International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

New Imperial Equation for Local Scour around Various Bridge Piers Shapes

Ameer Talib[1], Zaid Hadi Obeid[2], Husam Kareem Hameed[3]

Department of Structural Engineering Maharashtra Institute of Technology (MIT), Pune, India

M. Sc in Water Resources Engineering, Wasit-Iraq

Wasit University, Wasit-Iraq

Abstract: ***The assessment of the maximum scour depth around bridge piers is very important in design the foundations of bridges. Engineers are presently estimating the scour conditions at existing bridges and also thinking to design and build new bridges that should be safe from the problem of scour. In this paper,experimental data for local scour around different shapes of bridge piers are presented. The effects of velocity, Pier Froude Number and pier shape factor on the maximum scour depth are given. By analyzing the data, an empirical equation is formulated to estimate the maximum scour depth around various shapes bridge piers. The formula gave a good coefficient of determination between the observed and predicted scour depths and give a good idea to calculate the maximum depth of scour in cases similar to that covered in the present study. It has been observed that the reduction of the maximum depth of scouring highly dependent on pier shape factor.***

Keywords: pier shape factor, local scour, imperial equation, pier Froude number.

1. Introduction

Scour is the removal of the river bed material by the water erosive action. Local scour can be defined as the lowering of the level of the riverbed around an obstruction as a result of the impact of water flow on the obstruction. Local scour can occur with either clear water flow or live bed flow conditions. Clear water scour occurs when bed material at upstream of the scour hole is at rest. Live-bed scour occurs when there is general sediment transported by the flow.

The principles of experiences and economic analyses with damages caused by floods give always cost-effective to save a bridge foundation that will not collapse. Pier scour is the number one cause of bridge foundation failure in rivers with seasonal flooding **(Arneson et al., 2012)**.

Many studies were conducted led to developing numerous equations to predict the maximum depth of scouring, most of these equations derived from experimental dataand other equations by using limited field data.In this paper, the analyzing of pier local scour done by using a limited laboratory data to get a new formulato compute the maximum scour depth at different shapes ofpiers. Where this study is concerned only the shapes of piers and their effects on the depth of local scour.

Parameter influences local scour

The parameters that influences the magnitude of the local scour depth at bridge piers can be divided into four main groups:

1) Parameters characterizing the fluid: dynamic viscosity (μ), theacceleration due to gravity (g) and density of water (ρ).
2) Parameters characterizing the stream flow: Flow intensity, flow depth (y), mean velocity (V), shear velocity and critical mean flow velocity (V_c)
3) Parameters characterizing the bed materials: sediment density (ρ_s), particle shape, geometric standard deviation of the sediment particle size distribution (σ_g), angle of repose and soil cohesiveness.
4) Parameters characterizing pier foundation; pier size, pier length (a), pier width (b),spacing between piers and angle of attack (θ).

Dimensional Analysis

Engineers should rely on interpretation and judgment based on experimental observations and experiences. Dimensional analysis is a powerful tool in formulating problems. The physical mechanism of the local scour can be understood better if appropriate dimensionless parameters describing the phenomenon are defined. A dimensional analysis is made below for the parameters that affect the local scour mechanism and governed in this paper by using Buckingham π-theorem. The variables that used in this study can be summarized by this relationship:

$$f(y_s, \rho, V, \mathrm{g}, V_c, b, K_s) = 0 \text{ eq. } 1$$

The repeated parameters are selected as ρ, V, and b so the dimensionless π-terms that influence the scour depth around piers can be rested the following form:

$$\frac{y_s}{b} = f_1\left(\frac{V}{V_c}, \mathrm{K_s}, \frac{V}{\sqrt{gb}}\right) \text{eq. } 2$$

Where: the term $\frac{V}{\sqrt{gb}}$ is known as pier Froude number (Fr_p).

2. Experimental Setup

Laboratory Flume

The flume is 12 m in length and 0.5 m in width. It has toughened transparent glass side walls with aheight of 45 cm. The experimental flume is shown in Figure 1. The working section 2.4m length is filled with erodible uniform sand with depth 0.1 m. The inlet and outlet of working section contain raised gravels sloping ends of 1: 14 and 1: 8, respectively, to provide uniform flow in thetest section.The discharge is measured by a V- notch weir of 90o basis of the USBR standard placed at the end of the flume inlet. A vertical gate is installed at downstream of theflume to regulate water depth. All depth measurements were done using two movable carriages with point gauges, which have an accuracy of ± 0.1 mm. The velocity of flow is measured by mini-water velocity meter of accuracy ±2%.

Figure 1: The flume used in present study.

Pier Models

In this study, ten pier shapes were used and compared with each other (Figure 2). These ten shapes are the same as used by **Al-Shukur and Zaid, 2016**. Piers were manufactured from 18 mm MDF sheets. The MDF sheets were cut off by using CNC routing machine. The MDF wood sheets were then glued and laminated together, painted with pigments and coated with varnish to avoid the swelling of MDF by water. The models have a constant width of (4.5cm) with (length/width=4). The experiments are conducted with a constant depth of flow 0.12 m by changing the shape of thepier. **Chiew and Melville, 1987** recommended that the diameter of pier should not be more than 10% of flume width to avoid wall friction effect on local scour. In this study, the width of flume is more than 10 times of pier width, which satisfies the criterion that given by **Chiew and Melville, 1987**.

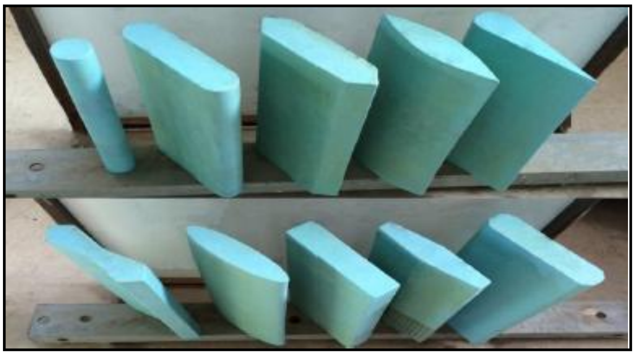

Figure 2: Piers models.

Material of Bed

After made the mechanical sieve analysis test, the results showed that the sand bed material with a median particle size (d_{50}) of 0.71 mm.The geometric standard deviation is 1.14, this value implies that the sand is of uniform size distribution. Figure 3 shows the plot of the grain size distribution of sand. The pier diameter was also carefully chosen so that there was no effect of sediment size on the depth of scour. According to **Melville, 1997**, the bed material grain size does not affect the depth of scour if the ratio of pier width to grain size exceeds 25.

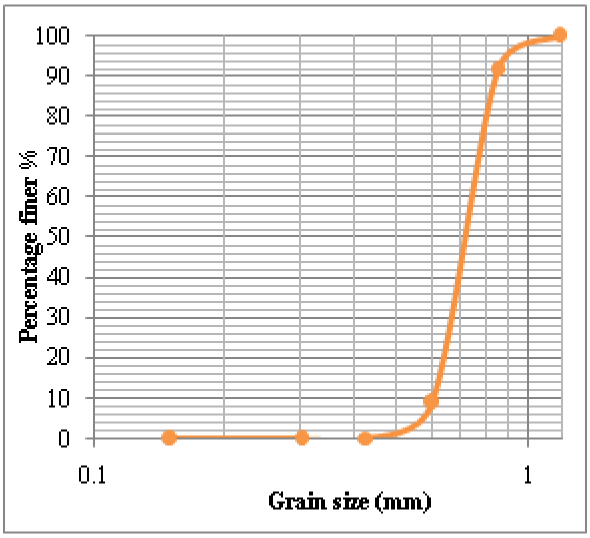

Figure 3: The curve of grain size distribution.

Summary of Test Program

Experiments were performed under subcritical flow and clear-water conditions at three water discharges 10.9 lit/sec, 15.42 lit/sec and 18 lit/sec. The test program was done on ten different shapes, Circular, Rectangular, Chamfered, Octagonal, Sharp, Oblong, Hexagonal, Elliptical, Joukowsky, and streamline. The test conditions for each shape of the ten piers are summarized in Table (1). Also, the summary of all experimental tests are given in Table (2).

Table 1: Test condition for test series (each shape)

No.	Flow Intensity	y (m)	Velocity in Flume (m/sec)	Q (lit/sec)	Fr	Re
1	0.56	0.12	0.18	10.9	0.166	14742
2	0.79	0.12	0.25	15.42	0.230	20817
3	0.92	0.12	0.30	18	0.276	24300

Table 2: Summary of all experimental tests

Run	*Shape*	V/V_c	K_{sh}	Fr_p	y_s	y_s/b
1	Circular	0.92	1	0.451	0.069	1.533
2	Rectangular	0.92	1.10	0.451	0.076	1.689
3	Octagonal	0.92	0.855	0.451	0.059	1.311
4	Joukowsky	0.92	0.884	0.451	0.061	1.356
5	Chamfered	0.92	0.97	0.451	0.067	1.489
6	Oblong	0.92	0.84	0.451	0.058	1.289
7	Elliptical	0.92	0.81	0.451	0.056	1.244
8	Sharp nose	0.92	0.71	0.451	0.049	1.089
9	Hexagonal	0.92	0.59	0.451	0.041	0.911
10	Streamline	0.92	0.43	0.451	0.03	0.667
11	Circular	0.79	1	0.376	0.061	1.356
12	Rectangular	0.79	1.11	0.376	0.068	1.511
13	Octagonal	0.79	0.85	0.376	0.052	1.156
14	Joukowsky	0.79	0.90	0.376	0.055	1.222
15	Chamfered	0.79	0.96	0.376	0.059	1.311
16	Oblong	0.79	0.75	0.376	0.046	1.022
17	Elliptical	0.79	0.80	0.376	0.049	1.089
18	Sharp nose	0.79	0.73	0.376	0.045	1.000
19	Hexagonal	0.79	0.59	0.376	0.036	0.800
20	Streamline	0.79	0.42	0.376	0.026	0.578
21	Circular	0.56	1	0.27	0.039	0.867
22	Rectangular	0.56	1.10	0.27	0.043	0.956
23	Octagonal	0.56	1.077	0.27	0.042	0.933
24	Joukowsky	0.56	1.20	0.27	0.047	1.044
25	Chamfered	0.56	1.05	0.27	0.041	0.911

26	Oblong	0.56	1.05	0.27	0.041	0.911
27	Elliptical	0.56	0.92	0.27	0.036	0.822
28	Sharp nose	0.56	0.77	0.27	0.03	0.685
29	Hexagonal	0.56	0.71	0.27	0.028	0.639
30	Streamline	0.56	0.48	0.27	0.019	0.434

Figure 4: Scour hole geometry around sharp nose pier (Run 8)

Figure 5: Scour hole geometry around chamfered pier (Run 15)

Figure 6: Scour hole geometry around circular pier (Run 21)

Development of a New Formula

The scour depth is a function of some variables, which are discussed previously. The dimensionless functional relationship of eq.2 should be presented as an empirical formula by using a multi-regression analysis. The confidence of suggested relationship evaluated according to the coefficient of determination (R^2). The IBM SPSS Statistics v23 software is used to make analysis for the equation through a non-linear regression analysis. The coefficient of determination can be calculated by equation (3-10) and standard error of estimate (SEE) by eq.3 (IBM, 2015):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_o - y_p)^2}{\sum_{i=1}^{n}(y_o - \bar{y})^2} \text{ eq. 3}$$

Where R^2 is the coefficient of determination, y_o is the observed value, y_p is the predicted value, $\bar{y}$ is the mean value of y_o. The following relationship is suggested to predict the scour depth around bridge piers including shape effects depending on the experimental data:

$$\boldsymbol{y_s}/\boldsymbol{B} = \left\{\left(\frac{\boldsymbol{V_c}}{\boldsymbol{V}}\right)^{c_1} \quad (\mathbf{K_{sh}})^{c_2} \quad (\boldsymbol{Fr_p})^{c_3}\right\} \text{eq. 4}$$

After analyzing the data in SPSS software, it is obtained on the following:

c_1=1.914, c_2= 1, c_3=-0.754 So, the equation becomes:

$$\boldsymbol{y_s}/\boldsymbol{B} = \left\{\left(\frac{\boldsymbol{V_c}}{\boldsymbol{V}}\right)^{\mathbf{1.914}} \quad (\mathbf{K_{sh}}) \quad (\boldsymbol{Fr_p})^{-\mathbf{0.754}}\right\} \text{eq. 5}$$

The coefficient of determination (R^2) is (0.996). The predicted and measured values of scour depths are shown in Figure 7.

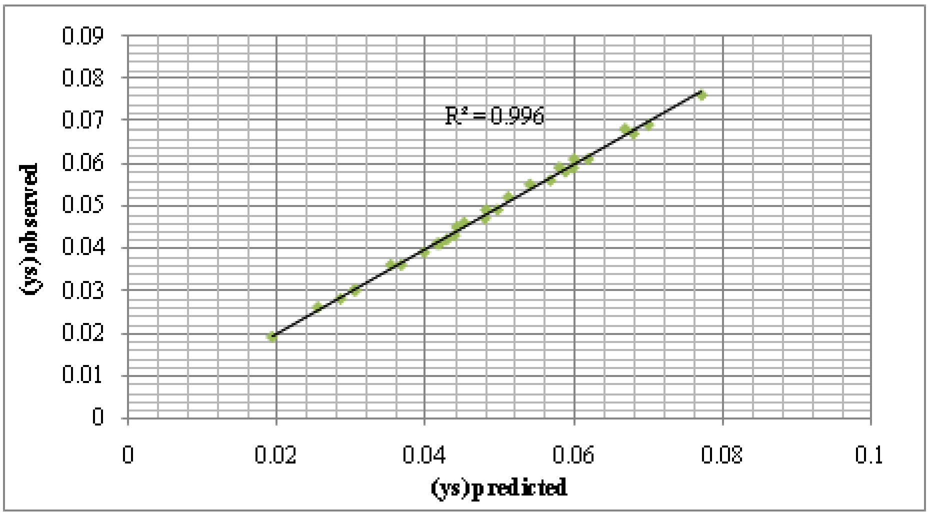

Figure 7: Comparison of eq.5 with Experimental Data.

3. Results Analysis and Discussion

Estimating of the maximum scour depth around bridge piers is very important in design the foundationsof bridges. To examine some phenomenon that affects the scour depth, sets of experiments are conducted using ten pier models with three different flow velocities.

As seen in dimensional analysis, the maximum scour depth (y_s/b) ratios is a function of the Pier Froude Number**Fr_p**=$V/(gb)^{0.5}$, where it is increasingasthe flow velocity increases. In this study, the gravity acceleration, g is constant. So, the **Fr_p**varies with only the approach velocity of the flow. From Figure8, it is clear that the maximum depth of scourincreases with the increased approach flow velocity. This plot shows a good agreement with that developed by **Shen et. al (1969)** for thisstudy.

Pier Froude Number

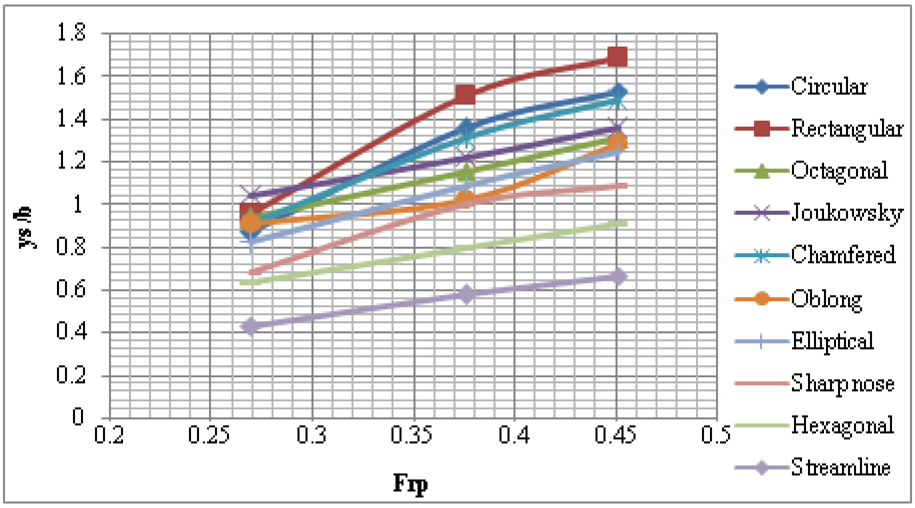

Figure 8: y_s/b ratio as a function of Fr_p

Flow Velocity
In general, the flow velocity has a direct impact on depth of scour regardless ofthe value of theflow depth. The results showed that there is a linear increasing in the depth of scour as the velocity is observed for velocities below the threshold value. This finding is agreed with some previous investigations in literature.

Shape Factor
Shape factors for uniform piers, that is piers having constant section throughout their depth (**Melville and Coleman, 2000**), have been proposed by several investigators, including **Tison, 1940, Laursen and Toch, 1956, Chabert and Engeldinger, 1956, Garde, 1961, Larras, 1963, Venkatadri et al., 1965, Dietz , 1972, Neill, 1973 and Richardson and Davis, 1995**. Shape factor is defined as the ratio of scour depth recorded for a particular shape to the scour depth for a circular pier shape. Values of shape factor in Table 3 calculated by eq.6 (**Melville and Coleman, 2000**),for L/b=4. Where L is the length of pier.

$$K_{sh} = \frac{y_{se\,(non-circular)}}{y_{se\,(circular)}} \quad \text{eq. 6}$$

Where:$y_{se\,(\mathbf{non-circular})}$ is equilibrium scour depth for non-circular piers and $y_{se\,(\mathbf{circular})}$ is the equilibrium scour depth for circular pier.

Table 3.11: Measured value of shape factor.

No.	*Geometry*	*L/b*	K_{sh}
1	Circular	1	1.000
2	Rectangular	4	1.106
3	Octagonal	4	0.928
4	Joukowsky	4	0.997
5	Chamfered	4	0.997
6	Oblong	4	0.882
7	Elliptical	4	0.846
8	Sharp nose	4	0.739
9	Hexagonal	4	0.634
10	Streamline	4	0.449

The values in the Table 3approximately close to the values of available articles as shown in literature (e.g. **Tison, 1940, Laursen and Toch, 1956, Chabert and Engeldinger, 1956, Garde, 1961, Larras, 1963, Venkatadri et al., 1965, Dietz, 1972, Neill, 1973 and Richardson, Davis, 1995** and **Maatooq, 1999**), in present study the calculated shape factor for Oblong pier is 0.88, it is approximately same as that found by **Maatooq, 1999** of 0.87 value. It is also found that the shape factor for octagonal and hexagonal piers shapes, they are not widely studied in theliterature.

4. Conclusions

In this study, the local scour problem around the bridge pier has been studied experimentally. Conclusions can be summarized by the restrictions imposed in this study to:

1) The maximum depth of scour increases with the increasing the down-flow (as the velocity increasing) and vice versa is right.
2) Initially,it is noted that there is ahigher increase in scour depth for all shapes then a decreases with time progress until reaching equilibrium.
3) The maximum depth of scour was observed at the upstream nose of bridge piers.
4) Shape factor with L/b ratio is equal to 4, was defined as 1, 1.106, 0.928, 0.997, 0.997, 0.882, 0.846, 0.739, 0.634 and 0.449 for circular, rectangular, octagonal, joukowsky, chamfered, oblong, elliptical, sharp edge, hexagonal and streamline piers, respectively.
5) The developed formula was derived by using the dimensional analysis techniques and restricted to the experimental data. The scour depth in this formula was represented as a function of Pier Froude number,shape factor, flow intensity. The formula gave a good coefficient of determination between the observed and predictedscour depths and give a good idea to calculate the maximum depth of scour in cases similar to that covered in the current study.

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