات دقة مقبولة. تم في الدراسة الحالية اختيار أربع معادلات لغرض التحقق من دقتها باستخدام معطيات موقعية تم جمعها من جسور تعرضت للحت وتقع في كل من باكستان وكندا والهند، وإن هذه المعطيات تم اقتباسها من دراسة منشورة بواسطة Qadar عام ١٩٨١م. إن معادلات الحت الموقعي الأربعة التي استخدمت في هذه الدراسة مقترحة بواسطة جامعة ولاية Colorado والباحثان Melville و Southerland، والباحثان Jain و Fisher، والباحثانLauren و Toch. استخدمت ثلاث اختبارات احصائية لإيجاد المعادلة التي تعطي أقل خطأ في تقدير الحت الموقعي عند الدعامات، والإختبارات الإحصائية المستخدمة هي معدل الخطأ المطل (MAE) ، وجذر معدل تربيع الخطأ (RMSE) ، ومعامل (TC)Theil. بينت هذه الدراسات أن الخطأ في تقدير الحت الموضعي كان قليلا عند استخدام معادلة جامعة ولاية Colorado مقارنة مع بقية المعادلات الأخرى، وإن قيم كل من (MAE) و (RMSE) و (TC) كانت ٠٫١١ و ٠٫٩٣ و ١٫٢٤ على التوالي.