Pak. J. Engg. & Appl. Sci. Vol. 16, Jan., 2015 (*p.33* –48)

Ranking Analysis of Clear Water Scour Depth Equations at Bridge Piers

Vaiza Shiraz[1], Abdul Sattar Shakir[2] and Noor Muhammad Khan[3]

1. *Civil Engineering Department, University of Engineering and Technology Lahore, Pakistan*
2. *University of Engineering and Technology Lahore, Pakistan*
3. *University of Engineering and Technology Lahore, Pakistan*

Corresponding author: *E-mail:vaizashiraz@yahoo.com*

Abstract

Scouring is one of the major threat to the stability of bridge piers. Both clear and live bed scour conditions are different phenomena and should be evaluated individually. In this evaluation, the available clear water scour prediction equations are evaluated using available laboratory and field data. The overall performance of these equations is quantified by using statistical parameters, namely 'Sum of squared errors', 'Mean Absolute error' and 'Root Mean square error'. The results show that no single equation can said to be accurate. The top-ranked three equations which manifest better estimation of clear water scour depth are Sheppard & Miller, Molinas and Gao equations, respectively.

Key Words: *Scouring, Clear water scour, Prediction equations, Evaluation.*

1. Introduction

Scouring is a natural phenomenon which is defined as the lowering of bed material. The erosive ability of the flowing water is mainly responsible for this process which can erode, transport and deposit the sediments in river causing a change in the river bed elevation and adjusting its boundaries. Scour can take place around any hydraulic structure, bed and banks of the stream or river.

The local scour around the bridge pier can be classified into two categories namely, Clear water scour and Live bed scour. Clear water scour occurs when there is no movement of bed sediments and live bed scour occurs when there is transport of bed sediments at the upstream of bridge pier. The term "Clear water scour" sometimes can be misleading as it gives the impression that the water is entirely clear of any type of sediments, but it is common to have suspended silt and clay particles in the clear water condition. Hence, the classification of the scour is based on the movement of sediments along the stream bed but not on the suspended sediments. The land areas which have the vegetation and also the piers situated in flood plains are most likely to be subjected to clear water scour [2].

Both of these scour conditions exhibit entirely different phenomena and stability conditions of the bridge piers is questionable. Failure of the bridges due to scouring has been reported all over the world. About 60% of the U.S. highway bridge failures were due to different hydraulic defects including scour [21]. Serious bridge scour problems were reported in many East- Asian countries, particularly in those areas which were subjected to flood induced by yearly typhoons [25]. Wardhana et al. [48] had reported a list of bridge failures due to the pier scour. Besides their human toll, bridge failure costs a million dollar expenditure related to restoration, replacement and transport facilities [21]. Hence, estimation of the local scour depth in the vicinity of bridge piers has been the main concern of engineers for years.

The local scour depth under clear and live bed conditions is different and should be treated differently. A number of studies have been carried out in recent years evaluating scour prediction equations based on their performance. For example, Jones et al. [15] compared most of the common equations using laboratory and limited field data. According to his analysis, CSU equations enclose all the field data points but this equation gave lower value of scour than other equations.

Landers and Mueller [23] carried out analysis using 139 data points including both clear and live bed scour conditions. They analyzed some selected pier scour predicting equations. The results of the analysis showed that none of the equation accurately estimated the scour depth for all the measured conditions. They also concluded that some equations performed well for the conservative design but overestimated the scour depth by a large amount.

Mueller [35] compared 22 pier scour predicting equations. Field data which was collected by the USGS, was used in the analysis. It was observed that the HEC-18 equation performed reasonably well by rarely under predicting and mostly overestimating the scour depth.

Garde [9] analyzed the Inglis-Lacey's, Laursen-I, Melville & Sutherland and Kothyari equations for the data of sandy beds. It was found that the method proposed by Melville & Sutherland and Kothyari gave more or less the same accuracy.

Boehmler [3] carried out the survey for USGS and checked the competence of pier scour measurement methods and the predicting equations. The study included the data of 20 different sites and compared most of the commonly used equations. It showed that the Shen, Blench-Inglis, and Gao equations closely predicted pier scour depths.

Mueller [36] conducted a detailed study on stream bed scour at bridges. Evaluation used 266 measurement points, which represented 106 different piers at 53 bridges. The results showed that the HEC-18, Froehlich Design, HEC-18-K4-Mu, HEC-18-K4, HEC-18-K4-Mo and Wilson equations performed better than other equations for the prediction of scour depth for design purposes.

Mohamed [32] conducted an analysis of four equations namely, Laursen-I, Jain and Fisher, CSU and Melville and Sutherland equations. Both field and laboratory data were used in the analysis. Laboratory data was compiled from the series of tests conducted on the model and field data comprised of 14 bridge sites. Comparison showed that Laursen-I and CSU equations performed well for the given laboratory and field data while other two equations over predicted the values. This observations were verified by using three different statistical tests namely; Mean Absolute Error (MAE), Theil's coefficient (U), and Root Mean Square Error (RMSE).

Gaudio [8] compared six equations (Breusers, Jain & Fischer, Froehlich, Kothyari, Melville and HEC-18-Kw) for the estimation of the scour depth around circular pier in clear water or live bed conditions by using synthetic and original field data. The comparison was done two by two. The HEC-18-Kw equation in both clear water and live bed scour and the Froehlich equation in live-bed condition predicted scour depths better than the other selected equations. None of the selected equations accurately predicted the scour depths in the field.

Sheppard [45] assembled 23 equations for evaluation and assessment. For the analysis, 441 laboratory and 791 field data points were used. Initial screening was applied to the equations based on unrealistic results which left only 17 equations for the evaluation. A statistical parameter named as 'Sum of squared errors" was also used in the analysis to rank the equations. The analysis showed that Sheppard & Miller equation and Melville equation both performed well. Furthermore the equations were melded and a new equation was formed named as Sheppard/Melville (S/M) equation for an accurate prediction.

Beg [1] evaluated 14 commonly used equations. The evaluation was carried out using both field and laboratory data. The analysis was carried out by using different statistical parameters including Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Theil's Coefficient (U). The results revealed that Laursen-I and Jain & Fischer gave reasonable results.

Above discussion showed that the previous researchers had tried to identify the best equations based on their performance of predicting the scour depth but these evaluations did not explicitly focus on clear water scour equations. This study, however, is conducted to evaluate clear water scour depth prediction equations and rank them based on certain evaluation criteria.

2. Clear Water Scour Depth Prediction Equations

There are number of equations available for the prediction of scour depth around the bridge piers. All the available equations can be sorted based on the scour conditions, over which they are applicable. Some of them are only applicable to clear water, some are for live bed scour conditions while others can be used for both conditions. Total 27 available clear water scour depth prediction equations are studied in this research work and summarized in Table-1 (For detail refer Appendix-1).

Table 1: List of Clear water scour depth prediction equations at bridge pier

1. Inglis-Poona-I (1949)	2. Inglis-Poona-II (1949)
3. Chitale's (1962)	4. Laursen- III (1963)
5. Shen (1969)	6. Hancu (1971)
7. CSU (1975)	8. Torsenthaugen (1975)
9. Breuser (1977)	10. Jain & Fischer (1979, 1981)
11. Melville & Sutherland (1988)	12. May & Willoughby (1990)
13. Gao (1992)	14. Kothyari (1992)
15. HEC-18-K3 (1993)	16. HEC-18-K4 (1995)
17. HEC-18-K4-Mu (1996)	18. Melville (1997)
19. Richard May (1998)	20. Jones & Sheppard (2000)
21. HEC-18-Kw (2001)	22. May, Acker & Kirkbay (2002)
23. HEC-18-K4-Mo (2003)	24. Molinas (2003)
25. Sheppard & Millar (2006)	26. Khwairakpam (2012)
27. HEC-18 (2012)	

3. Compilation of Clear Water Scour Data

The data set of clear water conditions was compiled from different sources. The data have information of observed scour depth ($Y_{se}^{Observed}$), approach flow conditions (i.e. flow depth, Mean approach flow velocity and angle of attack), pier geometry (i.e. pier size and pier shape) and bed material (i.e. coarseness, gradation and size) including both experimental and field data sets. The available information was further used to sort the data points into clear water and live bed scour conditions based on the flow intensity.

Flow intensity is defined as the ratio of the mean approach flow velocity (V) to the critical approach flow velocity (V_c) or the ratio of the shear velocity (U^*) to the critical shear velocity (U^*_c). Clear-water scour occurs when $V \leq V_c$ while live-bed scour occurs when $V > V_c$.

The sources through which data were collected, include Chiew [5], Southard [46], Wilson [49], Melville [31], Katherine [17], Mueller [36], Mohammad [33] and Beg [1]. 305 clear water scour condition points were collected by sorting all the available data and assuming suitable values for some missing and required information (Table-2).

Table 2: List of Data sets

Data Source	No. of Data Sets
Experimental Data	
Chiew (1984)	11
Melville (1999)	84
Mohammad (2006)	11
Beg (2013)	7
Field Data	
Southard (1992)	4
Wilson (1995)	5
Katherine (2004)	12
Mueller (2005)	171
Total	305

4. Comparative Evaluation

Ranking the performance of scour prediction equations is difficult because of the tradeoff between accuracy and under predictions. Considering only the accuracy, three statistical parameters were used to rank the equations with minimum prediction errors. These parameters are Sum of squared error (SSE), Mean Absolute error (MAE) and Root Mean square error (RMSE). These parameters were computed by following equations;

$$SSE\,(\%) = \frac{\sum(Y_{se}\,observed - Y_{se}\,computed)^2}{\sum(Y_{se}\,observed)^2} \times 100 \qquad (1)$$

$$MAE = \frac{\Sigma\left(\left|Y_{se}\text{observed} - Y_{se}\text{computed}\right|\right)}{\text{No. of observations}} \quad (2)$$

$$RMSE = \sqrt{\frac{\Sigma\left(Y_{se}\text{observed} - Y_{se}\text{computed}\right)^2}{\text{No. of observations}}} \quad (3)$$

The lower value of these parameters obtained from the equations indicate reliable predictions of the possible scour depth, hence are given a higher rank. The individual ranks of all the equations are computed based on above parameters and then summation of these ranks are computed to select reliable equations (Table-3).

Further an effort was made to evaluate the equations for the under prediction error. Under prediction error will quantify the error only in those data points where data is under predicted as compared to observed value. It was carried out using only "Sum of squared errors" just to understand its negative impact if analysis is only based on Overall error. Hence, the equations are evaluated for under prediction error using following criteria's;

1. Number of under predictions: Number of data points in which scour depth is under predicted.
2. SSE magnitude of under predicted values: Magnitude of the under predictions, because it is just as important, if not more so, than the number of under predictions.

Again, the lower value of these parameters indicated the reliable prediction, hence are given higher ranks (Table-4).

Table 3 : Summary of the Performance of Clear Water Scour Prediction Equations at Bridge Piers

Equation (1)	**No. of observations (2)**	**SSE (%) (3)**	**Rank (Based on 3) (4)**	**MAE (5)**	**Rank (Based on 5) (6)**	**RMSE (7)**	**Rank (Based on 7) (8)**	**Sum of Ranks (4+6+8) (9)**	**Rank (Based on 9) (10)**
Chithale's	336	114.858	11	1.508	23	2.425	21	55	21
Shen	381	80.363	6	1.202	19	2.632	23	48	16
Inglis-Poona -I	381	116.506	12	1.766	25	3.169	24	61	23
Inglis-Poona -II	381	75.420	4	1.006	13	2.550	22	39	13
Torsethaugen	26	99.083	10	0.447	9	0.601	4	23	5
CSU	336	84.415	8	1.277	20	2.079	18	46	15
breuser (1977)	322	210.501	17	0.517	11	1.001	10	38	12
Jain & Fischer	336	52.044	2	1.118	17	1.632	13	32	8
May & Willoughby	102	14976.092	26	1.488	22	1.691	14	62	24
Kothyari	334	116.587	13	1.063	15	2.417	20	48	16
HEC-18-K3	336	93.207	9	1.397	21	2.184	19	49	18
Melville	321	721.014	23	1.048	14	1.855	17	54	20
Richard & may	230	350.250	20	0.429	6	1.202	11	37	11
Jones & sheppard	289	211.230	18	0.443	8	0.887	9	35	10
HEC-18 Kw	321	119.201	14	0.418	5	0.754	7	26	6
May Acker & Kirkbay	322	305.256	19	0.617	12	1.205	12	43	14
Sheppard & Miller	228	33.471	**1**	0.212	**1**	0.309	**1**	3	**1**
Khwairakpam	366	482.589	21	2.084	26	4.759	25	72	25
Hancu	309	139.648	16	0.463	10	0.731	6	32	8
Gao	302	77.023	**5**	0.348	**3**	0.524	**3**	11	**3**
Melville & Sutherland	321	254957.097	27	7.217	27	34.882	27	81	27
HEC-18-K4	305	655.780	22	1.115	16	1.780	15	53	19
HEC-18-K4 Mu	322	81.607	7	0.372	4	0.623	5	16	4
Molinas	319	60.997	**3**	0.317	**2**	0.486	**2**	7	**2**
HEC-18-K4 (Mo)	322	121.237	15	0.437	7	0.760	8	30	7
Laursen-III	320	11954.481	25	1.521	24	6.794	26	75	26
HEC-18	320	836.214	24	1.176	18	1.797	16	58	22

Table 4 : Summary of the Performance of Clear Water Scour Prediction Equations for Under Prediction Error

Equations (1)	No. of observation with the under predicted values (2)	Rank (Based on 2) (3)	SSE of under predicted data (%) (4)	Rank (Based on 4) (5)	Total (3+4) (6)	Rank (Based on 6) (7)
Chithale's	103	10	61.85	12	22	9
Shen	129	13	74.64	17	30	17
Inglis-Poona –I	172	19	96.61	20	39	23
Inglis-Poona –II	175	21	74.32	16	37	19
Torsethaugen	24	2	125.43	22	24	10
CSU	60	8	39.98	7	15	4
Breuser (1977)	201	24	67.59	14	38	21
Jain & Fischer	37	6	20.88	2	8	2
May & Willoughby	9	1	21671.16	26	27	15
Kothyari	103	10	98.98	21	31	18
HEC-18-K3	48	7	35.68	6	13	3
Melville	28	3	79.71	18	21	8
Richard & may	154	18	404.20	24	42	24
Jones & sheppard	139	14	29.54	5	19	7
HEC-18 Kw	79	9	44.81	9	18	6
May Acker & Kirkbay	148	15	67.41	13	28	16
Sheppard & Miller	174	20	27.91	4	24	10
Khwairakpam	195	22	137.31	23	45	25
Hancu	128	12	24.47	3	15	4
Gao	148	15	54.91	11	26	14
Melville & Sutherland	233	26	280759.00	27	53	27
HEC-18-K4	34	5	88.81	19	24	10
HEC-18-K4 -Mu	149	17	40.87	8	25	13
Molinas	244	27	53.51	10	37	19
HEC-18-K4 (Mo)	197	23	68.27	15	38	21
Laursen-III	215	25	11216.42	25	50	26
HEC-18	31	4	11.46	1	5	1

5. Results and Discussion

Considering the overall accuracy of all the clear water scour prediction equations given in Table 3, the equation given by Sheppard & Miller seems to be the best by all three parameters and has attained the first rank. It is followed by Molinas and Gao equations, ranked as second and third respectively who have attained nearly same ranks by all the parameters individually. Evaluation carried out using SSE for under prediction error in Table 4 showed that the equation given by Sheppard & Miller under predicted the scour depth for nearly 76% data points although the magnitude of under prediction is not much. Similarly Gao and Molinas equations also did not performed well for under prediction error. The scatter plots of top three equations are also shown in Figure-1, 2 and 3 to verify the statistical evaluation. The deviation in the behavior of these equations may be attributed to various factors (e.g. conditions in the laboratory are different from prototype, the formulas are derived on the basis that upstream velocity profile is uniform, the bed around the cylinder is nearly horizontal, etc.) which are different than which were used in the development of these predictors.

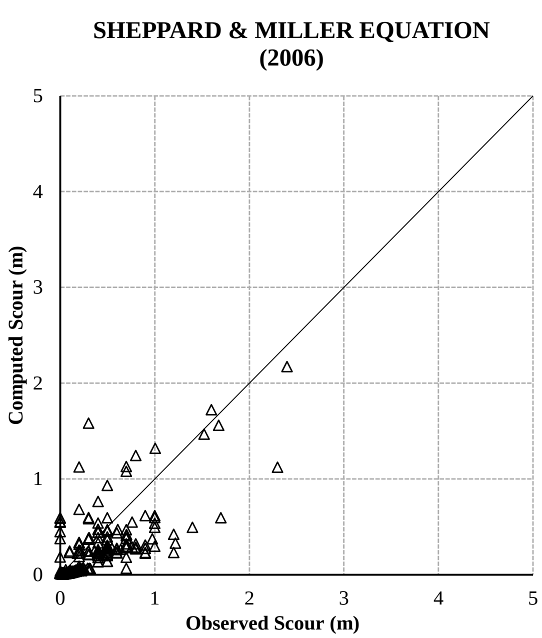

Fig. 1 Relation of computed scour depth to predicted scour depths for Sheppard & Miller equation

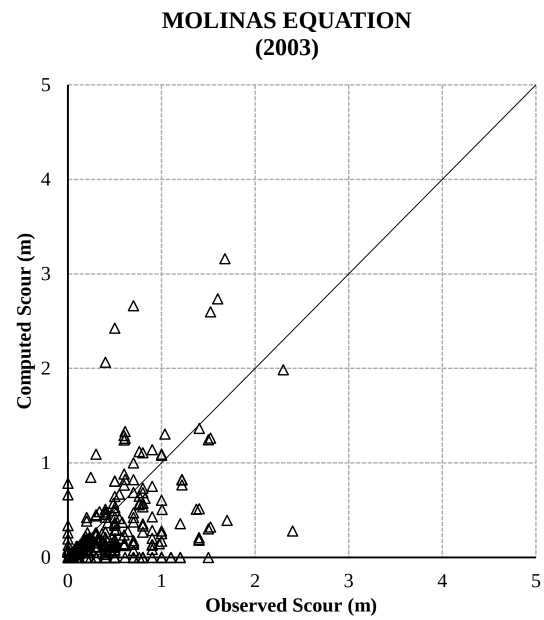

Fig. 2 Relation of computed scour depth to predicted scour depths for Molinas equation

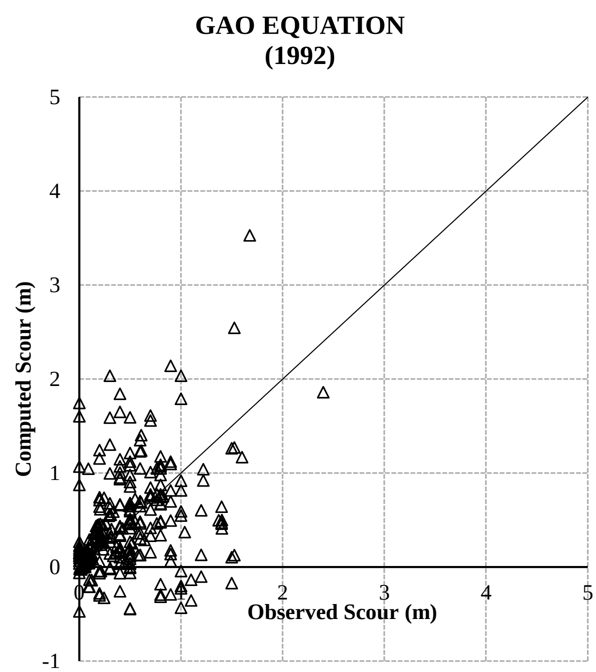

Fig. 3 Relation of computed scour depth to predicted scour depths for Gao equation.

6. Conclusions

a. This study indicates that the Sheppard & Miller (2006), Molinas (2003) and Gao (1992) equations give relatively better estimate of local scour depth around the bridge piers in clear water condition.

b. The Sheppard & Miller (2006), Molinas (2003) and Gao (1992) equations although performed relatively better when analyzed based on the overall error using statistical parameters namely "Sum of squared error", "Mean absolute error" and "Root mean square error". However, the evaluation of these equations for the under predicted data gives significant error which warrant the use of higher factor of safety when these equations are used.

References

[1] Beg, M., 2013, "Predictive competence of Existing Bridge Pier Scour Depth Predictors", European International Journal of Science and Technology, Vol. 2.

[2] Benedict, S. T. and Caldwell. A. W., 2006, "Development and Evaluation of Clear-Water Pier and Contraction Scour Envelope Curves in the Coastal Plain and Piedmont Provinces of South Carolina", U.S. Geological Survey Report 2005–5289.

[3] Boehmler, E. M. and Olimpio. J. R., 2000, "Evaluation of Pier-Scour Measurement Methods and Pier-Scour Predictions with Observed Scour Measurements at Selected Bridge Sites in New Hampshire, 1995-98", U.S. Geological Survey, Report No. FHWA-NH-RD-12323E.

[4] Breusers, H.N.C., Nicollet, G. and Shen, H.W., 1977, "Local scour around cylindrical piers", Journal of Hydraulic Research, 15(3): 211-252.

[5] Chiew, Y.M., 1984, "Local scour at bridgepiers", PhD thesis, Department of Civil Engineering, Auckland university, New Zealand.

[6] Chitale, S.V., 1962, Discussion of "Scour at bridge crossings," by E.M. Laursen: Transactions of the American Society of Civil Engineers, v. 127, part I, no. 3294, p. 191-196 (cited from Melville 1975, Breusers-1977).

[7] Gao, D.G., Posada, L.G., and Nordin, C.F., 1992, "Pier scour equations used in the People's Republic of China—review and summary: Fort Collins", CO, Colorado State University, Department of Civil Engineering, Draft Report (cited from Sheppard-2011, Mueller-2005, Boehmler-2000)

[8] Gaudio, R., Grimaldi, C., Tafarojnoruz, A. and Calomino, F., 2010, "Comparison of formulae for the prediction of scour depth at piers".

[9] Garde, R.J. and Kothyari, U.C., 1998, "Scour around bridge piers." PINSA 64, A, N0. 4. pp. 569-580.

[10] Hanco, S., 1971, "Sur le calcul des affouillements locaux dans la zone des piles de ponts", Proc. 14th IAHR Congress, Paris, 3, pp. 299/313 (cited from Melville 1975, Breusers-1977).

[11] Inglis, S.C., 1949 "The Behaviour and Control of Rivers and Canals", Research Publ. No. 13, Central Water Power Irrigation and Navigation Report, Poona Research Station, India (cited from Kothyari 2007, Melville 1975).

[12] Inglis, S.C., 1949 "The Behaviour and Control of Rivers and Canals", Research Publ. No. 13, Central Water Power Irrigation and Navigation Report, Poona Research Station, India (cited from Melville 1975, Breusers-1977).

[13] Jain, S. C., and Fischer, E. E., 1979, "Scour around bridge piers at high Froude numbers', Rep. No. FHWA-RD-79-104, Federal Highway Ad-ministration, Washington D.C (cited from Sheppard-2011, Mueller-2005, Boehmler-2000).

[14] Jain, S. C., 1981, "Maximum clear-water scour around circular piers", Journal of the Hydraulics Division, 107(HY5), 611–626 (cited from Sheppard-2011, Mueller-2005, Boehmler-2000).

[15] Jones, J. S., 1984. "Comparison of prediction equations for bridge pier and abutment scour', Proc., Transportation Research Record, Second Bridge Engineering Conf., Vol. 2,

Transportation Research Board, Washington, D.C., 202–209.

[16] Jones, J.S. and Sheppard, D.M., 2000, “Scour at wide bridge piers”, Joint Conference on Water Resources Engineering and Water Resources Planning and Management, ASCE, July 30 ñ August 2, 2000, Minneapolis, Minnesota, U.S., 10 p.

[17] Katherine, J. C. and Stephen R. H., 2004, “Evaluation of Pier-Scour Equations for Coarse-Bed Streams”, U. S. Geological survey, Scientific Investigations Report 2004-5111

[18] Khwairakpam, P. and Mazumdar, A., 2009, “Local scour around hydraulic structures”, short paper, international journal of recent trends in engineering, Vol. 1, no. 6.

[19] Kothyari, U.C., Garde, R.J., and Ranga Raju, K.G., 1992, “Temporal variation of scour around circular bridge piers.” Journal of Hydraulic Engineering, ASCE, 118(8), 1091-1106.

[20] Kothyari, U. C., 2007, “Indian practice on estimation of scour around bridge piers—A comment”, Sadhana, Vol. 32, Part 3, June 2007, pp. 187–197.

[21] Lagasse, P.F. and Richardson, E.V., 2001, “ASCE compendium of stream stability and bridge scour papers”, Journal of Hydraulic Engineering, ASCE, 127(7): 531-533.

[22] Landers, M. N., Mueller. D. S., and Martin. G. R., 1996, “Bridge scour data management system user’s manual” U.S. GEOLOGICAL SURVEY, Open-File Report 95-754.

[23] Landers, M. N., and Mueller, D. S., 1996, “Evaluation of selected pier-scour equations using field data”, Transp. Res. Rec., 1523, 186–195.

[24] Laursen, E.M., 1963, “An analysis of relief bridge scour”, American Society of Civil Engineers, Journal of the Hydraulics Division, v. 89, no. HY3, p. 93-118 (cited from Landers-1996).

[25] Lu, J. U., Hong, M. J., Su, C. C., Wang, C. Y. and Lai, J. S., 2009, “Field Measurements and Simulation of Bridge Scour Depth Variations during Floods”, Journal of Hydraulic Engineering, ASCE.

[26] May, R. W. P., and Willoughby, I. R.,1990, “Local Scour around Large Obstructions”, HR Wallingford, Wallingford, Oxford, and U.K (cited from Sheppard-2011).

[27] May, R.W.P., Ackers, J.C. and Kirby, A.M., 2002, “Manual on scour at bridges and other hydraulic structures”, Construction Industry Research and Information Association.

[28] Melville, M.W., 1975, “Local scour at bridge sites”, New Zealand, University of Auckland, School of Engineering, Project Report No. 117, 227 p.

[29] Melville, B. W. and Sutherland, A. J., 1988, “Design Method for Local Scour at Bridge Piers”, Journal of Hydraulic Engineering, ASCE, 114, No. 10, pp. 1210-1226.

[30] Melville, B.W., 1997, “Pier and abutment scour: integrated approach.” Journal of Hydraulic Engineering, ASCE, 123(2), 125-136.

[31] Melville, B.W. and Chiew, Y.M. 1999. Time scale for local scour at bridge piers. Journal of Hydraulic Engineering, ASCE, 125(1): 59-65.

[32] Mohamed, T. A., Pillai, S., Noor, M. J. M. M., Ghazali, A. H., Huat, G. B. K., and Yusuf, B., 2005, “Validation of some bridge pier scour formulae and models using field data.” American Journal of Environmental Sciences ISSN 1553-345X.

[33] Mohammed, T. A., Noor, M. J., Halim, A. G., Yusuf, B., and Saed, K., 2006, “Physical Modelling of Local Scouring around Bridge Piers in Erodible Bed”, J. King Saud Univ., Vol. 19, Eng. Sci.(2), pp. 195-207, Riyadh (1427H./2007).

[34] Molinas, A., 2004, “Bridge scour in non-uniform sediment mixtures and in cohesive materials”, Washington, DC, Federal Highway Administration Research Report FHWA–RD–03–083.

[35] Mueller, D. S., 1996, “Local scour at bridge

piers in non-uniform sediment under dynamic conditions", Ph.D. thesis, Colorado State Univ., Fort Collins (cited from Mueller-2005).

[36] Mueller, D. S., and Wagner, C. R., 2005, "Field observations and evaluations of streambed scour at bridges." Report no. FHWA–RD–03–052, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, USA.

[37] Richardson, E.V., Simons, D.B., Karaki, Susumu, Mahmood, Khalid, and Stevens, M.A., 1975, "Highways in the river environment: hydraulic and environmental design considerations", Federal Highway Administration, 476 p (cited from Landers-1996).

[38] Richardson, E.V. and Davies, S.R., 1993, "Evaluating scour at bridges. (HEC 18)", Federal Administration, U.S. Department of Transportation, Washington, D.C.

[39] Richardson, E.V. and Davies, S.R., 1995, "Evaluating scour at bridges", Rep. No. FHWA-IP-90-017 (HEC 18), Federal Administration, U.S. Department of Transportation, Washington, D.C.

[40] Richardson, E.V., D.B. Simons, and P.F. Lagasse, 2001, "River Engineering for Highway Encroachments", FHWA NHI 01-004, Federal Highway Administration, Hydraulic Series No. 6, Washington, D.C.

[41] Richardson, E.V. and Davis, S.R., 2001, "Evaluating Scour at Bridges", Fourth Edition, Hydraulic Engineering Circular No. 18, FHWA NHI 01-001, Washington, D.C. (www.fhwa.dot.gov/bridge/hydpub.htm)

[42] Richardson, E.V. and Davis, S.R. 2012, "Evaluating Scour at Bridges", Fifth Edition, Hydraulic Engineering Circular No. 18, FHWA NHI 01-001, Washington, D.C. (www.fhwa.dot.gov/bridge/hydpub.htm)

[43] Shen, H. W.; Schneider, V. R. and Karaki, S., 1969, "Local Scour around Bridge Piers." Proceedings of ASCE, No. 6, pp.1919-1940 (cited from Melville 1975, Landers-1996, and Breusers-1977).

[44] Sheppard, D.M, Demir, H., Melville, B.W., 2011, "Scour at wide piers and long skewed piers", NCHRP Report 682, Transportation Res. Board of National Academies, Washington, DC.

[45] Sheppard, D.M, Melville, B.W. and Demir, H., 2013, "Evaluation of existing equations for local scour at bridge piers", Journal of Hydraulic Engineering. doi:10.1061/(ASCE)HY.1943 7900.0000800

[46] Southard, R.E., 1992, Scour around bridge piers on streams in Arkansas: Little Rock, AR, U.S.

[47] Torsethaugen, K., 1975, "Local crosjonved store konstruksjoner Model lforsok (Norvcgian)", Vassdragsog Havne-laboratoriet, Trondheim (cited from Breusers-1977).

[48] Wardhana, K. and Hadipriono, F.C., 2003, "Analysis of recent bridge failures in the United States", Journal of Performance of Constructed Facilities, ASCE, 17(3): 144-150.

[49] Wilson, K.V., Jr., 1995, Scour at selected bridge sites in Mississippi: Reston, VA, and U.S. Geological Survey Water-Resources Investigations Report 94–4241, 44 p.

APPENDIX 1: Clear Water Scour Depth Prediction Equations at Bridge Piers

Sr. No.	Researcher	Equation
1.	Inglis-Poona-I (1949)	$Y_{se} = 2.32b^{0.22}V^{0.52}y^{0.52}-y$ b= pier width (m) V= mean approach flow velocity (m/sec)
2.	Inglis-Poona-II (1949)	$Y_{se} = 1.73b^{0.22}y^{0.78}-y$
3.	Chitale's (1962)	$\frac{Y_{se}}{y} = -5.49F_r^2 + 6.65F_r - 0.51$ Where, F_r = Approach flow Froude number = $\frac{V}{\sqrt{gy}}$
4.	Laursen-III (1963)	$\frac{b}{y} = 5.5\left(\frac{Y_{se}}{y}\right)\left[\frac{\left(\frac{Y_{se}}{11.5y}+1\right)^{7/6}}{\left(\frac{t}{\tau_c}\right)^{0.5}} - 1\right]$ Where, τ = Approach flow shear stress τ_c = critical shear stress at threshold of motion
5.	Shen (1969)	$Y_{se} = 0.00022\ R_p^{0.619}$ Where, R_p = Pier Reynolds number $= \frac{Vb}{v}$ ν =Kinematic viscosity of water= 1×10^{-6} (m^2/sec)
6.	Hancu (1971)	For clear water scour: $\frac{y_{se}}{b} = 2.42\left(\frac{2V}{V_c}-1\right)\left(\frac{V^2}{gb}\right)^{1/3}$ For sediment transporting scour (live bed scour): $\frac{y_{se}}{b} = 2.42\left(\frac{V_c^2}{gb}\right)^{1/3}$ This equation is only applicable for the values corresponding to $V/V_c \geq 0.5$ Where, V_c= critical approach flow velocity (m/sec)
7.	Torsethaugen (1975)	$\frac{y_{se}}{b} = 1.8\left(\frac{V}{V_c}-0.54\right)\frac{y}{b}$ for Y/b<1.0
8.	CSU (1975)	$Y_{se} = 2.0YK_1K_2g^{-0.215}y^{0.135}b^{0.65}V^{0.43}$ K_1 = Correction factor for pier shape (it is 1.1 for square piers, 1.0 for circular or round piers, 0.9 for sharp piers, and 1.0 for a group of piers); K_2 = Correction factor for the ratio of the pier length to pier width (L/b) and the angle of the approach flow with reference to the bridge pier
9.	Breusers (1977)	$\frac{Y_{se}}{b} = f\left(\frac{V}{V_c}\right)\left[2.0\tanh\left(\frac{y}{b}\right)\right]K_s\ K_a$ Where $f\left(\frac{V}{V_c}\right) = 0$ For $\frac{V}{V_c} \leq 0.5$ $f\left(\frac{V}{V_c}\right) = \left(2\frac{V}{V_c}-1\right)$ For $0.5 < \frac{V}{V_c} < 1$

		$f\left(\frac{V}{V_c}\right)=1 \quad \text{For} \quad \frac{V}{V_c}>1$ K_s = pier shape factor(it is1.0 for circular and rounded piers, 0.75 for streamlined shapes, 1. 3 for rectangular piers) K_α = pier alignment factor
10.	Jain & Fischer (1979, 1981)	$Y_{se}=2.0b(F_r-F_{rc})^{0.25}\left(\frac{y}{b}\right)^{0.5}$ $(F_r - F_{rc}) \geq 0.2$ in the live bed condition. $Y_{se}=1.85b(F_{rc})^{0.25}\left(\frac{y}{b}\right)^{0.3}$ $(F_r - F_{rc}) < 0$ in the clear water condition. Where F_{rc} = critical Froude number = $\frac{V_c}{\sqrt{gy}}$ For $0 < (F_r - F_{rc}) < 0.2$, the larger of the two above computed scour depths is used.
11.	Melville & Sutherland (1988)	$Y_{se} = K_i K_d K_y K_\alpha K_s b$ Ki = factor for flow intensity $K_i=2.4\left[\frac{V-(V_a-V_c)}{V_c}\right]$ if $\frac{V-(V_a-V_c)}{V_c}<1$ $K_i=2.4$ if $\frac{V-(V_a-V_c)}{V_c}>1$ Kd = factor for sediment size $K_d=1.0,$ if $\frac{b}{d_{50}} > 25$ $K_d=0.57\log\left(2.24\frac{b}{d_{50}}\right),$ if $\frac{b}{d_{50}}<25$ Ky = factor for flow depth $K_y=0.78\left(\frac{y}{b}\right)^{0.255}$ for $\frac{y}{b}<2.6$ $K_y=1.0$ for $\frac{y}{b}>2.6$ Kα = factor for pier alignment Ks = factor for pier shape
12.	May & Willoughby (1990)	$Y_{se}=2.4f_s\left(\frac{Y_{se}}{Y_{sc}}\right)\left(\frac{Y_{sc}}{Y_{sm}}\right)$ Where, f_s= 1 (For circular pier) $\frac{Y_{se}}{Y_{sc}}=1-3.66\left(1-\frac{V}{V_c}\right)^{1.76}$ if $0.52\leq\frac{V}{V_c}\leq1.0$ $\frac{Y_{se}}{Y_{sc}}=1$ if $\frac{V}{V_c}>1.0$ $\frac{Y_{sc}}{Y_{sm}}=0.55\left(\frac{y}{b}\right)$ if $\frac{y}{b}\leq 2.7$ $\frac{Y_{sc}}{Y_{sm}}=1.0$ if $\frac{y}{b}> 2.7$

13.	Kothyari (1992)	$\frac{Y_{se}}{b} = 1.0\left(\frac{b}{d_{50}}\right)^{-0.25}\left(\frac{y}{d_{50}}\right)^{0.16}\left(\frac{V^2 - V_{cp}^2}{\frac{\Delta Y_s}{pf} d_{50}}\right)^{0.4} \sigma^{-0.3}$ Where, $V_{cp}^2 = 1.2\left(\frac{\Delta Y_s}{pf} d_{50}\right)\left(\frac{b}{d_{50}}\right)^{-0.11}\left(\frac{y}{d_{50}}\right)^{0.16}$ V_{cp} = critical velocity for the motion of sediment particles at the pier nose, γ_s = sediment specific weight, γ_f = fluid specific weight, ρ_f = fluid mass density and σ= (B-b)/B the opening ratio, B = flume width or center-to-center spacing between two piers.
14.	Gao (1992)	For clear water scour condition: $Y_{se} = 0.78 K_s b^{0.6} y^{0.15} d_{50}^{-0.07}\left[\frac{V - V_c'}{V_c - V_c'}\right]$ For Live bed scour condition: $Y_{se} = 0.46 K_s b^{0.6} y^{0.15} d_{50}^{-0.07}\left[\frac{V - V_c'}{V_c - V_c'}\right]^{\eta}$ Where, $V_c = \left(\frac{y}{d_{50}}\right)^{0.14}\left[17.6\left(\frac{\rho_s - \rho}{\rho}\right)d_{50} + 6.05\times10^{-7}\left(\frac{10+y}{d_{60}^{\ 0.72}}\right)\right]^{0.5}$ K_s is the simplified pier-shape coefficient (it is 1.0 for cylinders, 0.8 for round- piers, 0.66 for sharp piers) V'_c = the incipient velocity for the local scour at the pier= $V_c = 0.645\left(\frac{d_{50}}{b}\right)^{0.053} V_c$ $\eta = \left(\frac{V_c}{V}\right)^{9.35 - 2.23\log_{10} d_{50}}$
15.	HEC-18-K3 (1993)	$Y_{se} = 2.0 Y K_1 K_2 K_3 g^{-0.215} y^{0.135} b^{0.65} V^{0.43}$ Where, K_3 = coefficient which is based on the bed conditions
16.	HEC-18-K4 (1995)	$Y_{se} = 2.0 Y K_1 K_2 K_3 K_4 g^{-0.215} y^{0.135} b^{0.65} V^{0.43}$ Where, $K_4 = [1 - 0.89(1 - V_r)^2]^{0.5}$ V_r = velocity ratio = $\left[\frac{V - V_{i50}}{V_{c90} - V_{i50}}\right]$ V_{i50} = approach flow velocity which is required to initiate scour at the pier for the particle size of d_{50} (m/sec) $= 0.645\left[\frac{d_{50}}{b}\right]^{0.053} V_{c50}$ V_{c50} = critical flow velocity which is required for incipient motion of the particle size of d_{50} (m/sec). $V_{c50} = 6.19 y^{1/6} d_{50}^{1/3}$ V_{c90} = critical flow velocity which is required for incipient motion of the particle size of d_{90} (m/sec) = $6.19 y^{1/6} d_{90}^{1/3}$ d_{90} = particle size for which 90 percent of the bed material is finer (m).

17.	HEC-18-K4-Mu (1996)	$Y_{se} = 2.0\,YK_1K_2K_3K_4g^{-0.215}y^{0.135}b^{0.65}V^{0.43}$ Where, $K_4 = 0.4\left(\frac{V - V_{i50}}{V_{c50} - V_{i95}}\right)^{0.15}$ $V_{i95} = 0.645\left[\frac{d_{95}}{b}\right]^{0.053} V_{c95}$
18.	Melville (1997)	$Y_{se} = K_y\ K_i\ K_d\ K_s\ K_\alpha\ Kg$ Where, K_i = factor for flow intensity = $\begin{cases} \frac{V}{V_c} & \text{for } \frac{V}{V_c} < 1 \\ 1 & \text{for } \frac{V}{V_c} \geq 1 \end{cases}$ K_d = factor for sediment size = $\begin{cases} 0.57\log\left(2.24\frac{b}{d_{50}}\right) & \text{for } \frac{b}{d_{50}} \leq 25 \\ 1 & \text{for } \frac{b}{d_{50}} > 25 \end{cases}$ K_y = factor for flow depth = $\begin{cases} 2.4b & \text{for } \frac{b}{y} < 0.7 \\ 2\sqrt{yb} & \text{for } 0.7 < \frac{b}{y} < 5.0 \\ 4.5y & \text{for } \frac{b}{y} > 5.0 \end{cases}$ K_α = factor for pier alignment K_s = factor for pier shape K_g = channel geometry coefficient= 1 for piers.
19.	Richard May (1998)	$\frac{Y_{se}}{y} = k\left[0.55\left(\frac{b}{y}\right)^{0.40}\right]_{max=1.0}\left[0.6\left(\frac{2.07\times V}{V_c} - 1\right)\right]_{max=1.0}$ Where; for rectangular piers k= 3.2, for round piers k=2.4 and the maximum value in either of these brackets is 1.0.
20.	Jones & Shepperd (2000)	For clear water scour condition: $(0.4 \leq \frac{V}{V_c} \leq 1.0)$ $\frac{Y_{se}}{b} = c_1\left[\frac{5}{2}\left(\frac{V}{V_c}\right) - 1.0\right]$ Also; $c_1 = \frac{2}{3}k$ And $k \equiv \tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]\left[-0.279 + 0.049\exp\left(\log_{10}\frac{b}{d_{50}}\right) + \frac{0.78}{\log_{10}\frac{b}{d_{50}}}\right]^{-1}$ For Live bed scour condition: $(1.0 < \frac{V}{V_c} \leq \frac{V_{1p}}{V_c})$ $\frac{Y_{sc}}{b} = c_2\left(\frac{V_{1p} - V}{V_c}\right) + c_3$ Where $c_2 = \frac{k - 2.4\tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]}{\left(\frac{V_{1p}}{V_c} - 1\right)}$ And $c_2 = 2.4\tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]$

		If $\frac{V}{V_c} > \frac{V}{V_c}$ then $\frac{Y_{sc}}{b} = 2.4\tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]$ V_{LP} = velocity at which the bed upstream of the pier will become flat and gives a plain surface
21.	HEC-18-Kw (2001)	$\frac{Y_{se}}{b} = 2.0K_1K_2K_3K_4K_w\left(\frac{y}{b}\right)^{0.35} Fr^{0.43}$ If $d_{50} < 2mm$ or $d_{95} < 20mm$, then $K_4 = 1$ If $d_{50} \geq 2mm$ and $d_{95} \geq 20mm$, then $K_4 = 0.4(V_r)^{0.15}$ Where: $V_r = \frac{V - V_{icd50}}{V_{cd50} - V_{icd50}} > 0$ K_w =correction factor for the wide piers in shallows flow $K_w = 2.58\left(\frac{y}{b}\right)^{0.34} F_r^{0.65}$ for $\frac{V}{V_c} < 1$ $K_w = 1.0\left(\frac{y}{b}\right)^{0.13} F_r^{0.25}$ for $\frac{V}{V_c} > 1$
22.	May, Acker & Kirkbay (2002)	$\frac{Y_{se}}{b} = S_f\ \varphi_{shape}\ \varphi_{depth}\ \varphi_{velocity}\ \varphi_{angle}$ S_F is a factor of safety=1.6 φ_{shape} = shape factor (using table) $\varphi_{depth} = 0.55\left(\frac{y}{b}\right)^{0.60}$ for $\frac{y}{b} \leq 2.7$ $\varphi_{depth} = 1.0$ for $\frac{y}{b} > 2.7$ $\varphi_{velocity} = 0$ for $\frac{V}{V_c} \leq 0.375$ $\varphi_{velocity} = 1.6\left(\frac{V}{V_c}\right) - 0.6$ For $0.375 \leq \frac{V}{V_c} \leq 1.0$ $\varphi_{velocity} = 1.0$ For $\frac{V}{V_c} > 1.0$ $\varphi_{angle} = \left[\cos\alpha + \left(\frac{L}{b}\right)\sin\alpha\right]^{0.62}$
23.	Molinas (2003)	$\frac{Y_{se}}{b^{0.66}y^{0.17}} = K_uK_1K_2K_3K_4\psi^{0.55};\ 0 \leq \psi \leq 1$ Where K_U = 0.99; K_1, K_2, and K_3 are the factors already defined; and, ψ = excess velocity factor (dimensionless) $\psi = \frac{V - V_i}{V_c - V_i};\ 0 \leq \psi \leq 1$

		$V_c = K_c D_{cfm}^{1/3} y^{1/6}$ $V_i = K_i D_{35}^{1/3} y^{1/6}$ Where K_c= 6.625; K_i= 2.65; and D_{cfm}= median size of the coarse material fractions (meters). It is computed from following relation; $D_{cfm} = \frac{D_{95}+2D_{90}+2D_{95}+D_{99}}{6}$ K_4= factor for the coarse fraction reduction. It is given by: $K_4 = 1.25+3\sqrt{\frac{D_{cfm}}{D_{50}}}\psi^{0.60}\ln(\psi+0.5);\ 0 \le K_4 \le 1;\ 0 \le \psi \le 1$ By definition, K_4 and ψ, both factors cannot have value greater than 1.
24.	HEC-18-K4-Mo (2003)	$\frac{Y_{se}}{b} = 2.0 K_1 K_2 K_3 K_i K_4 \left(\frac{b}{y}\right)^{0.65} Fr^{0.43}$ Where K_1, K_2, and K_3 are the factors already defined $K_i = \left(1-\frac{V_i}{V}\right)^{0.45};\ V > V_i$ For values of $V \le V_i$, the value of Ki(the factor for initiation of scour) is 0. $K_4 = 1.25+3\sqrt{\frac{D_{cfm}}{D_{50}}}\psi^{0.60}\ln(\psi+0.5);\ 0 \le K_4 \le 1;\ 0 \le \psi \le 1$
25.	Sheppard & Miller (2006)	$\frac{Y_{sc}}{b_c} = 2.5 f_1 f_2 f_3 \quad \text{for} \quad 0.47 \le \frac{V}{V_c} \le 1.0$ $\frac{Y_{sc}}{b_c} = f_1\left[2.2\left(\frac{\frac{V}{V_c}-1}{\frac{V_{1p}}{V_c}-1}\right)+2.5f_3\left(\frac{\frac{V_{1p}}{V_c}-\frac{V}{V_c}}{\frac{V_{1p}}{V_c}-1}\right)\right] \quad \text{for } 1 < \frac{V}{V_c} < \frac{V_{1p}}{V_c}$ $\frac{Y_{sc}}{b_c} = 2.2 f_1 \quad \text{for} \quad \frac{V}{V_c} > \frac{V_{1p}}{V_c}$ Where; Shape factor = 1 (circular pier) $= 0.86+0.97\left(\left\lvert \alpha-\frac{\pi}{4}\right\rvert\right)^4$ (for square pier) α = flow skew angle (radians) $f_1 = \tanh\left[\left(\frac{y}{b_e}\right)^{0.4}\right]$ $f_2 = 1-1.75\left[\ln\left(\frac{V}{V_c}\right)\right]^2$ $f_3 = \frac{\frac{b_c}{d_{50}}}{0.4\left(\frac{b_c}{d_{50}}\right)^{1.2} 10.6\left(\frac{b_c}{d_{50}}\right)^{-0.13}}$ $V_{lp1} = 0.8\sqrt{gy}$

		$V_{lp2} = 29.31 U_{\bullet c} \log_{10}\left(\frac{4y}{d_{50}}\right)$ $V_{1p} = \begin{cases} V_{1p1} & \text{for } V_{1p1} \geq V_{1p2} \\ V_{1p2} & \text{for } V_{1p2} \geq V_{1p1} \end{cases}$
26.	Khwairakpam (2012)	$\frac{Y_{se}}{b} = \left[0.744\left(\frac{y}{b}\right) - 0.367\right] F_{d50} + \left[-2.438\left(\frac{y}{b}\right) + 2.683\right]$ Where $F_{d50} =$ Densimetric Froude number $= \frac{V}{\sqrt{\Delta g d_{50}}}$ In sediment- water interaction, the parameters g, ρ and ρs are combined into one parameter where Δ=(ρs/ρ)-1
27.	HEC-18 (2012)	$\frac{Y_{se}}{b} = 2.0 K_1 K_2 K_3 K_w \left(\frac{y}{b}\right)^{0.35} Fr^{0.43}$