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Predicting Scour Depth around Non-uniformly Spaced Pile groups

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Abstract: *Pile scour may cause instability to the structures they support. Ensuring a safe and economically sound design is essential for the wider community. Although much laboratory research has been carried out on scour at pile groups, there are still significant gaps in prediction formulae. This study has been conducted to develop a formula for scour at pile arrangements of non-uniform spacing. The study was based on a laboratory experiment found in the literature. Previous empirical formulae for uniformly spaced pile groups were first used to gauge an idea of their performance. The formula that predicted the scour depth more accurately was then modified. The approach of Ghaemi et al. (2013) outperformed the other trialled empirical formulas. Using this formula, a correction factor was suggested to increase the prediction accuracy. The gap to diameter ratio was also corrected to include the non-uniformity of spacing in two directions.*

Keywords: *Empirical Formulae, Current, Scour, Bridges, Piers, Complex Piers.*

1. INTRODUCTION

When designing any bridge structure, an accurate prediction of the pile scour depth is necessary for engineers to ensure structural integrity and a safe design. Due to the complexity of the interaction between the current, seabed and pile group; prediction of the scour depth is a difficult task, and the available empirical formulas have limited accuracy (e.g. Ghaemi et al. 2013).Current-induced pile scour has received a range of attention in past literature including (Breusers et al. 1977; Hannah 1978; Breusers and Raudkivi 1991, Melville 1997; Salim and Jones 1998; Melville and Chiew 1999; Melville and Coleman 2000; Richardson and Davis 2001; Ataie-Ashtiani and Beheshti 2006; Amini et al. 2011; Ghaemi et al. 2013). At present, there is still a limited amount of research into current induced scour around non-uniformly spaced pile groups.

The objectives of this study are: (a) to evaluate the performance of existing formulae for predicting current-induced scour depth around non-uniformly spaced pile groups and (b) to develop a new formula for prediction of scour depth on the above-mentioned configuration. To achieve this, existing formulae are briefly reviewed first and then applied to the data sets collected from the literature. After qualitatively comparing the performances using accuracy metrics, the best formula will be modified using regression analysis to accommodate for the different gap spacing's in different directions.

1.1. Background

Salim and Jones (1998) investigated the scour around various pile arrangements. The study included current-induced scour around pile groups due to a steady flow. They concluded that an increase in the spacing between individual piles resulted in a decrease in scour. An empirical formula was presented by Richardson and Davis, (2001) in the US Federal Highway Administration (FHWA), reported in HEC 18. This formula was used to predict the scour depth around a singular pile. It may be noted that all empirical formulas within the study are presented in a dimensional form to assist with analysis purposes.

$$S/D= 2.0\, K_1K_2K_3K_4\, (h/D)^{0.35} Fr^{\,0.43} \qquad (1)$$

where K_1 is the correction factor for pier nose shape, K_2 is the correction factor for angle of attack, K_3 is the coefficient based on the channel bed condition, K_4 is the correction factor for armoring by bed material size, *h* is the water depth, *S* is the scour depth, *D* is the pile diameter, *Fr* is the pile Froude number ($U/(gD)^{1/2}$) and *U* is the mean current velocity. As recommended by HEC-18, the effective width of an equivalent full depth pile group (*D**) should be used in the above mentioned formula to predict the scour depth around pile groups. *D** is the product of the projected width of the piles onto a plane normal to the flow multiplied by a spacing factor and a number of aligned rows factor:

$$D^* = D_{proj} K_G K_m \qquad (2)$$

where D_{proj} is the sum of non-overlapping projected widths of piles, K_G is the coefficient for pile spacing and K_m is the coefficient for the number of aligned rows (Richardson and Davis, 2001). An example of D_{proj} for a 4 by 4 arrangement is shown in Figure 1.

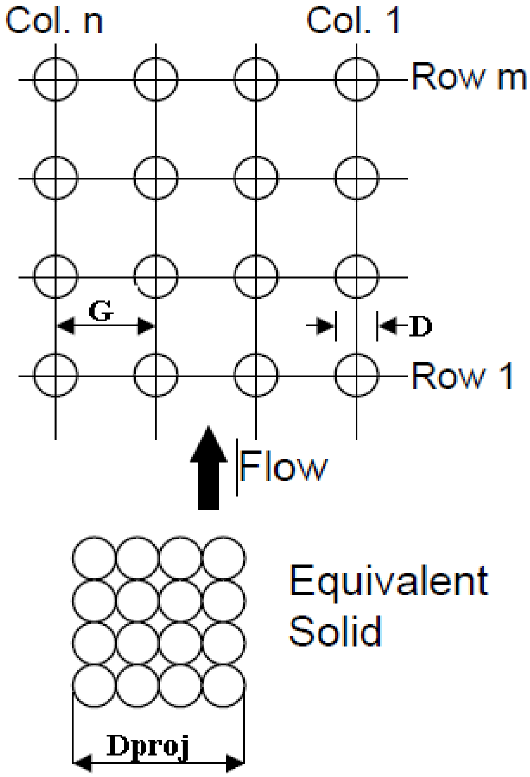

Figure 1 Example of D_{proj} at a (4 x 4) uniformly spaced pile group (Richardson and Davis, 2001)

Scour around pile groups was also investigated by Sumer et al. (2005). Their study involved square pile groupings of 2 x 2, 3 x 3 and 5 x 5 arrangements. The study concluded that the scour depth increased with an increased number of piles in a group. The scour depth increases due to the pile arrangement acting as a single, solid pier. Although the researchers performed a study on the different pile distributions, no empirical formula was suggested.

A study carried out by Ataie-Ashtiani and Beheshti (2006) investigated clear-water local scour at a range of uniformly spaced pile groups. A variety of different pile group arrangements, spacing's, flow rates and sediment grain sizes were considered. A correction factor K_{Gmn} was proposed to include the effects of the numbers of piles parallel and perpendicular to the flow direction, in the already devised Richardson and Davis, (2001) empirical formula. The formula is shown below:

$$S/D = 2.0\, K_1 K_2 K_3 K_4\, (h/D)^{0.35} Fr^{0.43} K_{Gmn} \qquad (3)$$

where *m* and *n* are number of piles parallel and perpendicular to the flow respectively, *G* is the pile spacing and $K_{Gmn} = 1.11 m^{0.0396} n^{-0.5225} (G/D)^{-0.1153}$.

Amini et al. (2011) conducted an experimental study on clear-water local scour at pile groups under steady flow. They investigated a wide range of pile arrangements, spacing's and submergence ratios. It should be noted that this was the first study on pile arrangements of uniform and non-uniform spacing. Figure 2 shows a representation of a pile arrangement and flow properties where *h* is the pile height, *y* is the approach depth, G_n is the centre to centre spacing of piles in line with the flow and *Gm* is the centre to centre spacing of piles parallel to the flow.

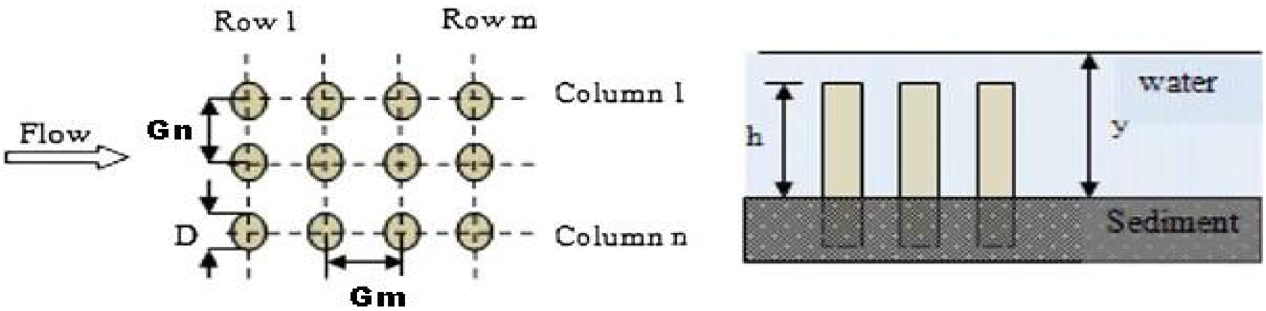

Figure 2 Definition sketch for 3 x 4 pile group (Amini et al. 2011)

They devised a correction factor to be applied to the scour depth of a single pile for estimation of the pile group scour depth.

Recently, data mining approaches have been used in different fields of Civil Engineering (e.g. Zanganeh et al. 2009, Etemad-Shahidi and Bonakdar 2009, Kazeminezhad et al. 2010). Ghaemi et al. (2013) used the model tree to develop a robust and clear formula for the prediction of the pile scour depth around various pile arrangements. They used previous experiments (Hannah 1978; Coleman 2005; Amini et al. 2011) to compare the performances of different approaches. Their suggested formulae are:

$$S/D = 2.06\,(G/D)^{-0.09}\,(h/D)^{0.32}\,Fr^{0.35}\,n^{0.37} \quad \text{for } G/D < 0.8 \tag{4a}$$
$$S/D = 3.06\,(G/D)^{-0.06}\,(h/D)^{0.26}\,Fr^{0.37}\,n^{0.07} \quad \text{for } 0.8 < G/D < 3.1 \tag{4b}$$
$$S/D = 1.86\,(h/D)^{0.45}\,Fr^{0.41} \quad \text{for } G/D > 3.1 \tag{4c}$$

2. RESULTS AND DISCUSSION

The laboratory-based experiments conducted by Amini et al. (2011) were used to test existing approaches' performances. In their study, non-uniformly spaced pile arrangements of (2 x 2) and (3 x 5) were investigated. Each pile arrangement was tested for an eight hour duration. The experiments were conducted in a rectangular flume that was 46m long, 1.52m wide and 1.9m deep. The flume utilised a 15 m long recess to conduct the experiment. Sediment was placed along the 15 m recess with uniform thickness of 0.55 m. An adjustable tail-gate was used as a control mechanism for water level within the flume. Flow depth (*h*) was maintained constant at 0.24 m. The bed material was made of cohesion-less uniform sediments with a median particle size of 0.8 mm. Critical shear velocity (U_C) was used as a parameter for sediment entrainment based on the equation expressed in Melville and Coleman (2000). Pile diameter (*D*) was kept constant throughout the investigation at 0.06 m.

To perform the first phase of the investigation, the accuracy of each individual formula was examined both qualitatively and quantitatively. The following accuracy measurements were used as an indication of formula performance.

$$CC = \frac{\sum \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum \left(x_i - \bar{x}\right)^2 \sum \left(y_i - \bar{y}\right)^2}} \tag{5}$$

$$RMSE = \sqrt{\frac{1}{N} \sum \left(x_i - y_i\right)^2} \tag{6}$$

$$SI = \frac{\sqrt{\frac{1}{N} \sum (x_i - y_i)^2}}{\bar{x}} \times 100 \quad (7)$$

$$DR = \frac{1}{N} \sum \frac{y_i}{x_i} \quad (8)$$

where x_i and y_i denote the measured and the predicted values, respectively. *N* is the number of measurements and over-bar indicates the mean value of the parameter. The root mean square error (*RMSE*) is a measure of the difference between predicted and measured values. The scatter index (*SI*) is the dimensionless form of the *RMSE* indicating the error in percentage. The Correlation Coefficient (*CC*) determines the linear relationship between measured and predicted values. Values range between -1 and +1. The discrepancy ratio (*DR*) indicates whether a set of predictions is overestimating or underestimating observations. A *DR* greater than one indicates overestimation and a perfect *DR* value is unity (no bias in the predictions). *DR* of unity does not imply a perfect agreement. The use of the *SI* provides another representation of the true scattering of results.

Non-uniformly spaced pile groups have different spacing perpendicular to the flow and parallel to the flow. To ensure this could be included in each formula, two average spacing, i.e., $G_1=(G_n+G_m)/2$ and $G_2= (G_n^2+ G_m^2)^{1/2}$ were tested to further investigate the accuracy of existing formulae. Table 1 shows the accuracy metrics of different formulae using different average spacing.

Table 1 Accuracy metrics of scour predicting formulae.

Formula	**Accuracy Metrics**			
	RMSE	*SI (%)*	*CC*	*Dr*
Richardson and Davis (2001) using G_1	1.046	256	0.824	4.19
Richardson and Davis (2001) using G_2	1.051	258	0.819	4.10
Ataie-Ashanti and Beheshti (2006) using G_1	0.590	145	0.798	2.74
Ataie-Ashanti and Beheshti (2006) using G_2	0.604	144	0.791	2.70
Ghaemi et al. (2013) using G_1	1.125	44	0.735	1.38
Ghaemi et al. (2013) using G_2	1.216	43	0.827	1.50
Ghaemi et al. (2013) using G_2, corrected	0.114	4.5	0.612	1.09

As seen, Richardson and Davis formula using G_1 performed poor when evaluating all accuracy metrics. The average error was more than 200% and on average it over predicts the scour depth by four times. These accuracy metrics are high, indicating the used formula is very conservative and do not mimic the observed measurements. Using G_2 in the Richardson and Davis formula (Second row) were almost identical to those of using G_1.

The predictions using Ataie-Ashtiani and Beheshti (using G_1) approach were an improvement on the Richardson and Davis G_1 formula but still inaccurate. The scatter index (145%) was high). This formula overestimated the measurements by more than twice the measured values. Similar results were obtained when using the G_2 spacing components in the Ataie-Ashtiani and Beheshti (2006) formula.

The Ghaemi et al. (2013) formula was the last investigated approach. It should be mentioned that all of the measured data points had a $0.8 < G/D < 3.1$. Therefore, only equation 3b was used in this case. Figure 3 indicates that this formula performed better than the previous formulae but still over predicts the scour depth by more than 50%. The *RMSE* was once again high, indicating the predicted values do not accurately match the measured ones. The scatter index was reasonable (43%) and the *DR* indicates the measurements are over predicted by 1.5 times on average. The CC value also indicates a linear relationship for this model. Analysis of accuracy metrics showed that using the G_2 spacing yield a slightly more accurate prediction rather than using G_1.

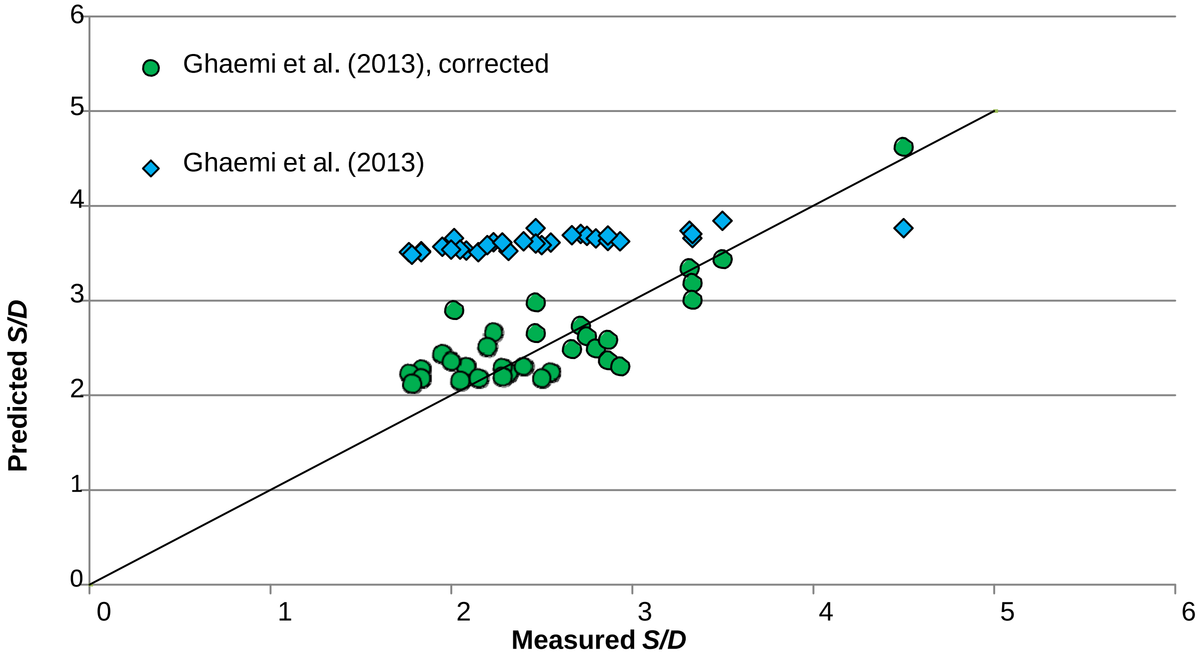

Figure 3 Comparison of the measured and predicted scour depths utilising the correction factor for Ghaemi et al. (2013) formula

To further improve the predictive proficiency of the Ghaemi et al. (2013) formula, various correction factors were trialled. The best correction factor was found to be a function of G2/D. Therefore, the corrected formula was developed as

$$S/D=K_G\ 3.06\ (G_2/D)^{-0.06}\ (h/D)^{0.26}\ Fr^{\ 0.37} n^{\ 0.07} \qquad (9)$$

where K_G= 0.89$G_2^{\ -0.35}$. This formula can be simplified as

$$S/D=2.74\ (D^2/(G^2_{m+}G^2_{n}))^{0.21}(h/D)^{0.26}\ Fr^{\ 0.37} n^{\ 0.07} \qquad (10)$$

The accuracy metrics (table 1) shows that introducing this correction factor has reduced the *SI* significantly, and the bias of the model is less than 10%. It should be noted the developed formula may not be valid outside the range of the used dataset.

3. SUMMARY AND CONCLUSION

The investigation has concluded that a correction factor can be introduced into an existing empirical formula, to accurately predict scour depth around non-uniformly spaced pile groups. The Ghaemi et al. (2013) approach was superior to other empirical formulae when applied to non-uniformly spaced pile groups. To incorporate the effects of non-uniformity of pile spacing in two directions, a correction factor was introduced. This yielded a quite simple and accurate formula that can be used easily by engineers to predict scour depth around non-uniformly spaced pile groups.

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