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Scour Depth Estimation Methods around Pile Groups

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Abstract

Pile groups have become more popular in structural designs due to economical and geotechnical reasons. It is also known that scour as the main cause of bridge failure can make serious damages and considerably threaten the safety of our environment. Thus, predicting scour depth is an essential step in designing bridges. This paper is a comprehensive review of local scour depth estimation methods around pile groups. Few studies investigated the effect of various parameters on the scour depth and some of them derived empirical equation for estimating the scour depth. Therefore, this review is divided into two different parts. In the first part, the experimental studies and results in the literature are reviewed. In the second part, those works that introduced methods for estimating scour depth are described. The methods of the second part are categorized into two sections: (1) empirical equations; (2) neural network procedures. The first section is the summary of those works that introduced empirical equations for estimating scour depth and the second section is the summary of recently introduced neural network procedures.
Keywords: *scour depth, pile group, review, experimental studies, empirical equations, neural networks*

1. Introduction

The main cause of the bridge failure is the scour phenomenon. From 1996 to 2005, at least 1502 bridge failures were documented in the United State, of which 58% were the result of the hydraulic conditions (Hunt, 2009). Richardson and Davis (2001) mentioned that flooding from storm Alberto in Georgia caused damages to over 500 bridges and the damage attributed to scour costed $130 million. Therefore, one of the essential factors in designing bridges is accurate prediction of scour depth.

Unlike single pier, experimental data and studies done on the pile groups were few in the past. Therefore, there are only few equations available for estimating the scour depth around pile groups. Some works that derived empirical equations recommended using their equation with caution (Elliott and Baker, 1985; Richardson and Davis, 2001). This shows the little confidence that one could have in using those equations. Recently, new experimental data made available by new experimental studies (Ataie-Ashtiani and Beheshti, 2006; Amini *et al.*, 2012). These available data and possible future data could help in improving available equations. The current paper reviews those few experimental studies done on pile groups that are scattered in the literature along a half century period of time. This could facilitate the literature review for those who want to improve available equations or design new ones.

Deng and Cai (2010) review the previous works done on prediction, modeling, monitoring, and countermeasures for the bridge scour at a single pier. Ettema *et al.* (2004) is a review of the studies related to the scour conditions and scour-estimation difficulties for bridge abutments. However, these papers does not review any study related to scour around pile groups. Since there is no review paper on such an important subject, there is a necessity of such a review.

The present up-to-date and comprehensive review paper is organized in several sections. In the coming section, a short overview on the scour phenomenon is given. This section summarizes different types of fluid flows that cause scour around single pier and pile groups. Section three overviews several experimental studies that help in understanding the effect of different factors on the scour depth around pile groups. Afterwards, available empirical equations for estimating the scour depth around pile groups are described. Some recent works used neural network procedure for estimating the scour depth. These works are summarized in the last section.

2. Short Overview on Scour Phenomenon

2.1 Types of Scour

There are three types of scour: local scour, general scour and degradation. As the result of obstruction in the flow crossing area, flow velocity increases and it may cause local scour to happen. Acceleration in the flow causes creation of vortices and

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subsequently it removes bed material around a pier. General scour happens by contraction of the flow and diminishes the stream bed level across hole or part of the channel width. General scour takes place when a flood passes through the contracted flow crossing area. Degradation means a decrease in the stream bed level due to the deficit in sediment supply from upstream. Degradation process occurs during a long period of time but can move huge amounts of sediment.

Local scour may occur in two types: clear-water and live-bed scour. In the clear-water, bed shear stress is less than the critical or threshold shear stress for the initiation of particle movement. Therefore, in the clear-water scour generally there is no movement of bed materials. When the threshold shear stress for the initiation of particle movement has been reached, transportation of bed material from the upstream occurs. Subsequently, transported sediment from upstream refill the local scour hole and the sour depth is reduced. This type of scour is called live-bed scour.

2.2 Mechanism of Local Scour at Pile Groups

Local scour mechanism around a single pier identified by different forms of fluid flows. The main scour-causing flows are classified as downflow, horseshoe vortex and wake vortex. Fig. 1 illustrates different kinds of flows and vortices around a pier. For better understanding of how vortices form, the position of each vortex and its direction in the profile view, plan view and 3*D* view are shown in this figure.

Downflow happens when water collides with the upstream surface of the pier. Downflow moves bed material around piles like vertical jet. Horseshoe vortex is caused by the abstraction and flow acceleration at the front of the pile, which is the result of the vertical gradient in stagnation pressure at the edge of the pile. By increasing the depth of scour, the strength of this vortex is reduced. Wake vortices are formed just downstream of the pile where the flow separation happens. Wake vortices have a vertical flow direction at its center similar to tornado. This vertical flow helps in lifting bed materials out of the scour hole. The strength of wake vortex decreases rapidly by increasing the distance.

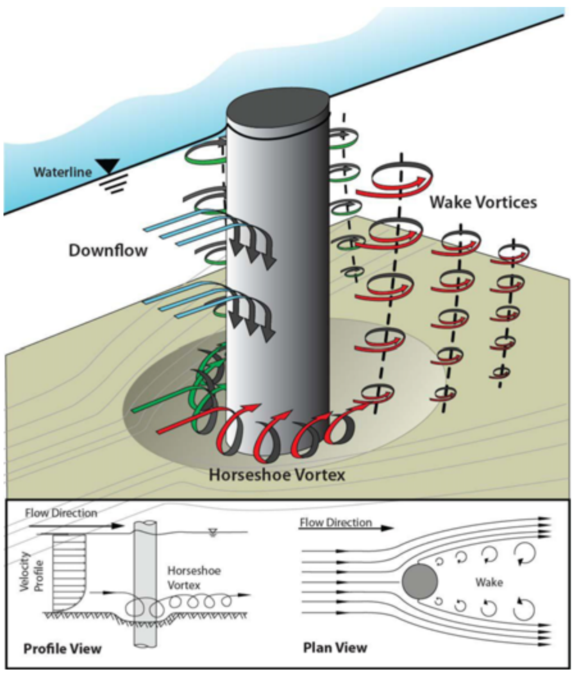

Fig. 1. Schematic Drawing of the Hydraulic Processes Causing Local Scour at a Cylindrical Pier. Position of Downflow, Horseshoe Vortex and Wake Vortex and Also Their Directions in the Profile, Plan and 3D Views are Shown (Sheppard and Renna, 2010)

In addition to the single pier mechanisms four other mechanisms cause scour at pile groups. These mechanisms are reinforcing, sheltering, shed vortices and compressed horse-shoe vortex (Hannah, 1978).

In the reinforcing mechanism, the movement of bed materials in the vicinity of the upstream pier increases by virtue of overlapping the scour hole around upstream and downstream piers. Overlapping scour holes reduce exit slop and the level of bed in the scour hole around upstream pier. Thus, required energy to move the bed materials is decreased. The strength of reinforcing depends on the distance between the upstream and downstream piers and the flow skew angle. The intensity of reinforcing decreases by increasing the distance between piers and changing the flow skew angle from 0º to 90º. Fig. 2 illustrates the effect of reinforcing in reduction of the exit slop and the height of the scour hole for piers in-line with the flow. In this figure, the exit slop for single pier has been shown by dotted line and solid line depicts the exit slope in the presence of a downstream pier.

Sheltering may happen in two forms, the first form may occur when the flow collide upstream piers and subsequently its velocity decreases. Therefore, the power of the flow velocity reduces for the downstream pier. The second form may happen when the scoured materials from the upstream pier deposit in front of the downstream pier. This causes a reduction in the power of the

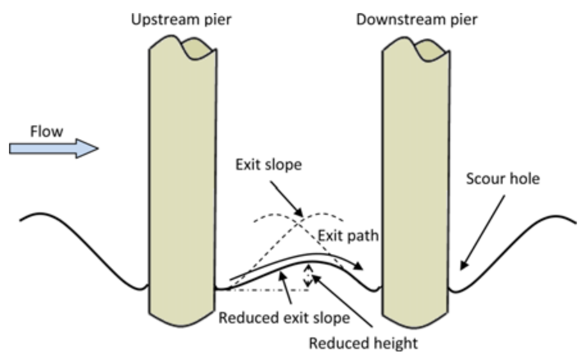

Fig. 2. Schematic Drawing Showing the Reinforcing Effect. The Exit Slop and the Height of the Scour Hole are Reduced in the Upstream Pier by Placing the Downstream Pier Near to the Upstream Pier. By Increasing the Distance Between Piers and Changing the Flow Skew Angle from 0º to 90º, the Strength of Reinforcing Decreases (Redrawn from Nazariha (1996))

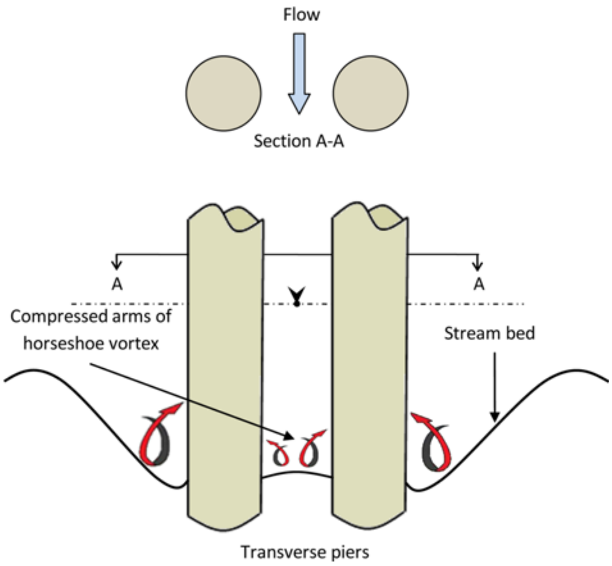

Fig. 3. Compressed Arms of Horse-shoe Vortex. By Increasing the Distance Between Piers, the Power of Compressed Horse-shoe Vortex and the Depth of Scour Hole Decrease (Redrawn from Nazariha (1996))

horse-shoe vortex by pushing the flow upward in front of the downstream pier. Reduction of velocity and strength of the horse-shoe vortex around downstream pier leads to a decrease in the depth of scour hole. Similar to reinforcing, the occurrence of sheltering and its effect on the level of the scour depth depend on the distance between the upstream and downstream piers.

Shed vortices happen when a downstream pier is placed in the path of the vortices that shed from the upstream pier. These vortices assist lifting the bed materials from the downstream pier. The strength of this lifting depends on the shed vortex convection speed and the distance between the path of shed vortex and the affected pier. The volume of removed bed materials by shed vortices depends on the strength of velocity and pressure distribution. In the tandem arrangement, the downstream pier is not on the path traced by the shed vortices. Thus the power of the shed vortices in moving material are less than staggered arrangements.

By decreasing the distance between two piers, horse-shoe vortex is compressed and thereby the flow velocity will increase. Increased flow velocity prompts a growth in moving more bed materials around piers and therefore it increases the depth of scour hole. In Fig. 3 the compressed arms of horse-shoe vortex and the flow direction are shown.

3. Experimental Studies

This section is a collection of different well known older works and some recent works that gives the reader a conceptual understanding of scour phenomenon and different factors that can affect the scour depth. Some of the reliable old works and all recent works, that have introduced procedures for estimating scour depth around pile groups, will be explain in Section 4.

3.1 Dietz

Dietz (1973) studied the effect of pile spacing (S) and flow skew angle (α) on the scour depth for pile groups containing two piles. He observed that scour depth around the downstream pile is less than the upstream pile. Furthermore, he reported that the scour hole around the upstream pile is independent of the pile spacing. It is noticeable that by increasing the pile spacing to 25 diameters, the scour depth around the downstream pile is still less than the upstream pile. When the pile spacing is greater than 4 diameters ($S/D > 4$), the scour holes around piles are independent from each other and the flow skew angle. In twin piles condition, the scour depth increases with the flow skew angle. For $\alpha < 30^o$ and $0.5 < S/D < 1$, the scour depth is larger than that of twin piles. For $\alpha > 30^o$, the scour is shallower. For $\alpha < 15^o$ and $2 < S/D < 4$, the scour depth shows less sensitivity to the non-aligned flow.

3.2 Hannah

Hannah (1978) conducted a series of experiments for groups of 1×2, 1×3, 2×2 and 2×3 cylindrical piles. In a pile arrangement that is shown by $n \times m$, n is the number of piles normal to the flow and m is the number of piles in-line with the flow. The experiments were done in clear-water condition with grains mean diameter equal to 0.75 ($d_{50} = 0.75$) and geometric standard deviation of particles equal to 1.32 ($\sigma_g = 1.32$). To determine the effect of flow skew angle on the scour depth, Hannah (1978) examined different flow skew angles from 0^o to 90^o only for the case of the groups of two piles with pile spacing equal to 5 diameter ($S/D = 5$). The author concluded that for $\alpha < 15^o$ sheltering affects the downstream pile, therefore the scour near upstream pile is greater than the downstream pile. When the flow skew angle increases, the effect of sheltering decreases and the power of shed vortices and compressed horse-shoe vortex increases. Therefore, the scour depth around the downstream pile increases and reaches its maximum at $\alpha = 45^o$. This maximum scour depth is greater than the scour depth around the upstream pile.

Hannah (1978) also investigated the effect of the number of piles normal to the flow and the number of piles in-line with the flow. It was observed that by increasing the number of piles normal to the flow, the scour depth increases. The effect of this mechanism decreases when piles spacing increases. The author also observed that the number of piles in-line with the flow has a minor effect on the scour depth.

3.3 Nouh

Nouh (1986) investigated local scour at pile groups by placing a group of 4 piles consisting of 2 lines in parallel at different locations in the meandering section of the channel. He observed that the turbulence intensity outside the pile group was greater than that inside the group. Furthermore, the maximum scour depths at upstream piles were larger than the downstream piles. He also observed that the maximum scour depth at the outer piles were larger than the inner piles. The author also observed that by increasing transversal pile spacing, the scour depth decreases.

3.4 Nazariha

Nazariha (1996) performed several experiments in a 7.7 m long,0.5 m wide and 0.6 m deep aluminium flume. The flume had 3 m long and 0.2 m deep sand-bed test section with d_{50} = 0.49 and σ_g = 1.4. The experiments conducted for groups of 1 × 2, 1 × 3, 2 × 2 and 2 × 3 cylindrical piles with 1.27 m diameter in the clear-water condition with the steady state flow.

Nazariha (1996) observed that in the case of pile groups with 2 and 3 piles and if $S/D \leq 5$ and $\alpha = 0^{\circ}$, dominant factors are pile spacing, sheltering and reinforcing. With increasing the flow skew angle (α), the sheltering and reinforcing effect diminish and compressed horse-shoe vortex effect increases. For $S/D > 5$ and $\alpha = 0^{\circ}$, the group effect diminishes. In the case of 3 piles in the group and when $S/D = 2$ and 4, the maximum scour depth for front pile occurred at $\alpha = 40^{\circ}$ and 30º and for rear pile, it occurred at $\alpha = 30^{\circ}$ and 20º. Also, the sheltering and reinforcing effects diminished with increasing the S/D value. In the case of 4 and 6 piles in the group and when $S/D \leq 4$ and for all values of flow skew angle, the dominant factor is compressed horse-shoe vortex.

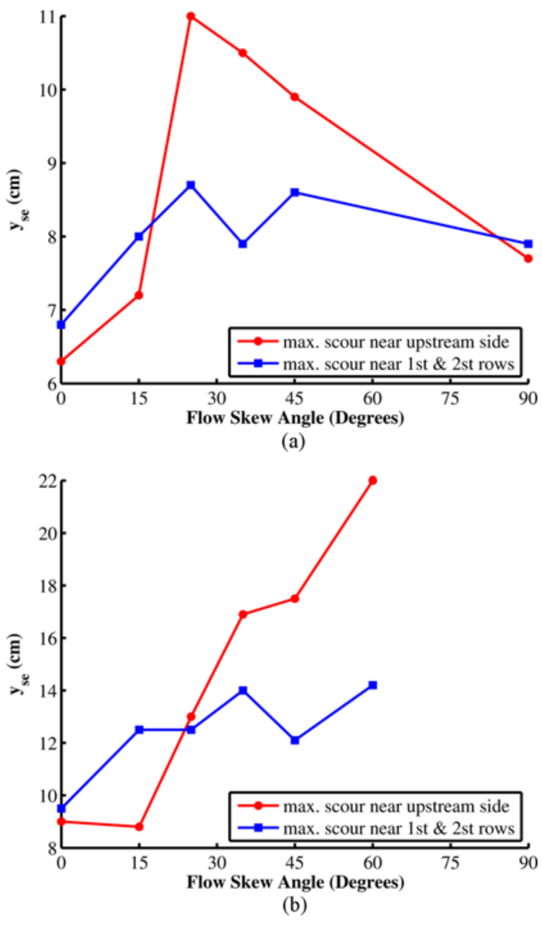

Fig. 4. Maximum Scour Depths at the Front and Upstream Sides of the Pile Group: (a) Circular Piles and (b) Square Piles (Redrawn Zhao and Sheppard (1998))

With decreasing the pile spacing between two rows the compressed horse-shoe vortex increases, therefore the scour depth increases for all values of α. With increasing the flow skew angle, the projected area increases that results in a deeper scour hole.

3.5 Zhao and Sheppard

Zhao and Sheppard (1998) conducted several experiments in a flume with 30.5 m long, 2.44 m width and 0.76 m deep. T he experiments were done for the flow skew angle raging from 0º to 90º and two types of pile groups (circular and square piles) with 3.18 m pile diameter, 9.53 m pile spacing (3D) and 3 × 8 piles arrangement.

Zhao and Sheppard (1998) observed that when the flow skew angle is less than 20º, the maximum scour depth happens near the front of the pile group. When the flow skew angle is greater than 20º, the maximum scour depth occurs at the upstream edge of the pile group. The greatest scour depth for circular piles occurs at α = 25º and for square piles occurs at α = 60º. At zero skew angle the scour depth for square piles was greater than circular piles. In Fig. 4 maximum scour depths at the front and upstream sides of the pile group for both square and circular piles are demonstrated.

Zhao and Sheppard (1998) observed that the Laursen's k_α curve is a good fit to their data for square piles. However, this curve overestimated the scour depth at circular piles for the skew angle greater than 25º. In Fig. 5, k_α is plotted for different flow skew angles and different ratios of l/w, where l is the length of the pile and w is its width.

3.6 Sumer *et al.*

Seven different configurations of pile groups experimented by Sumer *et al.* (2005) in a flume with 23 m long, 0.2 m wide and 0.5 m deep. The sandbed section was 4 m long and 0.10 m deep. The sediments size (d_{50}) was 0.2 mm. Circular plastic pipes with smooth-surface and 3.2 cm pile diameter were used in the experiments.

Sumer *et al.* (2005) divided pile groups scours into two different types: global and local scour. Based on experimental

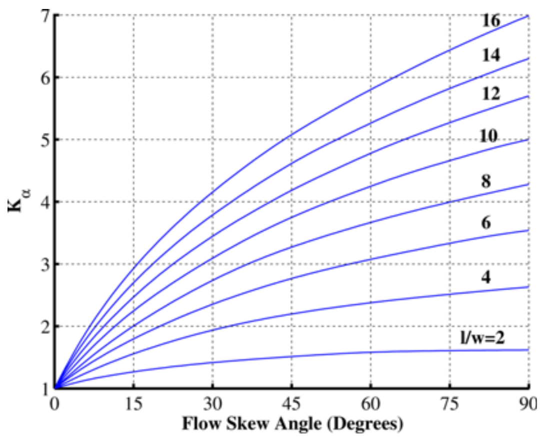

Fig. 5. Flow Skew Angle Correction Factor k_α (Redrawn from Laursen and Toch (1956))

observations, the authors concluded that when a group of piles is exposed to the flow, two kinds of scour patterns emerge. The first pattern is the scour in the vicinity of individual piles, which is local scour. The second pattern is the scour around the pile groups in the form of a saucer-shape depression, which is global scour. They found that the global scour depth increases with the number of piles up to five. Further increase in pile number dose not effect the scour depth.

Furthermore, Sumer *et al.* (2005) described that the local scour is influenced by the horseshoe vortex, the vortex shedding, the contraction of streamline and the downflow. On the other hand, the global scour is affected by the change in the flow velocity in the gaps between the piles and the turbulence generated by the individual piles.

3.7 Ataie-Ashtiani and Beheshti

Ataie-Ashtiani and Beheshti (2006) tested eight arrangements of pile groups with 16, 22 and 28 mm pile diameters. The experiments carried out in a flume with 4 m long, 0.41 m wide and 0.25 m deep. Working section was 4 m long and in the form of a 0.08 m depth recess below the bed of the flume. Two different sediments with $d_{50} = 0.25$, $\sigma_g = 1.54$ and $d_{50} = 0.98$, $\sigma_g = 1.13$ were used. Pile groups were installed at 2.5 m downstream of the flume inlet.

They observed that for pile spacing less than 1.15 diameters, the pile group behaves as a single body. The interference reduces when the pile spacing is between 3-5 diameters, depending on the pile group arrangement. For side-by-side arrangement and pile spacing equal to 1.25, the maximum scour depth increases by a factor of 1.5 while for tandem arrangement and pile spacing equal to 3, this factor is about 1.2. For 2 × 4 arrangement and pile spacing equal to 1.25, this growth factor is about 2. The maximum and minimum scour depths were observed at 3 × 2 and 1 × 2 arrangements, respectively. This shows that the effect of compressed horseshoe vortices on scour depth is grater than the reinforcing mechanism. The authors observed that for a given pile spacing, the most important factor in determining the scour depth is the number of piles normal to the flow.

3.8 Amini *et al.*

Amini *et al.* (2012) investigated the scour depth for ten different pile group arrangements in a rectangular flume with 46 m long, 1.52 m wide and 1.9 m deep. Cohesionless uniform sediment with $d_{50} = 0.8$ and $\sigma_g = 1.34$ used as the bed material. The flow depth for all of the experiments was 0.24 m. Two different pile diameters (60 mm and 42 mm) were used. Uniform ($S_n = S_m$) and nonuniform ($S_n \neq S_m$) pile spacing were tested, where S_n and S_m are pile spacings normal to the flow and in-line with the flow, respectively. Amini *et al.* (2012) also investigated the effect of submergence ratio ($S_r = h/y$, where h *is the height of piles from the undisturbed bed and y is the flow* depth) on the scour depth. For submerged pile groups, submergence ratios were approximately 0.25, 0.50, and 0.75 with the pile spacing varied from $S = D$ to $S = 6.4D$.

Amini *et al.* (2012) observed that for nonuniform pile groups, the scour depth reduces with increasing the pile spacing normal to the flow. In the range of $1 < S_n/D < 3$, the scour depth for nonuniform pile groups reduces faster than uniform pile groups. For nonuniform pile groups and when $1 < S_m/D < 3.5$, the scour depth increases by increasing the pile spacing in-line with the flow. Further increase in the pile spacing ($S_m/D > 3.5$), leads to a decrease in the scour depth due to wake vortices shed from the front piles interfering with flow at the rear of the piles.

Amini *et al.* (2012) observed that for pile groups with attached piles ($S/D = 1$), the pile group acts like a single pier with large horse-shoe vortex. When $S/D > 1$, the small horse-shoe vortices around individual piles can be distinguished. If $S/D < 3.5$, the scour depth decreases with increasing the pile spacing. In this case, the maximum scour depth occurred in front of the first row for all pile group arrangements. If $S/D > 3.5$, the interference of the scour mechanisms around different piles decreases and this resulted in a further slight decrease of the scour depth. When $S/D > 5$, no significant decrease in the scour depth was observed. The functional relationship between the scour depth and the pile spacing for both submerged and unsubmerged pile groups is similar. With decreasing the submergence ratio, the scour depth reduces due to a reduction in the blockage.

4. Empirical Equations

To estimate the maximum scour depth around a single pier for both live-bed and clear-water conditions, numerous studies have been done and vast variety of equations have been introduced by different researchers (Inglis, 1949; Laursen and Toch, 1956; Larras, 1963; Shen *et al.*, 1969; Breusers *et al.*, 1977; Jain and Fischer, 1979; Melville and Sutherland, 1988; Froehlich, 1989; Melville and Chiew, 1999; Sheppard *et al.*, 2004; Heza *et al.*, 2007).

Regarding scour prediction at piled foundations, typically the scour depth is estimated using existing equations for simple piers, assuming an equivalent solid pile group or a single cylindrical pier with an effective diameter (Salim and Jones, 1996; Sheppard *et al.*, 2004). Therefore, equations for estimating single piers are also presented together with their correction procedures. Most of equations and procedures for predicting scour depth around pile groups are based on corrections to HEC-18 equation (Richardson and Davis, 2001). Therefore, we explain this method as a separate subsection.

4.1 HEC-18 for a Single Pier

The most used and reliable equation for predicting scour depth around a single pier is recommended by Federal Highway Administration. This recommended equation is called HEC-18 in the literature derived from the name of the circular wherein this equation was appeared (Richardson and Davis, 2001). HEC-18 equation is given by:

$$\frac{y_{se}}{y} = 2.0K_1K_2K_3K_4\left(\frac{D}{y}\right)^{0.65}Fr^{0.43} \tag{1}$$

where y_{se} is the scour depth, y is the flow depth, K_1 is the shape factor, K_2 is the flow skew angle factor, K_3 is the dune factor, K_4 is the correction factor for armoring by bed material size, D is the pile diameter and Fr is the Froude number that is given by:

$$Fr = \frac{v}{\sqrt{gy}} \tag{2}$$

where v is the mean velocity of flow,g is the gravity and y is the flow depth. The correction factors K_1, K_2 and K_3 can be obtain from tables 1, 2 and 3, respectively. It is noticeable that the correction factor in Table 1 is used for flow skew angles up to 5 degrees. For greater flow skew angles, K_1 is 1.0. In addition to Table 2, the correction factor for the flow skew angle (K_2) can be calculated by the following equation:

$$K_2 = \left(\cos\alpha + \frac{1}{D}\sin\alpha\right)^{0.65} \tag{3}$$

where α is the flow skew angle and l is the length of pile. If l/D is greater than 12, l/D is set to be 12 for calculating the correction factor in Table 2 or Eq. (3).

Correction factor for armoring by bed material size (K_4) is equal to 1 ($K_4 = 1$) if $d_{50} < 2$ mm or $d_{95} < 20$ mm. If $d_{50} \geq 2$ mm and $d_{95} \geq 20$ mm, K_4 is calculated by the following equation:

$$K_4 = 0.4\left(\frac{V_1 - V_{icD_{50}}}{V_{cD_{50}} - V_{icD_{95}}}\right)^{0.15} \tag{4}$$

where V_1 is the flow velocity in the upstream of the pile and V_{icD_x} is the threshold velocity for initiating scour at the pile for the grain size D_x, which is estimate by:

$$V_{icD_x} = 0.645\left(\frac{D_x}{D}\right)^{0.053} V_{cD_x} \tag{5}$$

where V_{cD_x} is the critical velocity that starts the movement of the materials with the grain size D_x. It is given by:

$$V_{cD_x} = K_u y_1^{\frac{1}{6}} D_x^{\frac{1}{3}} \tag{6}$$

where y_1 is the flow depth in the upstream of the pile, K_u is the constant and D_x is the grain size for which x percent of the bed materials is finer. K_u is equal to 6.19 in SI Units and is equal to 11.17 in English Units. If K_u is smaller than 0.4, its value is set to 0.4.

In the case of scour at a single pier, Sheppard *et al.* (2013) used 441 laboratory and 791 field data to evaluate predictive equations. They showed that no method gives accurate estimations of scour depth at a single pier indicating needs for more researches in this field.

Table 1. Correction Factor K_1 for Pier Nose Shape (Richardson and Davis, 2001)

Shape of pier nose	K_1
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Group of cylinders	1.0
Sharp nose	0.9

Table 2. Correction Factor K_2 for Flow Skew Angle (Richardson and Davis, 2001)

Angle	$l/D = 4$	$l/D = 8$	$l/D = 12$
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	1.5	3.9	5.0

Table 3. Correction Factor K_3 for Bed Condition (Richardson and Davis, 2001)

Bed condition	dune height (m)	K_a
Clear-water scour	N/A	1.1
Plane bed & antidune flow	N/A	1.1
Small dunes	0.6 ≤ H ≤ 3	1.1
Medium dunes	3 ≤ H ≤ 9	1.1-1.2
Large dunes	H ≥ 9	1.3

4.2 Elliott and Baker

Based on an experimental study, Elliott and Baker (1985) suggested a pile spacing correction factor for the design equation introduced by Breusers *et al.* (1977). The design equation for predicting scour depth at the single pile is given by:

$$\frac{y_{se}}{D} = f_1\left(\frac{v}{v_c}\right)\cdot\left[2.0\tanh\left(\frac{y}{D}\right)\right]\cdot f_2(Shape)\cdot f_3\left(\alpha, \frac{l}{D}\right) \tag{7}$$

where D is the pile diameter, v is the flow mean velocity, v_c is the critical flow velocity, α is the flow skew angle and l is the pile length. The value of $f_1(v/v_c)$ is calculated by:

$$f_1\left(\frac{v}{v_c}\right) = \begin{cases} 0 & \frac{v}{v_c} \leq 0.5 \\ \left(2\frac{v}{v_c} - 1\right) & 0.5 \leq \frac{v}{v_c} \leq 1.0 \\ 1 & \frac{v}{v_c} > 1.0 \end{cases} \tag{8}$$

The value of $f_2(Shape)$ for circular and rounded piles is equal to 1.0, for stream-lined shapes is equal to 0.75 and for rectangular piles is equal to 1.3. The value of $f_3(\alpha, l/D)$ can be estimated from Fig. 5.

The aforementioned multiplicative correction factor for estimating scour depth around pile groups is define by:

$$K_s = \begin{cases} 1 + \frac{1.79}{\left[\left(\frac{S}{D}\right) - 1\right]^{0.695}} & \frac{S}{D} < 4 \\ 4.34 - 0.62\left(\frac{S}{D}\right) & 4 < \frac{S}{D} < 7 \\ 1 & \frac{S}{D} > 7 \end{cases} \tag{9}$$

where K_s is the correction factor for pile spacing and S is the spacing between piles. This equation was derived for (S/D) ranging from 1.6 to 13.2, rectangular blocks with semi-circular noses and uniformly graded sand with 0.5 mm diameter. For other conditions, this equation should be used with caution.

4.3 Gao *et al.*

Gao *et al.* (1993) introduced a different spacing correction factor for an equation for estimating scour depth that has been used in designing bridges in China. This correction factor in its rearranged form is as follows (Salim and Jones, 1996):

$$K_s = 1+5\left[\frac{1}{1+\left(\frac{S}{D}\right)}\right]^2 \tag{10}$$

It is worth mentioning that the scour depth around pile group estimated using this equations is 2.25 times bigger than the scour depth at single pile when the relative spacing (S/D) is set to unity. Chinese equation for predicting the maximum scour depth in the clear-water condition is given by (Gao *et al.*, 1993):

$$y_{se} = 0.46K_{sh}D^{0.60}y^{0.15}d^{-0.07}\left(\frac{v-v_c'}{v_c-v_c'}\right) \tag{11}$$

where K_{sh} is the shape factor, d is the size of particles, v is the mean velocity, v_c is the critical velocity and v_c' is the initial velocity of the local scour of pile. This equation has been written in "Code of Investigation and Design of Highway Bridge Crossing" published by Ministry of Communications, People's Republic of China, 1991.

4.4 Salim and Jone

A method to modify Eq. (1) for predicting scour around pile groups has been given by Salim and Jones (1996). For estimating scour depth around pile group using Eq. (1), They recommended to replace the pile group by a single pile with dimensions equal to all of the piles touching one another and then multiply the answer by one of the following correction factors:

$$K_s = 0.57\left(1-e^{\left(1-\frac{S}{D}\right)}+e^{0.5\left(1-\frac{S}{D}\right)}\right) \tag{12}$$

$$K_s = 0.47\left(1-e^{\left(1-\frac{S}{D}\right)}+e^{0.5\left(1-\frac{S}{D}\right)}\right) \tag{13}$$

Equation (12) is the envelop curve of the data and Eq. (13) is the best fit curve. The envelop curve gives more conservative estimate of the scour depth. Whereas, the best fit curve gives smaller predicion error. These correction factors only consider the influence of the pile spacing and pile diameter on the scour depth around pile groups. It is obvious that when the number of piles normal to the flow is 3 or more, this procedure gives conservative results (Ataie-Ashtiani and Beheshti, 2006). We observed that even envelop curve highly underestimate the data and a correction factor of at least 2 is needed to avoid underfitting.

They also modified the Chinese correction factor (see Eq. (10)) by adding a new variable to the equation. The modified correction factor is:

$$K_s = 1+0.85\left[\frac{(m-1)}{\left(1+\left(\frac{S}{D}\right)\right)^2}\right] \tag{14}$$

where m is the number of piles in-line with the flow. If the number of piles in-line with the flow is set to be one, estimated scour depth around pile groups will be equal to the scour depth at a single pile. However, in reality for pile groups with small distance between piles, the scour depth can be 1.5 times greater than the scour depth at a single pier.

4.5 Melville and Coleman

Melville and Coleman (2000) presented an equation for calculating scour depth at single pile (New Zealand equation). This equation is defined by:

$$y_{se} = K_{yD}K_IK_dK_sK_\alpha K_t\,, \tag{15}$$

where K_{yD} is the flow depth-pile size factor, K_I is the flow intensity factor, K_d is the sediment size factor, K_s is the foundation shape factor, K_α is the foundation alignment factor and K_t is the time factor. The foundation shape factor (K_s) can be obtain form Table 1. The flow depth-pile size factor (K_{yD}) is calculated by:

$$K_{yD} = \begin{cases} 2.4D & \frac{D}{y}<0.7 \\ 2\sqrt{yD} & 0.7<\frac{D}{y}<5 \\ 4.5y & \frac{D}{y}>5 \end{cases} \tag{16}$$

The flow intensity factor (K_I) is given by:

$$K_I = \begin{cases} \frac{v-(v_a-v_c)}{v_c} & \frac{v-(v_a-v_c)}{v_c}<1 \\ 1 & \frac{v-(v_a-v_c)}{v_c}\geq 1 \end{cases} \tag{17}$$

where v_a for non-uniform sediment is equal to v ($v_a = v$), and for uniform sediment is equal to v_c ($v_a = v_c$).

The sediment size factor (K_d) for $D/d_{50}>25$ is equal to 1 and for $D/d_{50}\leq 25$ is calculated by:

$$K_d = 0.57\log\left(2.24\frac{D}{d_{50}}\right) \tag{18}$$

The foundation alignment factor (K_α) for circular pile is equal to 1 and for non-circular pile is given by:

$$K_\alpha = \left(\frac{l}{D}\sin\alpha+\cos\alpha\right)^{0.65} \tag{19}$$

where l is the length of the pile. The time factor (K_t) for $v/v_c > 1$ is equal to 1 and for $v/v_c \leq 1$ is given by:

$$K_t = \exp\left(-0.03\left|\frac{v_c}{v}\ln\left(\frac{t}{t_e}\right)\right|^{1.6}\right) \quad (20)$$

where t_e is the development time for the equilibrium scour that is defined by:

$$t_e = \begin{cases} 48.26\frac{D}{v}\left(\frac{v}{v_c}-0.4\right) & \frac{y}{D}>6,\ \frac{v}{v_c}>0.4 \\ 30.89\frac{D}{v}\left(\frac{v}{v_c}-0.4\right)\left(\frac{y}{D}\right)^{0.25} & \frac{y}{D}\leq 6,\ \frac{v}{v_c}>0.4 \end{cases} \quad (21)$$

The maximum of t_e occurs at the threshold velocity ($v = v_c$) and $y/D > 6$. This maximum value is calculated by:

$$t_{e,\max} = 28.96\frac{D}{v} \quad (22)$$

For calculating scour depth around pile groups, Melville and Coleman (2000) recommended to replace the correction factor K_sK_α by the values that is given in Table 4. The correction factor is given only for pile groups that have either single row arrangement or double row arrangement.

4.6 HEC-18

In order to estimate scour depth around pile groups, Federal Highway Administration recommends to replace pile diameter in the Eq. (1) with effective width of an equivalent full depth pile and multiply the answer with pile group height adjustment factor (K_h), which is calculated by:

$$K_h = (3.08S_r - 5.23S_r^2 + 5.25S_r^3 - 2.1S_r^4)^{\left(\frac{1}{0.65}\right)} \quad (23)$$

where S_r is the submergence ratio defined by the pile group height divided by the flow depth ($S_r = h/y$). In Fig. 6, pile group height adjustment factor as submergence ratio has been shown.

The effective width of an equivalent full depth pile is define by the following equation:

$$D^* = D_pK_{sp}K_m \quad (24)$$

where D^* is the effective width of an equivalent full depth pile, D_p is the sum of non-overlapping projected widths of piles onto a plane normal to the flow direction, K_{sp} is the correction factor for the pile spacing and K_m is the correction factor for the number of piles in-line with the flow.

Table 4. Multiplying Factor (K_sK_α) for Pile Groups (Melville and Coleman, 2000)

Type	S/D	K_sK_α		
		$\alpha < 5°$	$\alpha < 5°$ to $45°$	$\alpha = 90°$
Single row	2	1.12	1.4	1.2
	4	1.12	1.2	1.1
	6	1.07	1.16	1.08
	8	1.04	1.12	1.02
	10	1	1	1
Double row	2	1.5	1.8	-
	4	1.35	1.5	-

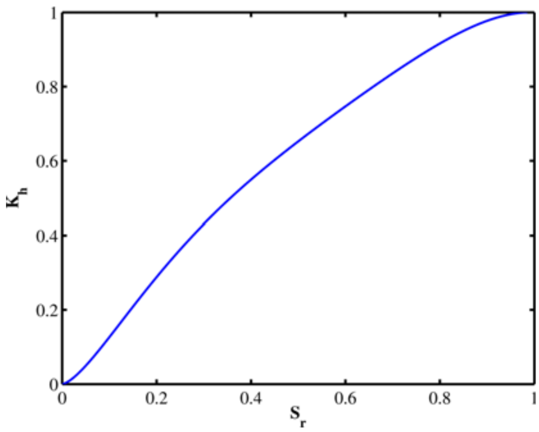

Fig. 6. Pile Group Height Adjustment Factor as a Function of Submergence Ratio

The sum of projected widths is calculated by union of projected ranges of all piles on the plane of projection. The projection range is the range between two edges of the projected pile on the plane of projection (Jones, 1989; Smith, 1999). In Fig. 7, the projection plane and the method of calculating the projected width of pile have been shown. Note that in this figure, only the closest two rows and one column to the plane of projection are chosen for calculating the sum of projected widths. The two rows and one column closest to the plane of projection

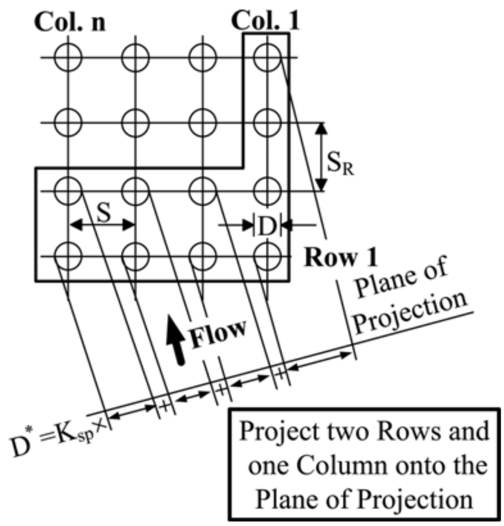

Fig. 7. A Diagram Showing How to Calculate Sum of Non-overlapping Projected Width of Piles onto the Plane Normal to the Flow Direction. The Two Rows and One Column Closest to the Plane of Projection are Separated by the Bold Outline. As it Can Been Seen in the Figure, the Sum of Projected Widths is Calculated by the Area Occupied by the Projected Ranges of the Piles in the Bold Outline onto the Plane of Projection (Redrawn from (Richardson and Davis, 2001))

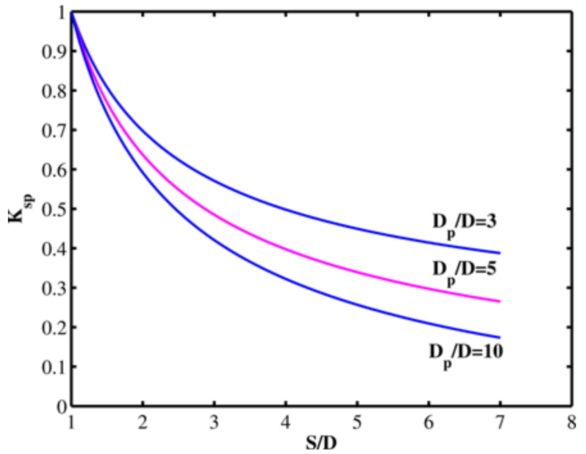

Fig. 8. Pile Spacing Correction Factor as a Function of Pile Spacing Divided by the Pile Diameter (S/D) for Different Sum of Projected Widths Divided by the Pile Diameter (D_p/D). By Increasing the Spacing between Piles, One Sees a Decrease in the Effect of the Spacing Correction Factor on the Scour Depth

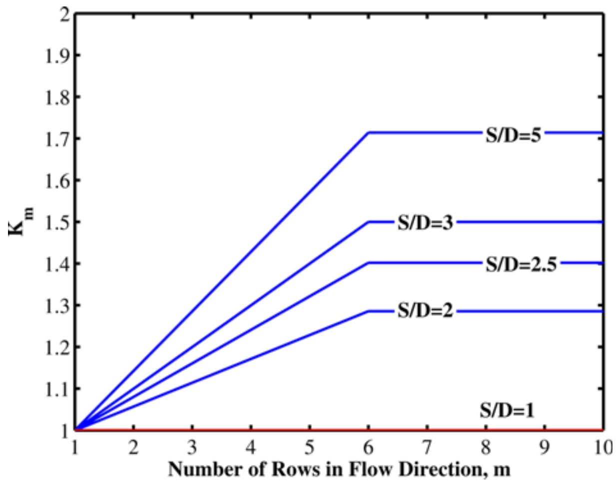

Fig. 9. Adjustment Factor for the Number of Piles In-line with the Flow (m) Plotted for Different Values of Pile Spacing Divided by the Pile Diameter (S/D)

illustrated in Fig. 7 by the bold outline. The reason for this choice is that closer piles to the flow have more influence on the scour.

Correction factor for the pile spacing (K_{sp}) and the number of piles in-line with the flow (K_m) are given by the following equations and illustrated in and , respectively:

$$K_{sp} = 1-\frac{4}{3}\left(1-\frac{1}{\frac{D_p}{D}}\right)\left(1-\left(\frac{S}{D}\right)^{-0.6}\right) \quad (25)$$

$$K_m = 0.9+0.1m-0.0714(m-1)\left(2.4-1.1\left(\frac{S}{D}\right)+0.1\left(\frac{S}{D}\right)^2\right) \quad (26)$$

The value of K_m for skewed or staggered pile groups is equal to 1.0. This is because the effect of the number of row already considered in the projection technique for skewed flows and it is already a conservative estimate for staggered rows. In Fig. 8, pile spacing correction factor for different ratios of D_p/D were plotted. According to Fig. 8, the effect of the spacing factor on the scour depth is reduced by increasing the spacing between piles. In Fig. 9, the correction factor for the number of piles in-line with the flow for different ratios of S/D were plotted. It is noticeable that the value of K_m is constant for all S/D values when there are more than 6 rows of piles.

Richardson and Davis (2001) mentioned that equations in this section can also be used were the column spacing and the row spacing are not equal. However it was recommended that a physical model study be conducted to arrive at the final design and to determine the scour depth. The value of the predictions by this method almost systematically underestimate the scour depth; for the case of skewed pile groups, the underestimation can be more than 50%. Both single pier estimation formula and the correction factor for the number of piles aligned with the flow contribute to this deviation (Lança *et al.*, 2013).

4.7 Sheppard *et al.*

Sheppard *et al.* (2004) expressed a state-of-the-art equation for predicting scour depth at a single pier (Sheppard *et al.*, 2011). This equation is an updated version of an equation given in Sheppard *et al.* (1995). The equation for predicting the scour depth at a single pier in clear-water condition ($0.47 < v/v_c < 1$) is given by:

$$\frac{y_{se}}{D} = 2.5 f_1\left(\frac{y}{D}\right) f_2\left(\frac{v}{v_c}\right) f_3\left(\frac{D}{d_{50}}\right) \quad (27)$$

The values of $f_1(y/D)$, $f_2(v/v_c)$, $f_3(D/d_{50})$ are calculated by:

$$f_1\left(\frac{y}{D}\right) = \tanh\left[\left(\frac{y}{D}\right)^{0.4}\right] \quad (28)$$

$$f_2\left(\frac{v}{v_c}\right) = 1-1.75\left[\ln\left(\frac{v}{v_c}\right)\right]^2 \quad (29)$$

$$f_3\left(\frac{D}{d_{50}}\right) = \left[\frac{\left(\frac{D}{d_{50}}\right)}{0.4\left(\frac{D}{d_{50}}\right)^{1.2}+10.6\left(\frac{D}{d_{50}}\right)^{-0.13}}\right] \quad (30)$$

Sheppard and Renna (2005) (also in slight modified versions in Sheppard (2003), Sheppard and Renna (2010)) recommended a procedure for predicting scour depth around pile groups by introducing an effective width for a pile group. For calculating the scour depth for pile groups, it is enough to replace D in Eq. (27) by the effective width. The effective width equation is:

$$D^* = K_m K_{sp} K_h K_{sh} D_p \quad (31)$$

where D^* is the effective width, K_m is the correction factor for the number of piles in-line with the flow (m), K_{sp} is the correction factor for the pile spacing, K_h is the pile group height adjustment factor, K_{sh} is the shape factor and D_p is the sum of projected width. The method for calculating the sum of projected width is the same as the method that was described in HEC-18 procedure for the sum of non-overlapping projected widths of piles. Correction factor for the pile spacing (K_{sp}) is estimated using Eq. (25). When the pile spacing between rows and columns are not equal, S in this equation is the minimum of the row spacing and the column spacing. In Eq. (25) for non-circular piles, instead of the pile diameter (D) the projected width of a single pile on the plane of projection (D_{pi}) is used. The value of D_{pi} for circular piles is equal to the pile diameter (D). The shape factor is the determine by the following equation:

$$K_{sh} = \frac{K_{sh(pile)} - K_{sh(pile\ group)}}{9}\left(\frac{S}{D_{pi}}\right) + K_{sh(pile)} - \frac{10}{9}\left(K_{sh(pile)} - K_{sh(pile\ group)}\right) \quad (32)$$

$K_{sh(pile)}$ for circular piles and $K_{sh(pile\ group)}$ for pile groups with circular arrangements are equal to 1. $K_{sh(pile)}$ for square piles and $K_{sh(pile\ group)}$ for pile groups with rectangular arrangement are given by:

$$K_{sh(pile)} = K_{sh(pile\ group)} = 0.86 + 0.97\left(\alpha\frac{\pi}{180^\circ} - \frac{\pi}{4}\right)^4 \quad (33)$$

where α is the flow skew angle. The correction factor for the number of piles in-line with the flow is calculated by:

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5^\circ, \text{ and } m \le 5 \\ 1.19 & |\alpha| < 5^\circ, \text{ and } m > 5 \\ 1 & |\alpha| > 5^\circ \end{cases} \quad (34)$$

where m is the number of piles in-line with the flow. The pile group height adjustment factor is defined by the following equation:

$$K_h = \begin{cases} 1.5\tanh\left(0.8\sqrt{\frac{h}{y_{\max}}}\right) & 0 \le \frac{h}{y_{\max}} \le 1 \\ 1 & \frac{h}{y_{\max}} > 1 \\ 0 & \frac{h}{y_{\max}} < 0 \end{cases} \quad (35)$$

$y_{\max}$ estimated by the following equation:

$$y_{\max} = \begin{cases} y & y \le 2K_s D_p K_{sp} Km \\ 2K_s D_p K_{sp} Km & y > 2K_s D_p K_{sp} Km \end{cases} \quad (36)$$

where y is the flow depth.

Sheppard *et al.* (2011) recommended a modification to the equation of local-scour depth estimation to get more accurate results in the case of single pier. In this modification, the coefficient 1.75 in Eq. (29) is changed to 1.2 and the value of local scour initialization is changed from 0.47 to 0.4 ($0.4 < v/v_c < 1$). Sheppard *et al.* mentioned that these recommendations must be used with caution in the case of pile groups. The predictions of Sheppard and renna (2005) are scattered around the line of perfect agreement within a band defined by –20% and +40%. In the case of skewed pile group Sheppard's methods may underestimate the scour depth (Lança *et al.*, 2013).

4.8 Ataie-Ashtiani and Beheshti

Ataie-Ashtiani and Beheshti (2006) proposed a correction factor to Eq. (1) that incorporates the number of piles in addition to S/D in it. The correction factor is given for pile groups aligned to the flow and is expressed by the following equation:

$$K_{Smn} = 1.11\frac{(m)^{0.0396}}{\left[(n)^{0.5225}\left(\frac{S}{D} - 1\right)^{0.1153}\right]} \quad (37)$$

where K_{Smn} is the correction factor, m is the number of piles in-line with flow and n is the number of piles normal to the flow. The maximum scour depth around pile groups is estimated by multiplying correction factor and scour depth obtained from Eq. (1) for equivalent solid pile. Equivalent solid pile has the dimensions of a solid constructed by putting all piles together were the piles are touching one another.

Ataie-Ashtiani and Beheshti (2006) presented a different correction factor for New Zealand equation (Eq. (15)). This correction factor is also for estimating the scour depth around pile groups aligned to the flow. The correction factor is given by:

$$K_{Smn} = 1.118\frac{(m)^{0.0895}}{\left[(n)^{0.8949}\left(\frac{S}{D} - 1\right)^{0.1195}\right]} \quad (38)$$

The correction factor introduced by Ataie-Ashtiani and Beheshti (2006) is based on fitting a curve to the data that minimizes the prediction error. However, usually, the scour depth is intentionally overestimated. Another approach to correct for the possible under-stimation is to use a multiplicative safety factor. Therefore, it is important to design a reliable safety factor before using this method.

4.9 Amini *et al.*

Amini *et al.* (2012) introduced a modified version of the correction factor given in Eq. (37). The correction factor is calculated by the following equation:

$$K_{Smn} = Cm^{0.05}n^{-0.44}\left(\frac{S}{D}\right)^{-0.38} \quad (39)$$

where $C = 1.31$ for unsubmerged pile groups and $C = 1.1$ for submerged pile groups. In addition to this correction factor, they introduced another correction factor (K_h) for the effect of submergence ratio (S_r) on the scour depth. K_h is calculated by one of the following two equations:

$$K_h = S_r^3 - 2.4S_r^2 + 2.4S_r \quad (40)$$

$$K_h = 1.7S_r^3 - 4S_r^2 + 3.3S_r \quad (41)$$

Eq. (40) is the result of the best fit to the data and Eq. (41) is the result of the envelope curve fit. For computing the total scour depth around pile groups these correction factors are multiplied by the scour depth calculated by Eq. (1) wherein D is replaced by nD. For unsubmerged pile groups $K_h = 1$. The data used in this research were collected based on short time test duration. Therefore, the predicted scour depth may underestimate true equilibrium scour depth. Like Ataie-Ashtiani and Beheshti (2006), one should consider a safety factor before using this method.

5. Neural Network Procedure

Most of the empirical equations are derived by correlation analysis or by dimensionality analysis (Gibbings, 2011). However, since the scour around pile groups is a complicated phenomenon with complex mechanism, it's difficult to achieve a reliable prediction for the scour depth around pile groups with the conventional techniques (Hosseini *et al.*, Submitted).

Conventional methods have fewer parameters and in cases that they have good performance, they are the method of choice and design equations are usually derived based on these methods (Sheppard *et al.*, 2011). However, as validated by empirical evaluations (Zounement-Kermani *et al.*, 2009; Hosseini *et al.*, Submitted) for the case of scour depth estimation around pile groups conventional methods have very low performance and therefore researchers tempted to use soft-computing methods like neural networks for scour depth estimation around pile groups.

Artificial neural network is a flexible, semi-parametric regression method that can approximate theoretically any function and find the relationship between the input and the output data in complex systems, where conventional regression methods usually fail. These abilities are due to arbitrary squashing functions used in the network structure (Hornik *et al.*, 1989).

Artificial intelligence methods have been applied successfully in different areas of hydraulic and water resource engineering (Toprak and Savci, 2007; Toprak and Cigizoglu, 2008; Toprak *et al.*, 2009; Toprak, 2009; Toprak *et al.*, 2014). It has been reported that they can predict the quantity of interest, for example scour depth, from the input data more accurate than other conventional approaches (Nagy *et al.*, 2002; Azmathullah *et al.*, 2005; Azamathulla *et al.*, 2008). Among artificial intelligence methods, neural network procedure has been successfully used for predicting scour depth around pile groups and its success has been validated by several studies (see Choi and Cheong (2006); Bateni *et al.* (2007a, b); Lee *et al.* (2007) for predicting the scour depth around bridge piles and Kambekar and Deo (2003); Zounement-Kermani *et al.* (2009) for predicting the scour depth around pile groups). Hosseini *et al.* (Submitted) is a statistically more rigorous study that again uses the neural network procedure for estimating the scour depth around pile groups.

Zounement-Kermani *et al.* (2009) also applied Adaptive Neuro-Fuzzy Inference System (ANFIS) to predict scour depth around pile groups. Neuro-fuzzy methods and similar methods like geno-fuzzy does not have the physical interpretation that the pure fuuzy logic approch has. SMRGT is a new fuzzy modelling technique (Toprak *et al.*, 2009) that keeps the physical base of fuzzy logic method. This new method has not yet been tried to predict scour depth around pile groups.

The current empirical evaluation showing higher performance of neural network method is done on a limited available data. More datas and experiments are needed to validate the high performance of neural network procedure to make it a possible standard method for scour depth estimation around pile gorups. Some prior knowledge incorporated into the model also increases the chance of generalization of the performance to the unseen data. One option that has already been considered is having dimensionless input parameters to the neural network architecture.

5.1 Zounement-Kermani *et al.*

Zounement-Kermani *et al.* (2009) used two types of artificial neural networks, namely Feedforward Backpropagation Neural Network (FFBP-NN) and radial basis Function Neural Network (RBF-NN), in addition to an ANFIS for estimating the scour depth around pile groups. In the FFBP-NN model, one, two and three hidden layers with different numbers of neurons were examined. For the RBF-NN model, one hidden layer with different numbers of nodes were tested.

Furthermore, in the AFNIS structure, networks with 1, 2 and 3 triangular membership functions were trained.

For each neural network type, two different sets of input-output variables (original and normalized) were used to train two different networks for predicting the scour depth. One of these networks finds the functional relationship between the input variables and the scour depth for the original quantities. This functional relationship is demonstrated by the following equation:

$$y_{se} = f_1(n, m, D, d_{50}, y, v, v_c, S) \tag{42}$$

where n is the number of piles normal to the flow, m is the number of piles in-line to the flow, D is the pile diameter, d_{50} is the grains mean diameter, y is the flow depth, v is the flow mean velocity, v_c is the critical flow velocity, S is the spacing between piles and y_{se} is the maximum equilibrium scour depth. For normalized set of variables, the number of input quantities is reduced to seven. The function estimated by a neural network is represented by:

$$\frac{y_{se}}{D} = f_2\left(\frac{v}{v_c}, \frac{v^2}{gD}, \frac{y}{D}, \frac{D}{d_{50}}, \frac{\rho v D}{\mu}, \frac{S}{D}, \frac{m}{n}\right) \tag{43}$$

where g is the gravitational acceleration, ρ is the fluid density and μ is the fluid dynamic viscosity.

Zounement-Kermani *et al.* (2009) observed that FFBP-NN with 17 neurons in the hidden layer, RBF-NN with 27 neurons and ANFIS with 3 membership functions achieved the best performance in each structure for the original variables. Moreover, the author concluded that the networks learned on the original variables give more accurate results that the networks learned on the normalized variables. Among the three structures, the FFBP-NN structure achieved more accurate prediction of the scour depth around pile groups. This structure also outperformed several empirical procedures. Furthermore, the sensitivity analysis determined that D and S/D were the most influential factors for networks learned on the original data and the normalized data, respectively.

Table 5. The Values of Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) for Neural Networks and Five Other Empirical Procedures. Early-stopping (E), Bagging (B) and Regularization (R) Were Used for Improving the Generalization Performance. Bold Numbers Show the Best Result in Each Column (Hosseini *et al.*, Submitted)

Methodology	Original		Normalized	
	MAE	RMSE	MAE	RMSE
E. dimensional NN	0.565	0.594	0.567	0.592
E. dimensionless NN	0.618	0.638	0.577	0.587
B. dimensional NN	0.584	0.601	0.567	0.591
B. dimensionless NN	**0.44**	**0.45**	**0.493**	**0.511**
R. dimensional NN	0.579	0.602	0.559	0.593
R. dimensionless NN	0.441	0.451	0.541	0.584
HEC-18	2.093	2.637	0.889	0.981
Salim & Jones	2.794	3.123	1.064	1.135
A.-Ashtiani & Beheshti	2.282	2.675	0.639	0.712
Amini *et al.*	2.547	2.819	0.721	0.767
Sheppard	2.107	2.248	0.788	0.847

5.2 Hosseini *et al.*

Hosseini *et al.* (Submitted) used more rigorous statistical procedures to train FFBP-NNs on the training data. To exploit the full potential of the neural network procedure, the authors compared three different methods for improving the generalization performance of the neural networks. These methods were early-stopping, regularization and bagging. For the fair comparison between the networks learned on the original and normalized inputs, the authors trained four different networks, two dimensional and two dimensionless networks. The networks trained on the original variables was called dimensional network. The other network learned on the normalized variables was called dimensionless network. For each of dimensional and dimensionless networks, two different objective functions were used for training. One of the objective functions of the minimization problem was the error of the scour depth. The other objective function was the error of normalized scour depth (y_{se}/D).

The functional relationship between input and output variables for the dimensional network is the one expresses in Eq. (42). For dimensionless network, the functional relationship is expressed by the following equation:

$$\frac{y_{se}}{D} = f_2'\left(\frac{v}{v_c}, \frac{v^2}{D}, \frac{y}{D}, \frac{D}{d_{50}}, vy, \frac{S}{D}, m, n\right) \quad (44)$$

Hosseini *et al.* (Submitted) compared different networks to the empirical procedures and observed a significant improvement achieved by the neural network procedures (see Table 5). The empirical procedures used in the comparison were the ones already explained in the previous section. For the fare comparison, the predicted values are linearly transformed so that they are larger or equal to the target scour depth, i.e. they do not underestimate the scour depth. Among different methods for improving the generalization performance, the bagging method was the most effective one. Unlike Zounement-Kermani *et al.* (2009), they observed that the dimensionless network outperformed the dimensional network for predicting the scour depth. The number of neurons for the best network structure in the dimensionless case was eight. The sensitivity analysis showed that S and S/D were the most influential factors for the dimensional and dimensionless networks, respectively.

References

Amini, A., Melville, B. W., Ali, T. M., and Ghazli, A. H. (2012). "Clear-water local scour around pile groups in shallow-water flow." *Journal of Hydraulic Engineering,* ASCE, Vol. 138, No. 2, pp. 177-185, DOI: 10.1061/(ASCE)HY.1943-7900.0000488.

Ataie-Ashtiani, B. and Beheshti, A. A. (2006). "Experimental investigation of clear-water local scour at pile groups." *Journal of Hydraulic Engineering,* ASCE, Vol. 132, No. 10, pp. 1100-1104, DOI: 10.1061/(ASCE)0733-9429(2006)132:10(1100).

Azamathulla, H. M., Deo, M. C., and Deolalikar, P. B. (2008). "Alternative neural networks to estimate the scour below spillways." *Advances in Engineering Software*, Vol. 39, No. 8, pp. 689-698, DOI: 10.1016/j.advengsoft.2007.07.004.

Azmathullah, H. M., Deo, M. C., and Deolalikar, P. B. (2005). "Neural network for estimation of scour downstream of a ski-jump bucket." *Journal of Hydraulic Engineering,* ASCE, Vol. 131, No. 10, pp. 898-908, DOI: 10.1061/(ASCE)0733-9429(2005)131:10(898).

Bateni, S. M., Borghei, S. M., and Jeng, D.-S. (2007). "Neural network and neuro-fuzzy assessments for scour depth around bridge piers." *Engineering Applications of Artificial Intelligence*, Vol. 20, No. 13, pp. 401-414, DOI: 10.1016/j.engappai.2006.06.012.

Bateni, S. M., Jeng, D.-S., and Melville, B. W. (2007). "Bayesian neural networks for prediction of equilibrium and time-dependant scour depth around bridge piers." *Advances in Engineering Software*, Vol. 38, No. 2, pp. 102-111, DOI: 10.1016/j.advengsoft.2006.08.004.

Breusers, H. N. C., Nicollet, G., and Shen, H. W. (1977). "Local scour around cylindrical piers." *Journal of Hydraulic Research,* IAHR, Vol. 15, No. 3, pp. 211-252, DOI: 10.1080/00221687709499645.

Choi, S.-U. and Cheong, S. (2006). "Prediction of local scour around bridge piers using artificial neural networks." *Journal of the American Water Resources Association*, Vol. 42, No. 2, pp. 487-494, DOI: 10.1111/j.1752-1688.2006.tb03852.x.

Deng, L. and Cai, C. (2010). "Bridge scour: Prediction, modeling, monitoring, and countermeasures - a review." *Practice Periodical on Structural Design and Construction*, Vol. 15, No. 2, pp. 125-134, DOI: 10.1061/(ASCE)SC.1943-5576.0000041.

Dietz, J. W. (1973). "Kolkbildung an einem kreiszylindrischen pfeilerpaar." *Die Bautechnik*, Vol. 50, No. 6, pp. 203-208.

Elliott, K. and Baker, C. (1985). "Effect of pier spacing on scour around bridge piers." *Journal of Hydraulic Engineering,* ASCE, Vol. 111, No. 7, pp. 1105-1109, DOI: 10.1061/(ASCE)0733-9429(1985) 111:7(1105).

Ettema, R., Yoon, B., Nakato, T., and Muste, M. (2004). "A review of scour conditions and scour-estimation difficulties for bridge abutments." *Journal of Civil Engineering,* KSCE, Vol. 8, No. 6, pp. 643-650, DOI: 10.1007/BF02823555.

Froehlich, D. C. (1989). "Local scour at bridge abutments." *1989th National Conference on Hydraulic Engineering*, pp. 13-18. ASCE.

Gao, D. G., Posada, L. G., and Nordin, C. F. (1993). *Pier scour equations used in the people's Republic of China: REVIEW AND SUMMARY,* Tech. Rep., Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Gibbings, J. (2011). *Dimensional analysis,* Springer.

Hannah, C. R. (1978). *Scour at pile groups,* MSc Thesis, University of Canterbury, Christchurch, New Zealand.

Heza, Y. B., Soliman, A. M., and Saleh, S. A. (2007). "Prediction of the scour hole geometry around exposed bridge circular-pile foundation." *Journal of Engineering and Applied Science*, Vol. 54, No. 4, pp. 375-392.

Hornik, K., Stinchcombe, M., and White, H. (1989). "Multilayer feed-forward networks are universal approximators." *Neural Networks*, Vol. 2, No. 5, pp. 359-366, DOI: 10.1016/0893-6080(89)90020-8.

Hosseini, R., Fazloula, R., and Amini, A. (Submitted). "Bagged neural network for estimating scour depth around pile Groups.", *Journal of Hydroinformatics.*

Hunt, B. E. (2009). *Monitoring scour critical bridges.* Washington, D.C.

Inglis, C. C. (1949). *The behavior and control of rivers and canals,* Central Water Power Irrigation and Navigation Report 13, Poona Research Station, Poona, India.

Jain, S. C. and Fischer, E. E. (1979). *Scour around bridge piers at high froude numbers,* Tech. Rep., Federal Highway Administration, Washington D.C.

Jones, J. S. (1989). "Laboratory studies of the effect of footing and pile groups on bridge pier scour." *Bridge Scour Symposium*, pp. 340-359. Federal Highway Administration, Washington, D.C.

Kambekar, A. R. and Deo, M. C. (2003). "Estimation of pile group scour using neural networks." *Applied Ocean Research*, Vol. 25, No. 4, pp. 225-234, DOI: 10.1016/j.apor.2003.06.001.

Lanca, R., Fael, C., Maia, R., Pego, J., and Cardoso, A. (2013). "Clear-water scour at pile groups." *Journal of Hydraulic Engineering*, Vol. 139, No. 10, pp. 1089-1098, DOI: 10.1061/(ASCE)HY.1943-7900.0000770.

Larras, J. (1963). "Profondeurs maximales d'erosion des fonds mobiles autour des piles en riviere." *Ann. Ponts et Chaussées*, Vol. 133, No. 4, pp. 411-424.

Laursen, E. M. and Toch, A. (1956). *Scour around Bridge Piers and Abutments,* Bulletin, Iowa Highway Research Board, Ames Iowa.

Lee, T. L., Jemg, D. S., Zhang, G. H., and Hong, J. H. (2007). "Neural network modeling for estimation of scour depth around bridge piers." *Journal of Hydrodynamics, Ser. B*, Vol. 19, No. 3, pp. 378-386, DOI: 10.1016/S1001-6058(07)60073-0.

Melville, B. W. and Chiew, Y. (1999). "Time scale for local scour at bridge piers." *Journal of Hydraulic Engineering*, ASCE, Vol. 125, No. 1, pp. 59-65, DOI: 10.1061/(ASCE)0733-9429(1999)125:1(59).

Melville, B. W. and Coleman, S. E. (2000). *Bridge scour,* Littleton, Colorado: Water Resources Publications.

Melville, B. W. and Sutherland, A. (1988). "Design method for local scour at bridge piers." *Journal of Hydraulic Engineering*, ASCE, Vol. 114, No. 10, pp. 1210-1226, DOI: 10.1061/(ASCE)0733-9429(1988)114:10(1210).

Nagy, H. M., Watanabe, K., and Hirano, M. (2002). "Prediction of sediment load concentration in river using artificial neural network model." *Journal of Hydraulic Engineering,* ASCE, Vol. 128, No. 6, pp. 588-595, DOI: 10.1061/(ASCE)0733-9429(2002)128:6(588).

Nazariha, M. (1996). *Design relationships for maximum local scour depth for bridge pier groups,* PhD Thesis, University of Ottawa.

Nouh, M. (1986). "Local scour at pile groups in meandering channels." *IAHR, Symposium on Scale Effects In Modelling Sediment Transport Phenomena, Toronto, Canada*, pp. 164-179.

Richardson, E. V. and Davis, S. R. (2001). *Evaluating scour at bridges,* Hydraulic Engineering Circular No. 18, Federal Highway Administration, Washington, D.C.

Salim, M. and Jones, J. S. (1996). "Scour around exposed pile foundations." *North American Water and Environment Congress*, pp. 2202-2211. Anaheim, CA: ASCE.

Shen, H. W., Schneider, V. R., and Karaki, S. S. (1969). "Local scour around bridge piers." *Journal of the Hydraulics Division, ASCE*, Vol. 95, No. 6, pp. 1919-1940.

Sheppard, D. M. (2003). *Scour at complex piers*, Florida Department of Transportation.

Sheppard, D. M. and Renna, R. (2005). *Bridge scour manual,* 605 Suwannee Street. Tallahassee, FL 32399-0450.

Sheppard, D. M. and Renna, R. (2010). *Bridge scour manual,* 605 Suwannee Street. Tallahassee, FL 32399-0450.

Sheppard, D. M., Demir, H., and Melville, B. W. (2011). *Scour at wide piers and long skewed piers,* National Research Board, Washington, D.C.

Sheppard, D. M., Odeh, M., and Glasser, T. (2004). "Large scale clear-water local pier scour experiments." *Journal of Hydraulic Engineering,* ASCE, Vol. 130, No. 10, pp. 957-963, DOI: 10.1061/(ASCE)0733-9429(2004)130:10(957).

Sheppard, D. M., Ontowirjo, B., and Zhao, G. (1995). "Local scour near single piles in steady currents." *1st Hydraulic Engineering Conference.* San Antonio.

Sheppard, D., Melville, B., and Demir, H. (2013). "Evaluation of existing equations for local scour at bridge piers." *Journal of Hydraulic Engineering*, Vol. 140, No. 1, pp. 14-23, DOI: 10.1061/(ASCE) HY.1943-7900.0000800.

Smith, W. L. (1999). *Local structure-induced sediment scour at pile groups,* MSc Thesis, University of Florida.

Sumer, B. M., Bundgaard, K., and Fredsøe, J. (2005). "Global and local scour at pile groups." *International Journal of Offshore and Polar Engineering*.

Toprak, Z. F. (2009). "Flow discharge modeling in open canals using a new fuzzy modeling technique (SMRGT)." *CLEAN - Soil, Air, Water*, Vol. 37, No. 9, pp. 742-752, DOI: 10.1002/clen.200900146.

Toprak, Z. F. and Cigizoglu, H. K. (2008). "Predicting longitudinal dispersion coefficient in natural streams by artificial intelligence methods." *Hydrological Processes*, Vol. 22, No. 20, pp. 4106-4129, DOI: 10.1002/clen.200900146, DOI: 10.1002/hyp.7012.

Toprak, Z. F. and Savci, M. E. (2007). "Longitudinal dispersion coefficient modeling in natural channels using fuzzy logic." *CLEAN - Soil, Air, Water*, Vol. 35, No. 6, pp. 626-637, DOI: 10.1002/clen.200700122.

Toprak, Z. F., Eris, E., Agiralioglu, N., Cigizoglu, H. K., Yilmaz, L., Aksoy, H., Coskun, H. G., Andic, G., and Alganci, U. (2009). "Modeling monthly mean flow in a poorly gauged basin by fuzzy logic." *CLEAN - Soil, Air, Water*, Vol. 37, No. 7, pp. 555-564, DOI: 10.1002/clen.200800152.

Toprak, Z. F., Hamidi, N., Kisi, O., and Gerger, R. (2014). "Modeling dimensionless longitudinal dispersion coefficient in natural streams using artificial intelligence methods." *KSCE Journal of Civil Engineering*, Vol. 18, No. 2, pp. 718-730, DOI: 10.1007/s12205-014-0089-y.

Zdravkovich, M. M. (1987). "The effects of interference between circular cylinders in cross flow." *Journal of Fluids and Structures*, Vol. 1, No. 2, pp. 239-261, DOI: 10.1016/S0889-9746(87)90355-0.

Zhao, G. and Sheppard, D. M. (1998). "The effect of flow skew angle on sediment scour near pile groups." *Stream Stability and Scour at Highway Bridges, compendium of papers ASCE Water Resource Engineering conferences 1991-1998*, Reston, Virginia: ASCE, pp. 377-391.

Zounement-Kermani, M., Beheshti, A.-A., Ataie-Ashtiani, B., and Sabbagh-Yazdi, S.-R. (2009). "Estimation of current-induced scour depth around pile groups using neural network and adaptive neuro-fuzzy inference system." *Applied Soft Computing*, Vol. 9, No. 2, pp. 746-755, DOI: 10.1016/j.asoc.2008.09.006