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A New Equation for Predicting the Scour Depth Around Bridge Piers

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Abstract: One of the most important factors that damages bridges, especially during floods is the local scour around bridge piers. Therefore, determining the depth of scour around the piers of a bridge is an essential factor in designing bridges against this destructive phenomenon. The depth of scour is calculated by experimental equations. Different researchers with the help of experimental and field data and the regression method have acquired these equations. In order to predict the exact depth of scour, equations with less error should be used. Because the base of most of scour equations is experimental data, in this article, a new equation based on the field data and regression analysis is introduced for predicting the depth of local scour around bridge piers. A comparison between this new equation and six former equations has shown that relatively the results of the new equation are closer to actuality.

Key words: Local scour · Bridge pier · Scour equation · Field data

INTRODUCTION

Bridges are the most important and durable structures on the rivers that are essential for linking of pathway. Many of these bridges destroy yearly when flood occurred. If a pier places on the bed river vertically, the turbolent flow and set of vortex flow will occure. These vortex systems are the main mechanism of scour that can produce hole in the bridge pier location and destroy bridge [1].

In recently years, researchers studied about different aspects of determination scour depth around bridge piers. For example, Kirkil and *et al.* made used of detached eddy simulation to reveal the dynamics of large-scale coherent eddies in the flow around a circular pier with an equilibrium scour hole [2]. Azamathulla and *et al.* predicted the scour depth at bridge piers by ANNs and GP [3]. The temporal effect of hydrograph on local scour depth is investigated under clear-water scour condition by Lai and *et al.* [4]. A new methodology for the experimental analysis of the equilibrium scour depth at bridge piers is introduced and validated for clear-water conditions. The proposed experimental methodology determines the flow conditions for a given equilibrium scour instead of determining the equilibrium scour for given flow conditions, which is the usual practice [5]. Bolduc and *et al.* developed probabilistic models. Their probabilistic models are used to estimate the probability of exceedance of scour depth around bridge piers [6].

Because of estimation of scour depth around bridge pier is essential for safe design, investigations are carried out to finding creditable equations in order to estimation of maximum scour depth around bridge piers in recent decade.

Inaccuracy of equations based on limited data that obtained from laboratory physical models in different situation. Therefore, correctness of using these equations are unknown in order to exact estimation of maximum scour depth around of bridge pier. Assessment accuracy of various equations with experimental and field data is important.

Janson (1995) Compared different equations of scour around bridge piers by using of field data [7]. The most creditable equations in order to estimation of scour around bridge piers are showed in Table 1 [8, 9].

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Table 1: Important equations for calculation of local scour around bridge piers

Equation	Researcher and Date
$d_s = 1.7b\left(\frac{q^{\frac{2}{3}}}{b}\right)^{0.75} - y$	Inglis (1949)
$\frac{d_s}{y} = 2.0k_1.k_2.k_3.k_4.k_w\left(\frac{b}{y}\right)^{0.65}.(Fr)^{0.43}$	Richardson and Davis (1995)
$\frac{ds}{b} = 0.32\phi\left(\frac{b'}{b}\right)^{0.62}.\left(\frac{y}{b}\right)^{0.46}(Fr)^{0.2}.\left(\frac{b}{D_{50}}\right)^{0.08}$	Froehlich (1988)
$\frac{ds}{y} = 1.95\left(\frac{b}{y}\right)^{\frac{1}{6}} - 1$	Aronchelam (1965)
$d_s = 1.4b$	Breusers (1965)
$d_s = 1.05\, b^{0.75}$	Larras (1963)

Table 2: The value of k_3

K_3	The height of levee	Bed condition
1.1		Clear water scour
1.1		Smooth bed
1.1	2 to 10 ft	Peir on the levee
1.1-1.2	10 to 30 ft	Peir on the levee
1.3	More than 30 ft	Peir on the levee

ds: Maximum scour depth
y: Upstream flow depth
b: Pier width
Fr: Upstream Froude number
ϕ: Pier shape factor
b': Effective pier width
D_{50}: Median sediment size
k_1: Shape pier factor
k_2: Factor for angle between approach flow and pier axial
k_3: Bed condition factor from Table 2
k_4: Factor for armoring by bed material
k_w: Factor for width piers in shallow rivers

In this paper, new equation has been defined for estimation of local scour depth around bridge piers. Comparison between predicted results of new equation and six current equations is carried out by using SPSS 11.5 software.

General Equation for Scour Depth Around Bridge Piers: Because of several effective factors on local scour around bridge piers, consideration all of them is difficult. Therefore, previous scientists considered the most important factors that have extreme effects on scour depth. They made used of these factors in their developed equations.

These factors consist of pier geometry, flow variable, fluid and sediment property. These factors are illustrated in equation 1:

$$d_s = f(k_s, k_\theta, b, V, y, g, \rho, \mu, \rho_s\text{-}\rho, D_{50}, \sigma) \quad (1)$$

That $d_s, k_s, k_\theta, b, v, y, g, \mu, p_s, \rho, D_{50}$ and σ are defined maximum local Scour depth, pier shape coefficient, factor for angles between approach flow and pier axial, pier width, flow velocity, upstream flow depth, gravity acceleration, fluid dynamic viscosity, sediment density, fluid density, median sediment size and Standard deviation of bed material, sequentially. By using dimensional analysis and Buckingham π Theory, equation 1 converts to dimension less form that is illustrated in equations 2 and 3.

$$f_1 = \left(k_s, k_\theta, \frac{ds}{y}, \frac{y}{b}, \frac{b}{D_{50}}, \frac{gy}{V^2}, \frac{\mu}{\rho V y}, \frac{\rho_s - \rho}{\rho}, \sigma\right) = 0 \quad (2)$$

$$\frac{ds}{b} = f_2\left(k_s, k_\theta, \frac{y}{b}, \frac{b}{D_{50}}, \frac{V}{\sqrt{gy}}, \frac{\rho V y}{\mu}, \frac{\rho_s - \rho}{\rho}, \sigma\right) \quad (3)$$

$\frac{\rho V y}{\mu}$ In equation3 is Reynolds number that shows effect of viscosity force on amount of scour depth around bridge pier. In turbulent flow, effect of viscosity force in comparison with inertial force is negligible. Therefore, ignorance of Reynolds number is possible [10].

In most equations, does $\frac{\rho_s - \rho}{\rho}$ not appear because sediment materials of the experiments are quartz and quartz has not significant density variation.

$\frac{\rho_s}{\rho}$ Is between 2-2.7 [10].

Therefore, equation3 changes to simple form that shown in equation4.

$$\frac{ds}{b} = f_3\left(k_s, k_\theta, \frac{y}{b}, \frac{b}{D_{50}}, Fr, \sigma\right) \quad (4)$$

Field Data: Data from piers of 68 bridges in different state in USA are considered in this research. These data were assembled by united state Geological Survey (USGS) and available in its website.

Preference of these data against another field data is significant number and perfect range of them. The most effective factors in scour depth are defined by these data.

New Equation: Data of 271 piers of 35 bridges are made used to development a new equation. In order to using of considered parameters in equation4 in new equation a suitable analysis was accomplished.

SPSS 11.5 Software carried out this analysis. Regression coefficient of this nonlinear equation is R=0.94 that is acceptable for equation based on field data. New equation was illustrated in equation5.

$$\frac{ds}{b} = 0.636.k_s.k_\sigma.\left(\frac{b'}{b}\right)^{-0.53}.\left(\frac{y}{b}\right)^{0.69}.(Fr)^{-0.05} \quad (5)$$

That k_a is coefficient of pier shape.

(Sharp nose 0.8, cylindrical and circle nose 1 and square nose 1.2)

k_σ: Factor for standard deviation of bed material size and was calculated by equation6.

$$k_\sigma = \left(\frac{D_{84}}{D_{50}}\right)^{-0.52} \quad (6)$$

b': Effective width of pier that was calculated by equation7.

$$b' = b\cos\theta + L\sin\theta \quad (7)$$

L: Pier length

θ: Angle between approach flow and pier axial

$\left(\frac{b'}{b}\right)^{-0.53}$ In equation5 is equal to k_θ in equation4.

Analysis Accuracy of Equation about Different Kinds of Bed: For Assessment accuracy of new equation, obtained pier scour data from 17 bridges of different area in USA with Sandy and gravel beds were considered. List of bridges are shown in Table 3. Comparison of observed and calculated scour depth of these piers has been illustrated in Figure 1 and 2.

These data are not data that are made used for derivation of equation5.

In figure1 and2, spots around 45' line are next to it. Calculated RMSE errors were 0.54 and 0.86 for gravelly and Sandy bed consequently.

This equation has acceptable answer for various beds.

Table 3: List of bridges on rivers with gravely and sandy beds

State	River	Type of bed	Bridge
Montana	(Clarks Fork)	Gravel	Clarks Fork Bridge
Montana	(yellow stone)	Gravel	(U.S.98) Emigrant
New york	(Schoharie)	Gravel	(S.R.30) Middleburg
New york	(Susqueha)	Gravel	(C.R.314) Conklim
New york	(Genesee)	Gravel	Portageville on Baily road
Ohio	(Honey)	Gravel	(S.R. 67) Melmore
Ohio	(Little Miami)	Gravel	(S.R.350) Fort Ancient
Ohio	(Ottawa)	Gravel	(Road 122) Lima
Virginia	(North Fork)	Gravel	(S.R.633) North Holstan
Ohio	(Massies)	Gravel	(U.S.36) Urbana
Ohio	(Maumee)	Gravel	(U.S.127) Sherwood
Ohio	(Sugar)	Gravel	(U.S.250) Strasburg
Ohio	(Tascar was)	Gravel	(C.R.14) Port washington
Ohio	(Agulaize)	Gravel	(S.R. 198) Wapakoneta
Virginia	(Bush)	Sand	(U.S.460) Rice
Virginia	(Dan)	Sand	(U.S.501) South Boston
Ohio	(Clear)	Sand	Rockbridge (U.S.33)

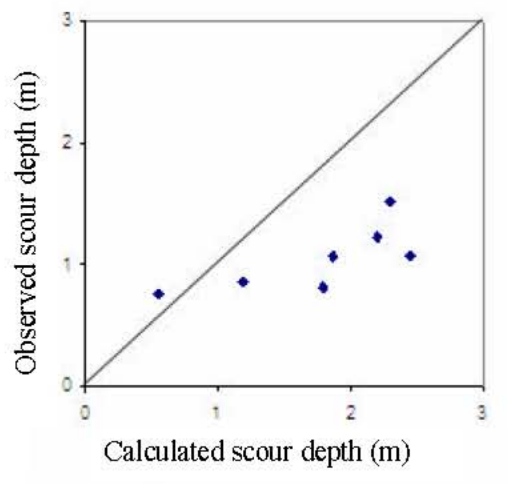

Fig. 1: Comparison between observed and calculated scour depth for sandy beds

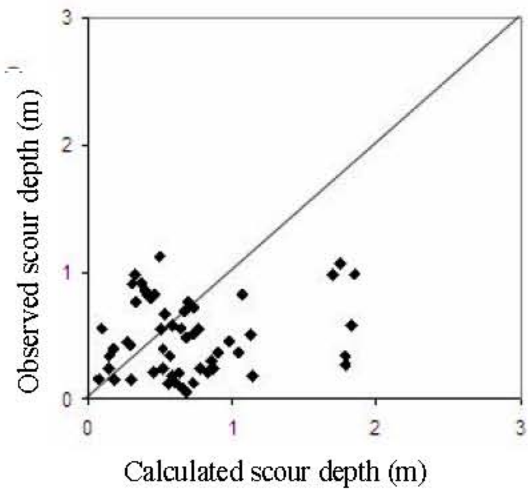

Fig. 2: Comparison between observed and calculated scour depth for gravely beds

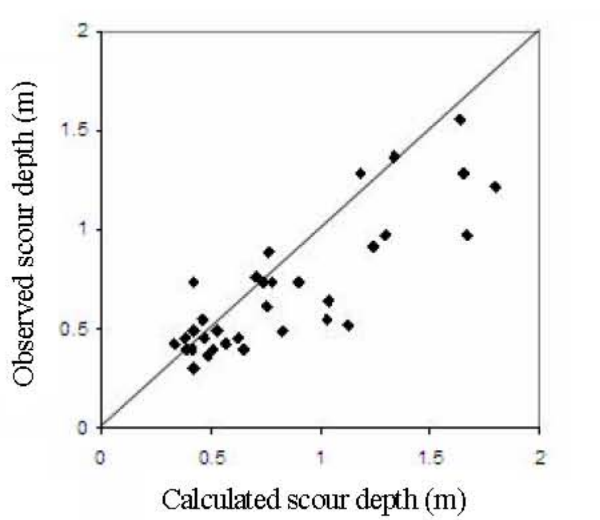

Fig. 3: Comparison between observed and calculated Scour depth by using of data of 9 bridges in various area of USA

Table 4: The name of 9 bridges in various area of USA

River	State	Bridge
(Salt)	Ohio	Lndonderry (U.S.50)
(Scioto)	Ohio	Prospect (S.R.4)
(Tascarwas)	Ohio	Port washington (C.R.14)
(Todd)	Ohio	Marrow (S.R.22)
(Walnut)	Ohio	Ashvill (C.R.17)
(Little notto way)	Virginia	Blackstone (C.R.603)
(Pamunkey)	Virginia	Hamover (S.R.614)
(Reed)	Virginia	Wytheville (S.R.649)
(Tye)	Virginia	Lovimgstone (S.R.56)

Table 5: RMSE error of equations of table 1 and new equation

New equation	Richardson & Davis (1995)	Froehlich (1988)	Aronchelam (1965)	Breusers (1965)	Larras (1963)	Inglis (1949)	Row
0.94	1.64	2.83	1.29	1.62	3.38	3.83	RMSE

Table 6: Calculated scour depth around bridge piers by new equation and equations of table1

	Scour depth (m)							
Row	Inglis (1949)	Larras (1963)	Breusers (1965)	Aronchelam (1965)	Froehlich (1988)	Richardson & Davis (1995)	New equation	Actual
1	1.34	1.34	0.53	0.69	0.47	0.8	0.7	0.34
2	2.25	2.11	1.08	0.98	1.68	2.3	0.85	0.52
3	2.84	2.22	1.16	1.43	1.56	1.64	1.95	2.07
4	3.12	2.31	1.22	1.71	2.77	3.22	1.65	1.04
5	2.21	1.85	0.91	1.09	1.58	2.46	1.07	0.7
6	1.98	1.95	0.98	0.85	1.34	1.52	0.46	0.58
7	1.34	1.22	0.52	0.75	0.61	1.59	0.95	0.95
8	1.34	1.22	0.52	0.76	1.05	3.04	0.59	0.58
9	1.26	1.22	0.52	0.96	0.55	0.83	1.65	1.31
10	0.98	1.35	0.6	0.38	1.06	3.15	0.13	0.11
11	0.78	1.35	0.6	0.28	0.8	2.49	0.15	0.15

Finally, data of 33 piers of9 bridges were selected in USA, scour depth of them was compared with calculated scour depth by new equation.

The names of these bridges are shown in Table 4. These data have been assembled from USGS site.

These data did not apply in derivation of equation5. Comparison between calculated scour depth by equation 5 and observed scour depth is shown in figure3. Spots are near to 45' line and RMSE is 0.27 that shows high accuracy of this equation.

Comparison Between New Equation and Available Equations for Calculation of Scour Depth Around Bridge Piers: In this part, by using of data of 11 piers related to7 bridges in New Hampshire, the results of six equations (Table 1) are compared with results of new equation. These data have been assembled from USGS website. According to these data and equations of table1 and new equation, scour depth for each pier is calculated. RMSE error for each equation was calculated and it was illustrated in Table 5. Scour depth around different piers was calculated by different equations. The results of different equations were illustrated in Table 6. The calculated scour depth by new equation is more exactly than calculated scour depth by other equations and RMSE error of new equation is less than other equations.

CONCLUSION

In recent years, many researchers have presented various equations due to estimation of local scour depth around bridge piers. These equations have derived by using from experimental data. Thus, estimation scour depth by these equations has great difference with actual scour depth. There fore, it is necessary that an equation be presented by using from field data. Equation5 have been presented by using from actual data of 35 bridges of several states in USA.

This equation have derived by using from regression method and correlation coefficient is R= 0.94.

Comparison between results of this equation with other equations illustrated that equation5 has scholastic estimation from local Scour depth around bridge piers.

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