Experimental Investigation of Clear-Water Local Scour at Pile Groups

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Abstract: Experiments of local scour around pile groups are carried out under steady clear-water scour conditions. A variety of conditions including different pile group arrangements, spacing, flow rates, and sediment grain sizes are considered. In total, 112 experiments are carried out. It is observed that the scour-hole depth for some cases of pile groups increases as much as two times more than its magnitude for the case of single piles. The data from this study and some laboratory experiment data from previous works are used to derive a correction factor to predict the maximum local scour depth for the pile groups. Two well-known equations, i.e., Federal Highway Administration, Hydraulic Engineering Circular No. 18, HEC-18 (reported by Richardson and Davis in 2001) and the New Zealand pier scour equation (reported by Melville and Coleman in 2000) are considered. The prediction of scour hole based on the present correction agrees well with the observations.

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Introduction

For geotechnical and economical reasons, multiple pile bridge piers have become more and more popular in bridge design. This type of pier can significantly reduce construction costs, compared to spread footer (gravity) structures when sediment scour is a consideration. However, the scour mechanisms for pile groups are much more complex, and design of local scour depths more difficult to predict.

While a substantial amount of knowledge has accumulated about scour around single piers over the past decade or so (Breusers and Raudkivi 1991; Melville and Coleman 2000), comparatively little is known about scour at pile groups (Hannah 1978; Salim and Jones 1998; Coleman 2005).

In the simplest case, pile groups are caped above the water surface and only the pile groups obstruct the flow field. Hannah (1978) investigated scour around tow-pile, side-by-side, and tandem arrangements, for different spacings between the piles. Salim and Jones (1998) observed that the scour depth decreases as the spacing between the piles increases. Coleman (2005) presented a new methodology to predict local scour depth at a complex pier. The objectives of the present study are to investigate in a systematic manner the scour around pile groups and to evaluate the success of some of the commonly used formulas for prediction of scour-hole depth.

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Experimental Setup

The experiments were carried out in a 4 m long, 0.41 m wide, and 0.25 m deep flume. The flume had a working section in the form of a 0.08 m depth recess below its bed. The recess was 4 m long. The first 0.6 m of recess was filled with 7–14 mm gravel in order to generate fully developed flows. The remaining recess was filled with movable sand. Two different bed materials (quartz sand) were used with the mean particle sizes of 0.25 and 0.98 mm with geometric standard deviation of particles, $\sigma_g=1.54$ and 1.13, respectively. Based on Raudkivi and Ettema (1983) and Melville and Chiew (1999), local scour depth is influenced by sediment size when $D/d_{50}<50$. Also, based on work by Melville and Sutherland (1988) D/d_{50} shall be more than 25. In our experiments this ratio varies from 16 to 124, which is a proper range. The water depth in the flume is adjusted by the position of the sluice gate at the downstream end of the flume. An electrical flow meter was used to measure flow discharge. For most of the tests, shallow water depths were used to get a fully developed flow in the flume. The boundary layer was theoretically estimated to occupy the whole depth before reaching the test section, which was 2.5 m from the inlet.

As shown in Fig. 1, eight types of pile group arrangements were tested, including the 2×1, 1×2, 2×2, 2×3, 2×4, and 3×2. The models of pile groups consist of 16, 22, and 28 mm pile diameters. The size of the models was such that the total blockage area did not exceed 12% of the total flow section for most of the tests in order to minimize contraction scour. The pile spacing, G, varied from zero to six times that of the pile diameter. The durations of the experimental runs were chosen based on the past investigations on clear-water scour; the experiment duration was kept more than 7 h for sand with $d_{50}=0.98$ mm, and 8 h for sand with $d_{50}=0.25$ mm. Some runs lasted more than 15 h to investigate the duration needed to achieve equilibrium scour. As the difference in the deepest scours for these durations was found to be less than 1.0 mm, the maximum scour depths obtained after 7 and 8 h were adopted as the equilibrium scour depths. It was estimated that scour depths at the end of 7 and 8 h for most of the

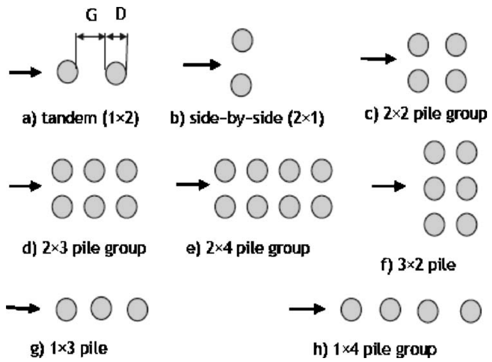

Fig. 1. Pile groups used in experiments

experiments were more than 90% their equilibrium value. Studies by other researchers such as Yanmaz and Altinbilek (1991) and Mia and Nago (2003) have shown that most of the scour occurs during the first 3 or 4 h of a test. Also, a calibration run was carried out for more than 45 h for a 2×4 pile group with $G/D=2$ and $U=0.21$ m/s to investigate the duration needed to achieve equilibrium scour ⟨http://sharif.ir/~ataie/Scour/Exp04_ASCEJH.html⟩. It was found that 86% of the equilibrium scour depth is attained at 5.5 h and 92% of the equilibrium scour depth is developed in a time 8 h. The maximum scour depth does not change after 29 h of test duration. All experiments were performed in the clear-water range. The critical flow condition was predicted using Shield's diagram and expressions of Melville and Coleman (2000). After each experiment the scour hole dimensions were measured with a point gauge with an accuracy of ±1 mm.

Results of Experiments and Analysis

The test conditions together with the experimental results are available at ⟨http://sharif.ir/~ataie/Scour/Exp04_ASCEJH.html⟩. Fig. 2(a) illustrates the equilibrium maximum scour depth at two pile groups normalized by the scour depth at a single pile, S/S_s, versus the normalized pile spacing, G/D, for the tandem arrangement.

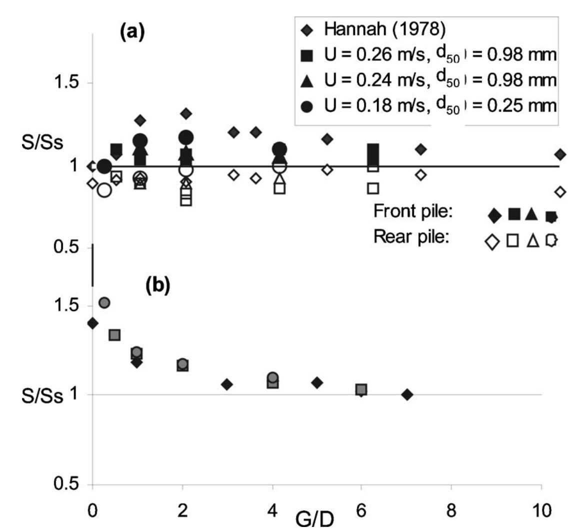

Fig. 2. Equilibrium scour depth plotted against pile spacing: (a) 1×2 pile group; (b) 2×1 pile group

Fig. 2(a) shows that the maximum scour depth increases with increasing G/D, and reaches the maximum value at $G/D=2$, then it decreases, and eventually it reaches its single-pile value. Also, it shows that the scour depth at the rear pile always is smaller than the single-pile case. The reason can be explained by the fact that the horseshoe vortex at the rear pile has a relatively smaller size than that of the single pile and live bed conditions exist there as material removed from around the front pile reaches the scour hole around the rear pile.

Fig. 2(b) shows the data obtained in this study and data from Hannah (1978) in the case of the side-by-side arrangement. The maximum scour depth is about 50% higher than the single-pile value at $G/D=0.25$. This may be partly due to the increased size of the horseshoe vortex for such small pile spacing, and partly to the very strong gap flow between the two neighboring piles. When $G/D<0.25$, the two piles act as a single pile.

For the case of the 2×2 pile group, the maximum scour depth is about 63% higher than that for the single pile at $G/D=0.25$. The scour depth increases with respect to that of the two-pile, side-by-side arrangement for gaps $G/D<4$, by about 10–13%. This can be attributed to the reinforcement effect of the downstream piles. The lowering of the bed level at the rear eases the escape of material from the scour hole and leads to deeper scour. The location of the maximum scour depth actually varies with the particular pile grouping, and also with the pile spacing. The way in which the scour depth of the 2×3 group changes with G/D is rather similar to that of the 2×2 group. The results showed that the maximum scour depth obtained for the 3×2 pile group. This may be due to the increased effect of compressed horseshoe vortices, the minimum scour depth obtained for the tow-pile, tandem arrangement (1×2 pile group). This indicates that the effect of compressed horseshoe vortices is larger than the reinforcement.

Estimating of Maximum Scour Depth around Pile Group

FHwA Pier Scour Equation (HEC-18)

The local pier scour equation recommended by the Federal Highway Administration (FHwA), Circular HEC–18 (Richardson and Davis 2001) was selected as a frame of reference for this analysis. The equation is stated as

$$\frac{S}{h} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{D}{h}\right)^{0.65} (\mathrm{F})^{0.43} \tag{1}$$

where S=scour depth (m); h=flow depth directly upstream of the pier (m); D=pier diameter (m); K_1=shape factor; K_2=angle of attack factor; K_3=dune factor; K_4=correction factor for size of bed material; F=Froude number=$U/(gh)^{0.5}$; and U=mean velocity of flow directly upstream of the pier (m/s).

The recommended procedure for determination of the pile group scour by applying this equation in HEC-18 is to use the effective width of an equivalent full depth pile group (D^*) that 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

$$D^* = D_{\mathrm{proj}} K_G K_m \tag{2}$$

where D_{proj}=sum of the nonoverlapping projected widths of piles; K_G=coefficient for pile spacing; K_m=coefficient for the number of aligned rows (m); and G=spacing between the piles (Richardson and Davis 2001).

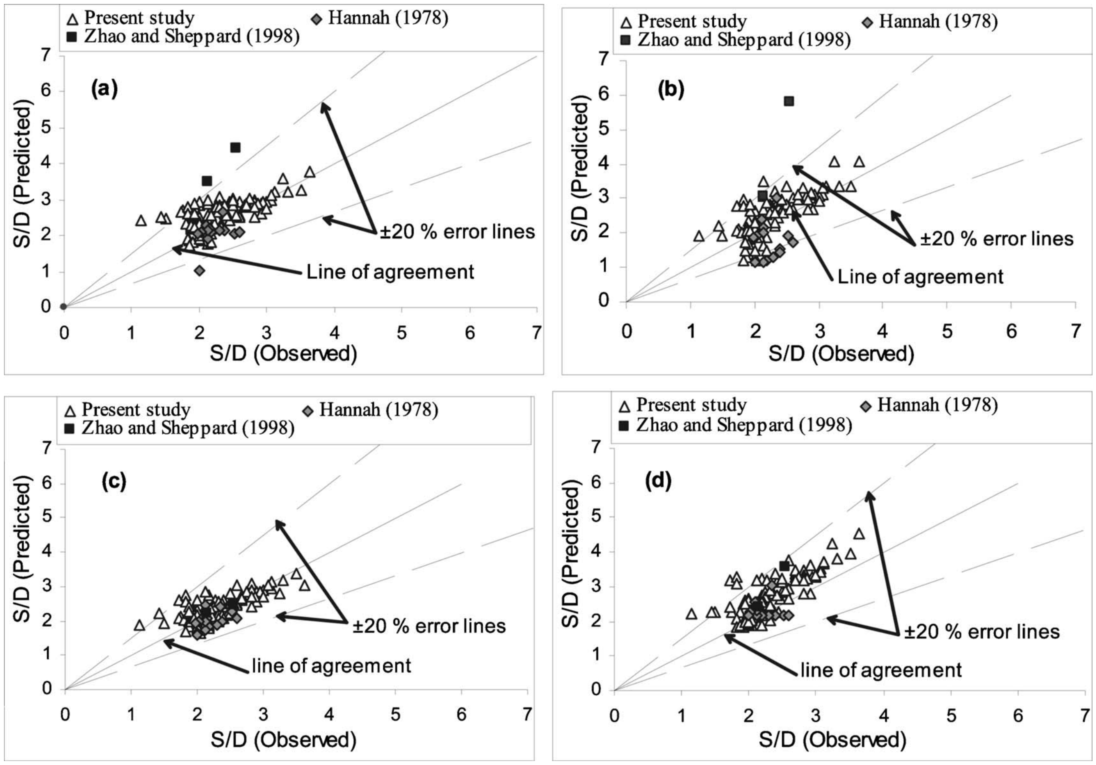

Fig. 3. Comparison of observed and predicted scour depth at pile groups: (a) HEC-18 procedure (Richardson and Davis 2001); (b) Salim and Jones (1998) procedure; (c) present procedure; and (d) Sheppard and Glasser (2004) procedure

Another procedure for pile groups has been given by Salim and Jones (1998). In this procedure, the scour depth is calculated using Eq. (1) assuming an equivalent solid pile group with piles touching each other set at the same skew angle to the flow direction, and then multiplying this scour depth by the correction factors for spacing and angle of attack on the pile group. The spacing correction factor proposed by Salim and Jones did not consider the number of piles normal to the flow, n, and the number of piles in-line with flow. This procedure was intended to be conservative when the number of piles normal to the flow is 3 or more. In this study a new correction factor, K_{Gmn}, was obtained for pile groups aligned to the flow using results from this experiment and data from Hannah (1978) and Zhao and Shepard (1998)

$$K_{Gmn} = 1.11\frac{(m)^{0.0396}}{[(n)^{0.5225}(G/D)^{0.1153}]} \tag{3}$$

In this equation, the correction factor, K_{Gmn}, was obtained by dividing the scour depth at a particular pile group and a particular value of G/D to that of the equivalent solid pier that has the dimensions of the pile group if the piles were made to touch one another.

Also, a recent procedure that has been recommended by Sheppard and Glasser (2004) is considered. This methodology is also tested against the results for the present data. Fig. 3 presents the comparison of existing and proposed procedures for HEC-18, Salim and Jones, and Sheppard and Glasser methodologies with 118 laboratory measured scour depths for pile groups aligned to the flow. Fig. 3 illustrates that HEC-18 and Salim and Jones procedures overpredicted the scour depth at pile groups with three or more piles normal to the flow. The Salim and Jones procedure also underpredicted the scour depth for tandem arrangement of piles. The present procedure predicted scour depths reasonably close to the observed scour depths. As may be seen from Fig. 3, the present procedure gives less than ±20% error for all the data. The Sheppard and Glasser procedure also gives reasonable results.

New Zealand Pier Scour Equation

Melville and Coleman (2000) present a design method for the estimation of the scour depth

$$S = K_{hD}K_IK_dK_SK_\alpha K_t \tag{4}$$

where K_{hD}, K_I, K_d, K_S, K_α, and K_t=multiplication factors to account for flow depth-pier size, flow intensity, flow depth, sediment size, pier shape, pier alignment, and time, respectively.

In this study a multiplying factor, K_{Gmn}, was obtained for the pile group aligned to the flow using data from this study, Hannah (1978), and Zhao and Shepard (1998)

$$K_{Gmn} = 1.118\frac{(m)^{0.0895}}{[(n)^{0.8949}(G/D)^{0.1195}]} \tag{5}$$

A comparison of computed and observed scour depths for data from this study, Hannah (1978), and Zhao and Shepard (1998), is shown in Fig. 4. The computed values of the scour depths are reasonably close to the observed scour depth.

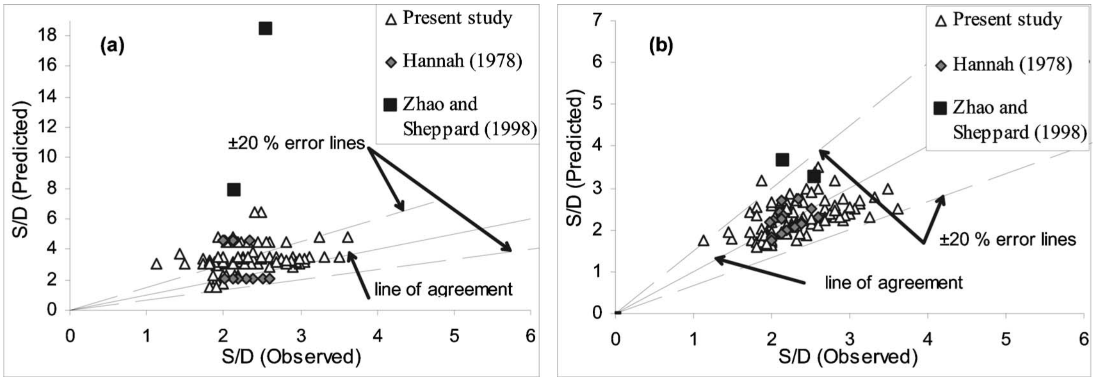

Fig. 4. Relation between observed and computed scour depths using the New Zealand pier scour equation: (a) without multiplying K_{Gm}; (b) with multiplying K_{Gmn}

Conclusions

In summary, the following observations were made based on the analysis of the existing data on scour around pile groups exposed to the steady currents.

1. The scour at a pile group is different from that around a single pile, depending on the pile spacing. Smaller pile spacing causes a larger interference between the piles. For very small pile spacing ($G/D \leq 0.15$), the pile group behaves as a single body. The interference effect diminishes for pile spacing of $G/D > 2-4$, depending on the pile-group arrangement.
2. For the two-pile side-by-side arrangement, the scour depth increases by as much as a factor of 1.5 at $G/D \cong 0.25$, while this value for the tandem arrangement is about 1.2 at $G/D \cong 2$. For the 2×4 pile group, the scour depth increases by a factor of 2 for $G/D \cong 0.25$ with respect to the corresponding single-pile values. Given the pile spacing, the scour depth is governed by the number of piles normal to the flow.
3. To improve the accuracy of the existing equation for the prediction of scour hole, a correction factor based on adding components of scour is proposed for pile groups. The prediction of scour hole based on the present correction agrees well with the observations. The Sheppard and Glasser procedure also provides a good agreement with the experimental data.
4. The number of variables associated with local scour depth at pile groups is large and larger when the pile group is skewed to the flow. These experiments are performed for pile groups aligned to the flow. More data are needed before generalized conclusions can be made.

Notation

The following symbols are used in this technical note:

D = diameter of cylindrical pile;
D_{proj} = sum of non-overlapping projected widths of piles;
D^* = effective width of an equivalent full depth pile group;
d_{50} = median particle size of sediment bed;
F = Froude number;
G = typical distance between piles in group;
g = acceleration due to gravity;
h = depth of approach flow;
K_d = sediment size factor;
K_G = correction factor for spacing;
K_{Gmn} = correction factor for spacing and type of pile group;
K_{hD} = flow depth–pier size factor;
K_I = flow intensity factor;
K_m = coefficient for number of aligned rows;
K_S = pier shape factor;
K_t = time factor;
K_α = pier alignment factor;
K_1 = shape factor;
K_2 = angle of attack factor;
K_3 = dune factor;
K_4 = correction factor for size of bed material;
m = number of piles inline with flow;
n = number of piles normal to the flow;
S = maximum equilibrium scour depth;
S_S = equilibrium scour depth at single pile;
U = mean velocity of the approach flow;
U_c = critical mean velocity for particle entrainment; and
σ_g = geometric standard deviation of particle size distribution.

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