Assessment on Applicability of Scour Depth Prediction around Pier Using Formulas

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Abstract Scours occur when the flow fields around the pier are disturbed due to the installation of structures in any area of river flow, like bridges. River flow causes bed materials like sand and gravel to move, which causes scour formation; such phenomenon is reported as the main cause of bridge failure. Various range of factors like velocity, water depth, discharge, river slope, river width, and bed materials altogether contribute to scour's complexity, thus making it difficult to accurately measure its predictability. In practice, an empirical formula is used to predict scour depth around the pier area. In this study, seventeen represented formulas are utilized to calculate the scour depth. The results are then compared to the results of the hydraulic model test from a previous study to assess the applicability of each respective formula. Results show how that the formulas of Coleman(1971), Froehlich(1987), Breusers(1965) CSU(1993) relatively possess the highest applicability.

Keywords: pier, scour, empirical formula, bridge, river

1. Introduction

Over the past half century, South Korea has exhibited a rapid economic growth. With the increase of economic scale and population, the expansion of transportation facilities like roads and rails caused an upsurge in the construction of bridges. As two thirds of South Korea's territory is mountainous, bridges are commonly constructed across rivers. Bridge constructions disturb the river flow within its periphery, which then causes scour formation.

Scour is the phenomenon where bed materials move due to disturbed river flow. The increased progression of scour can lead to further structural damages. According to the US Department of Transportation, scour is the main cause of bridge failure. The complexity of scour phenomenon can be explained by the reciprocal action of bed materials with topographical factors like velocity, water depth, hydraulic factor of discharge, river slope, and river width. Therefore, it is difficult to exactly predict for scour depth with the current technologies. From an engineering perspective, an empirical formula suggested by researchers from previous studies is used to predict and design scour depth. Though the majority of researchers suggest the following empirical formula, in reality the scour phenomenon is difficult to accurately predict. According to South Korea's River Design Standard(KWRA, 2009), four represented formules were proposed which provides the most suitable results based on the field situations.

For this study, seventeen formulas were selected for the purpose of evaluating each formula's applicability in calculating scour depth around the pier vicinity. In order to individually assess the applicability of each formula, the scour depth measurements from a hydraulic model test and that from the calculation results of the respective formulas are compared. Once the results from the study are produced, the data needed to accurately calculate scour depth can be obtained.

2. Calculation formula of pier-scour depth and measured data from hydraulic model test

2.1 Pier-scour depth formula

The following seventeen formulas are used to calculate for pier-scour depth (Park *et al.*, 2017; Yun, 2008; Min, 2017).

1) Inglis-Poona (1949)

From 1938 to 1939, Inglis (1949) investigated the scour that occurred at a single pier located in Poona, India and suggested the following formula.

$$\frac{d_s}{b} = 1.70\left(\frac{q^{2/3}}{b}\right)^{0.78} \quad (2.1)$$

Here, d_s is scour depth (m), b is the pier width, and q is the discharge per unit width (m^2/s).

2) Inglis-Lacey (1949)

Based on Inglis-Poona, Inglis suggests the following formula that is dimensionally homogenous.

$$d_s = 0.946\left(\frac{Q}{f}\right)^{1/3} - y \quad (2.2)$$

Here, ds is scour depth (m), y is the flow depth directly located upstream from the pier (m), Q is rate of dischrage (m^3/s), and f is the silt factor proposed by Inglis.

3) Laursen (1956)

Laursen and Toch (1956) proposes the following formula which considers the various influences of velocity, pier's shape, and the flow's angle of attack.

$$d_s = 1.5Kb^{0.7}y^{0.3} \quad (2.3)$$

Here, d_s is scour depth (m), b is pier width (m), y is the flow depth directly located upstream from the pier (m), and K is the proportional constant.

4) Chitalen (1962)

Using a 1:65 scale model test, Citalen (1962) proposes a formula that considers the effects of approach depth and the diameter of the bed materials.

$$\frac{d_s}{y} = 6.65F_r - 0.51 - 5.49F_r^2 \quad (2.4)$$

Here, d_s is scour depth (m), y is the flow depth directly located upstream from the pier (m), and Fr is the Froude number.

5) Ahmad (1962)

Based on research of the sand bed in Pakistan, Ahmad (1962) proposes the following formula.

$$\frac{d_s}{b} = \frac{y}{b}(4.77F_r^{2/3} - 1) \quad (2.5)$$

Here, d_s is scour depth (m), b is the pier width (m), y is the flow depth directly located upstream from the pier (m), and Fr is the Froude number.

6) Breusers (1965)

Based on the hydraulic model test situated near a borehole, Breusers (1965) proposes a formula that calculates maximum scour depth by 1.4 times the diameter.

$$d_s = 1.4b \quad (2.6)$$

Here, d_s is the scour depth (m) and b is the pier width (m).

7) Hancu (1965)

Basing the study at a cylindrical bridge pier, Hanch proposes the following formula.

$$\frac{d_s}{b} = 3.3\left(\frac{d_{50}}{b}\right)^{0.2}\left(\frac{y}{b}\right)^{0.3} \quad (2.7)$$

Here, d_s is the scour depth (m), b is the pier width (m), d_{50} is the median size of the bed material (mm), and y is the flow depth (m) directly located upstream from the pier.

8) Shen I (1966)

Shen proposes the following formula that considers the effects of Reynolds number within the pier area.

$$d_s = 0.00023\,(\mathrm{Re})^{0.619} \quad (2.8)$$

Here, d_s is the scour depth (m) and R is Reynolds number.

9) Blench (1969)

Blench (1969) modifies Inglis (1949) and proposes the following formula.

$$\frac{d_s + y}{y_r} = 1.8\left(\frac{b}{y_r}\right)^{0.25} \quad (2.9)$$

Here, d_s is the scour depth (m), b is the pier width (m), y_r is the depth for zero bed sediment transport (m), and y is the flow depth directly located upstream from the pier (m).

10) Shen-Karaki II (1969)

Shen et. al uses the Froude number to analyze the test data from the hydraulic model test and proposes the following formula.

$$\frac{d_s}{b} = 11F_r^2 \quad (2.10)$$

Here, d_s is the scour depth (m) and Fr is the Froude number.

11) Shen-Karaki III (1969)

Shen *et al*. modifies the Shen-Karaki II equation and proposes the following formula.

$$\frac{d_s}{b} = 3.4F_r^{0.67} \quad (2.11)$$

Here, d_s is the scour depth (m) and Fr is the Froude number.

12) Coleman (1971)

Using the hydraulic model test, Coleman's formula considers the Froude number, pier width, and flow depth directly located upstream fro the pier.

$$\frac{d_s}{y} = 1.39 F_r^{0.2} \left(\frac{b}{y} \right)^{0.9} \quad (2.12)$$

Here, d_s is the scour depth (m), b is pier width (m), y is the flow depth directly located upstream from the pier (m), and Fr is the Froude number.

13) Neill (1973)

Neill states that out of the different factors, pier width and water depth influences scour the most and proposes the following formula.

$$\frac{d_s}{b} = 1.5 \left(\frac{y}{b} \right)^{0.3} \quad (2.13)$$

Here, d_s is scour depth (m), b is pier width (m), and y is flow depth directly located upstream from the pier (m).

14) USGS (1975)

USGS proposes the following scour depth when mean particle size is over 8 mm.

$$d_s = 1.2 b^{0.8} \quad (2.14)$$

Here, d_s is scour depth (m) and b is pier width (m).

15) Basik-Basamily-Ergun (1975)

Based on analysis of data from the hydraulic model test, Basik proposes that pier width provides the greatest influence on scour.

$$d_s = 0.558 b^{0.586} \quad (2.15)$$

Here, d_s is scour depth (m) and b is pier width (m).

16) Froehlich (1987)

Froehilich considers the limits of equilibrium velocity and proposes the following formula.

$$\frac{d_s}{b} = 0.32 k_1 \left(\frac{b'}{b} \right)^{0.62} \left(\frac{y}{b} \right)^{0.46} F_r^{0.2} \left(\frac{b}{d_{50}} \right)^{0.08} + 1 \quad (2.16)$$

Here, ds is scour depth (m), b is pier width (m), b' is width of the bridge pier projected normally to the approach flow (m), d_{50} is the particle size for which 50 percent of the bed material is finer (mm), y is water depth (m), k_1 is the correction factor for pier, and Fr is the Froude number.

17) CSU

Colorado State University overall brings the data together and proposes the following formula.

$$\frac{d_s}{y} = 2.0 k_1 k_2 k_3 k_4 \left(\frac{b}{y} \right)^{0.65} F_r^{0.43} \quad (2.17)$$

Here, d_s is scour depth (m), b is pier width (m), y is the flow depth directly located upstream from the pier (m), k_1 is the correction factor for pier, k_2 is the correction factor for flow's angle of attack at the pier, k_3 is the correction factor for bed condition, k_4 is the corretion factor for coarse bed material, and Fr is the Froude number.

2.2 *Data from hydraulic model test*

In this study, the applicability of the scour depth calculation formula is assessed using the hydraulic model test data from previous studies as shown in Table 1. Please refer to the corresponding papers for the exact data.

Table 1. Measured scour depth around pier from previous studies.

Source	Number of Data
Johnson (1992)	130
Dey *et al*. (1995)	18
Melville and Chiew (199)	84
Mia and Nago (2003)	23
Sheppard *et al*. (2004)	14
Sheppard and Miller (2006)	24
Lai *et al*. (2009)	58
	351

3. Result and Discussion

To assess the applicability of the scour depth calculation formula, two performance metrics are used and given in Equation (3.1) and (3.2) (Sheppard *et al*., 2011). For Equation (3.1), the smaller the error value between test results and calculation results, the more the results will agree with each other. Equation (3.2) shows Equation (3.1) divided and normalized to the pier width.

$$SSE\ (\%) = \frac{\sum (d_s^{measured} - d_s^{calculated})^2}{\sum (d_s^{measured})^2} \quad (3.1)$$

$$SSEn\ (\%) = \frac{\sum \left(\frac{d_s^{measured}}{b} - \frac{d_s^{calculated}}{b} \right)^2}{\sum \left(\frac{d_s^{measured}}{b} \right)^2} \quad (3.2)$$

Table 2 shows the calculation results of Equation (3.1) and Equation (3.2).

Table 2. SSE and SSEn results from all formulas.

Formula	SSE (%)	Rank	SSEn (%)	Rank
Inglis-Poona	162.33	12	659.95	14
Inglis-Lacey	208.77	15	424.60	12
Laursen	28.18	9	34.23	6
Chitale	97.73	11	425.55	13
Ahmad	248.22	13	1074.55	15
Breusers	15.99	4	12.33	3
Hancu	1055.93	16	2678.11	16
Shen Ⅰ	19.10	6	54.72	10
Blench	1731.08	17	10994.9	17
Shen-Karaki Ⅱ	273.88	14	409.95	11
Shen-Karaki Ⅲ	31.30	10	36.90	7
Coleman	6.50	1	9.83	2
Neill	28.17	8	34.23	5
UGSG	18.23	5	37.64	9
Basik-Basamily-Ergun	20.01	7	23.66	4
Froehlich	8.58	2	9.64	1
CSU	11.44	3	37.75	8

Based on the results shown in Table 2, the deviation between the maximum and minimum values of both SSE(%) and SSEn(%) exhibit a great difference, 1724.6% and 10985.3%. As such, a big difference is also seen among the scour depth calculation formulas.

Within the test, the following formulas exhibit the greatest difference of scour depth measurements: Blench (1969), Hancu (1965), and Ahmad (1962). Compared to the other formulas, these show the greatest difference between the SSE(%) and SSEn(%). The formulas that exhibit the least difference are Coleman (1971), Froehlich (1987), CSU (1993), Breusers (1965), and UGSG (1975). The difference between the SSE(%) and SSEn(%) for these formulas were approximately 10%.

4. Conclusion

In this study, the applicability of empirical approaches for pier scour depth is reviewed using 17 formulas. Data of the hydraulic model test from previous studies and the calculated results are compared and the following conclusions have been made.

1. The measurements of scour depth are compared using both the hydraulic model test and the calculation results. The error metrics (SSE(%) and SSEn(%)) values produced show a minimum value of approximately 2% and a maximum of 200 times, showing that there are great differences between each formula.

2. The formulas that show the most differences in scour depth measurements are Blench (1969), Hancu (1965), Ahmad (1962) as they show the greatest difference between the SSE(%) and SSEn(%) value compared to the others. Also, the following formulas, Coleman (1971), Froehlich (1987), CSU (1993), and Breusers (1965), show a small difference between the SSE(%) and SSEn(%) values to approximately 10% and are considered more suitable compared to the other formulas. However, because data from the hydraulic model test were utilized rather than that from the field, there are limits in laying down a clear conclusion in terms of the formulas' applicability. Though it may be difficult with the current technologies, there is a need to develop numerical scour depth prediction formulas that can be commonly applied regardless of climate state or river characteristics.

References

Dey S., Bose S.K., and Sastry G.I.N. (1995), "Clearwater scour at circular piers-A model, *Journal of Hydraulic Engineering*, ASCE, **121**, 869-876.

Johnson P. (1992), Reliability-based pier scour engineering, *Journal of Hydraulic Engineering*, ASCE, **118**, 1344-1354.

Korea Water Resource Association (KWRA). (2009), River design standard , KWRA., Seoul.

Lai J., Chang W., and Yen C. (2009), Maximum local scour depth at bridge piers under unsteady flow, *Journal of Hydraulic Engineering*, ASCE, **135**, 609-614.

Melville B. and Chiew Y. (1999), Time scale for local scour at bridge piers, *Journal of Hydraulic Engineering*, ASCE, **125**, 59-65.

Mia M. and Nago H. (2003), Design method of time dependent local scour at circular bridge pier, *Journal of Hydraulic Engineering*, ASCE, **129**, 420-427.

Min B. (2017), Assessment of applicability for prediction formulas of scour depth around pier, Master's thesis, Chungbuk National University, Korea.

Park C., Park, H. and Cho, Y. (2017). Evaluation of the applicability of pier local scour formulae using laboratory and field data, *Marine Georesources and Geotechnology*, **35**, 1-7.

Sheppard D.M. Odeh M. and Glasser T. (2004), Large scale clear-water local pier scour experiment, *Journal of Hydraulics Engineering*, ASCE, **130**, 957-963.

Sheppard D. M. and Miller W. (2006), Live-bed local scour pier experiment, *Journal of Hydraulic Engineering*, ASCE, **132**, 635-642.

Sheppard D.M., Demir H. and Melville B. (2011), Scour at wide piers and long skewed piers, NCHRP Report 682, Transportation Research Board, Washington, D.C.

Yun B. (2008), Bridge scour assessment and countermeasure guide, Korea Institute of Construction and Transportation Technology Evaluation and Planning, Seoul.