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Temporal Evolution of Local Scour Depth around Side-by-side Piers

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ORIGINAL ARTICLE

ABSTRACT: Due to geotechnical and economic considerations, bridge designs often lead to use complex piers or pier groups. The estimation of temporal evolution of scour around bridge pier is important for design of bridge foundation. This study focuses on temporal variation of scour depth around two side-by-side piers with various distances between piers. Based on experimental data, an equation was developed based on new definition of equivalent pier diameter in Kothyari et al. (2007) equation for estimating the time evolution of scour depth by taking into account the effect of space between the piers. The results show that good agreement exists between proposed equation and measured scour data. It is also revealed that by increasing the distance between piers, the equilibrium scour depth around side by side piers decreases and close to values of single pier and scour depth reached to the isolated pier when G/D=6.

Keywords: Temporal Evolution; Scour Depth; Side By Side Piers, Equivalent Pier Diameter

INTRODUCTION

Occurrence of local scour around bridge piers is one of the main reasons for failure of bridges and is a process which develops with time and then reaches to equilibrium condition. Understanding this process and estimating the evolution of scour hole are important for bridge design. Estimating equilibrium scour depth around single pier has been investigated by many researchers (Breusers et al., 1997; Melville and Coleman, 2000; Sheppard and Renna, 2005), but few studies available on scour phenomenon around side by side piers. Scour pattern around group piers is different from single pier (Figure 1). The mechanisms which affect scour pattern around side by side piers, includes: reinforcing effect, sheltering effect, shed vortex and compressed horseshoe vortex.

Nouh (1986) performed a series of experiments to study the effect of transversal pier spacing on maximum clear-water scour depths at the piers. The pier diameter was changed in each test to provide a constant relative pier group size with respect to the channel width throughout the tests. It was found that the scour depths of the piers decrease as the transversal pier spacing increases. Scour around pile group with side-by-side and tandem arrangement were studied by Hannah (1987). The results showed that for two side-by-side piers, as the distance between piers increases, the effect of horse shoe vortex decreases. The results also showed that effect of reinforcement factor will be maximum when G/D=2.5 (G= space between the piers and D= diameter of the pier). Nazariha (1996) investigated the effect of pier spacing and flow angle of attack in different pier group arrangements, and presented a relation for estimating the maximum local scour depth. He also concluded that for G/D≥3, the maximum scour depth of side by side piers is independent of G/D. Ataie-Ashtiani and Beheshti (2006) conducted a series of experiments on various arrangements of two side-by-side pier. They concluded that the maximum scour depth is about 50% higher than the single pier value at G/D=0.25 and for G/D<0.25, the two piers act as a single pier. Zarrati et al. (2006) investigated the scour depth at groups of two piers in long term experiments. They concluded that in comparison with a single pier, horse shoe vortex caused the scouring to be more in group of two piers. Aghakhani (2010) examined the effect of a slot in reduction of local scour depth around side-by-side piers. The results showed that the maximum scour depth around side-by-side piers decreases with increase of G/D and reaches to a minimum value at G/D=1. Beg (2010) investigated the effect of mutual interference of bridge pier on the characteristics of scour hole in two side-by-side piers. He concluded that for G/D=7 the scour depth reached to the isolated pier, which indicated that the effect of mutual interference between the piers disappeared, so he suggested that two piers should be placed at G/D>7. Ataie-Ashtiani and Aslani-Kordkandi (2012) investigated the flow pattern around two-circular piers positioned in side-by-side arrangement. They concluded that the flow between two piers is accelerated into the scour hole so that it influences the vertical and transverse deflections of the flow around and especially between them. They concluded that between two piers, the magnitude of downflow and vertical turbulence intensity as well as turbulence kinetic energy are greater than that at the outer sides of two piers. Bed shear stresses have substantially large values between two piers, as much as two times in comparison to the other sides of the piers.

Temporal evolution of scour depth around single bridge pier has been investigated by many researchers (Kothyari et al., 1992; Melville and Chiew, 1999; Oliveto and Hager, 2002, 2005; Chang, 2004; Kothyari et al., 2007). Kothyari et al. (1992) conducted a series of experiments on temporal variation of scour depth around circular bridge pier with different diameters, sediment and under steady and unsteady clear-water flow conditions and developed a procedure for computing the temporal variation of scour depth. Melville and Chiew (1999) have presented a methodology for determining the time for development of equilibrium scour depth for a given pier, sediment and approach velocity. Oliveto and Hager (2002) presented an equation for temporal scour evolution based on a large data set. Also, their result showed that densimetric particle Froude number is the dominant parameter which controls the scour process. Chang et al. (2004) presented a relationship for evolution of scour depth at a single circular bridge pier under steady and unsteady flow condition. Kothyari et al. (2007) conducted extensive experiments and proposed a new relationship for the temporal scour evolution at bridge foundation elements based on Oliveto and Hager (2002) equation.

Physical and economic considerations often lead to pier groups, in which the direct application of the results derived from single piers maybe problematic (Landers and Mueller,1996). Looking at literatures show that all of the available relations for estimating the temporal scour evolution were obtained for single pier, therefore the goal of this study is to present a new relation for determination of scour depth evolution at side-by-side piers.

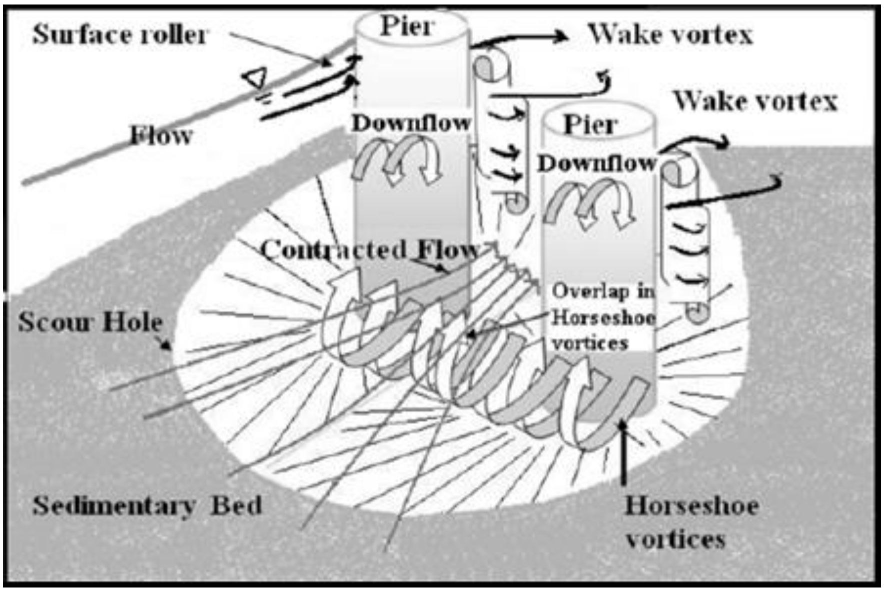

Figure 1. Sketch of flow pattern and local scour around side-by-side piers

MATERIALS AND METHODS

Dimensional analysis

The maximum scour depth in front of two side-by-side piers, d_s, which grows over time t, can be expressed as:

$$d_s = f\left(\rho, \upsilon, g.h_0, V, d_{50}, \rho_s, V_c, D, G, t\right) \quad (1)$$

Where ρ = fluid density, υ = kinematic viscosity, g = gravity acceleration, h_0 = flow depth, V = flow velocity, d_{50} = median diameter of sediment, ρ_s = sediment density, V_c = critical flow velocity, G= space between the piers, D= pier diameter and t=time.

Applying the Buckingham theorem on Eq.1, with considering ρ, D and V as repeatable parameters, the dimensionless parameters are obtained as follows:

$$\frac{d_s}{D} = f\left(\frac{h_0}{D}, \frac{V}{V_c}, \frac{d_{50}}{D}, Fr_p = \frac{V}{\sqrt{gD}}, \mathrm{Re}_p = \frac{VD}{\upsilon}, \frac{\rho}{\rho_s}, \frac{G}{D}, \frac{Vt}{D}\right) \quad (2)$$

By considering constant values for sediment size, pier diameter, discharge and flow depth and due to high Reynolds number (turbulent flow), the effect of V/V_c , h_0/D, D/d_{50}, Fr_p and Re_p can be negligible and Eq (2) yields:

$$\frac{d_s}{D} = f\left(\frac{G}{D}, \frac{Vt}{D}\right) \quad (3)$$

Experimental setup

The experiments were conducted in a flume 12 m long, 0.6 m wide and 0.6 m deep. Water was conveyed to the flume from an elevated tank by a pipe through an approach channel in which the discharge was measured by means of sharp crested rectangular weir and an ultrasonic flow meter with accuracy of 0.01 l/s. The flow rate and water depth in the flume were adjusted using a valve and a tailgate, respectively. The head over the sharp crested weir and the water surface were measured using a point gauge, sensitive to a variation of 0.1 mm. A mobile bed zone 0.3m long, 60 cm wide, and 0.25m deep was prepared at a distance 6.5m downstream of the flume beginning (Figure 2), and was filled with sediment of a median particle size d_{50}=0.9 mm and geometric standard deviation of σ = 1.25. A vertical circular pier of diameter *D*=2 cm was placed in the center of the mobile zone. According to Raudkivi and Ettema (1983) the effect of sediment size can be neglected (D/d50> 20-25). Also, the ratio of distance between the center of pier and flume wall to pier diameter is greater than 6.25, so the flume side wall will not affect the scour process (Raudkivi and Ettema, 1983). Two side-by-side piers used in the experiments, with spacing 0.5, 1, 2, 4 and 6 times of the pier diameter (i.e. G/D=0.5, 1, 2, 4 and 6)

The mobile bed was leveled before starting each test. The valve was slowly adjusted without causing any disturbance to the bed material until the preselected discharge was set. The uniform clear-water flow was fully developed for the required discharge. No significant scour

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was noticed during this period. The scour depths were recorded at different times from a scale attached to the pier and digital point gauge. In order to obtain the maximum scour depth, experiments were conducted in clear water condition, i.e., with V/V_c=0.95. The flow rate and flow depth were 0.024 m3/s and 0.13m, respectively.

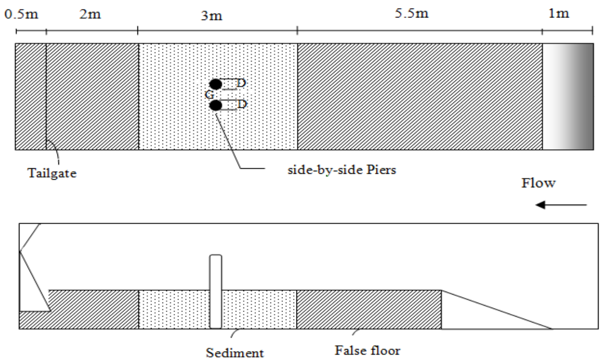

Figure 2. Flume-plan view and longitudinal profile

To find the maximum depth of scouring, experiments were continued until the equilibrium condition, that is when the variation of scour depth was negligible. This time was assumed based on Franzetti et al. (1994) and Ettema (1980) definitions. According to Franzetti et al. (1994), equilibrium condition achieved if Ut/D> 2. 10^6 and according to Ettema (1980), when depth of the scour hole does not change less than 1 mm during 4 hours of experiments, equilibrium condition is achieved. The primary experiments were conducted until 48 hours for the estimation of primary equilibrium time. About 24 hours was necessary in experiments of the present study to reach the equilibrium condition.

RESULTS AND DISCUSSION

For developing an equation for temporal scour evolution around side by side piers based on the available temporal scour evolution of single pier, equation of Kothyari et al. (2007) is used. The main reasons for selecting Kothyari et al. (2007) equation are independency with equilibrium time which is in doubt by various researches and extensive experiments for developing the equation. Kothyari et al. (2007) developed a relation for temporal scour evolution of single pier by relating the scour depth to the difference between the actual and the entrainment densimetric particle Froude numbers. The Kothyari equation is as follows:

$$Z = \frac{z}{z_R} = 0.272\sigma^{-1/2}(F_d - F_{d\beta})^{2/3}.\log T \quad (4)$$

$$t_R = z_R / [\sigma^{1/3}(g'.d_{50})^{1/2}] \quad (5)$$

$$F_d = \frac{V}{([(\rho_s - \rho)/\rho]g.d_{50})^{0.5}} \quad (6)$$

$$F_{d\beta} = \left[F_{di} - 1.26.\Sigma.\Sigma_s.\Sigma_{ca}.\beta^{\Sigma/4}.\left(\frac{R_h}{d_{50}}\right)^{1/6}\right]\sigma^{1/3} \quad (7)$$

where z = maximum scour depth, $z_R = (h_0 D^2)^{1/3}$, h_0 = approach flow depth, D = pier diameter, σ =$(d_{84}/d_{16})^{0.5}$= geometric standard deviation, T = t/ t_R, t = time, F_{di}=actual densimetric particle Froude number and $F_{d\beta}$= entrainment densimetric particle Froude number.

Hager and Oliveto (2002) proposed the following relation for F_{di} (10< D_*<150):

$$F_{di} = 1.08 \cdot D_*^{1/12} \cdot (R_h / d_{50})^{1/6} \quad (8)$$

where $D_* = (g'/\upsilon^2)^{1/3} \cdot d_{50}$= dimensionless grain size, υ= kinematic fluid viscosity, R_h= hydraulic radius, Σ = Σ_s =Σ_{ca}= shape parameter=1 (for circular pier), β= D/B and B= channel width.

Figure 3 shows the variation of measured and calculated dimensionless scour depth by using Kothyari et al. (2007) equation for single pier with D=4 cm. The results show that the calculated scour depths during the time are in good agreement measured data. Therefore, the goal of present study is defining the new definition of D in Kothyari et al. (2007) equation for estimating the time evolution of scour depth which takes into account the effect of space between the piers.

Figure 4 shows the variations of equilibrium scour depth around side by side piers (d_s) which is normalized by the equilibrium scour depth around single pier (d_{si}) against G/D. The results show that by increasing the distance between piers, the equilibrium scour depth around side by side piers decreases and closes to values of single pier. Different experimental source data like Ataei and Beheshti (2006), Beg (2010) are used to develop Eq. 9 for relating d_s/ d_{si} to G/D.

$$\frac{d_s}{d_{si}} = 1.24\left(\frac{G}{D}\right)^{-0.1} \quad (R^2=0.93) \quad (9)$$

As a similarity with Eq. (9) and due to the fact that the variations of scour depth around bridge piers is directly related to pier diameter, Eq. 10 can be obtained.

$$\frac{D_{eq}}{D} = M\left(\frac{G}{D}\right)^N \quad (10)$$

Where D_{eq}= equivalent pier diameter for side by side piers and D= single pier diameter in Kothyari et al. (2007) equation. To evaluate the coefficients M and N, the data of present study was used resulting in M = 1.287 and N = -0.07. So for calculating the temporal scour evolution of side by side piers, D_{eq} is substitute with D in Kothyari et al. (2007) equation.

A comparison of the estimated scour depths around side by side piers by using D_{eq} (Eq.10) instead of D in Kothyari et al. (2007) equation with measured data is shown in Figure 5, indicating good agreement with measured data, especially when the distance between piers increases.

To validation of Kothyari et al. (2007) equation by using new definition of pier diameter (D_{eq}), the data of Aghakhani (2010) were used. The results revealed that using D_{eq} (Eq.10) instead of D in Kothyari et al. (2007) equation give the temporal scour evolution of side by side piers within 20% error (Figure 6).

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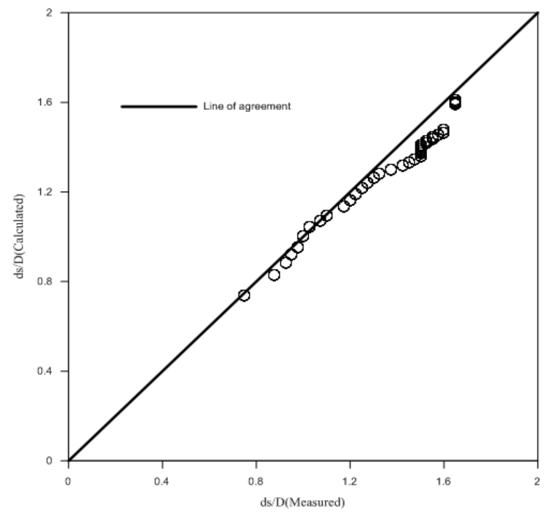


Figure 3. The variations of calculated dimensionless scour depth by using Kothyari et al. (2007) equation against measured data for single pier (D=4cm)

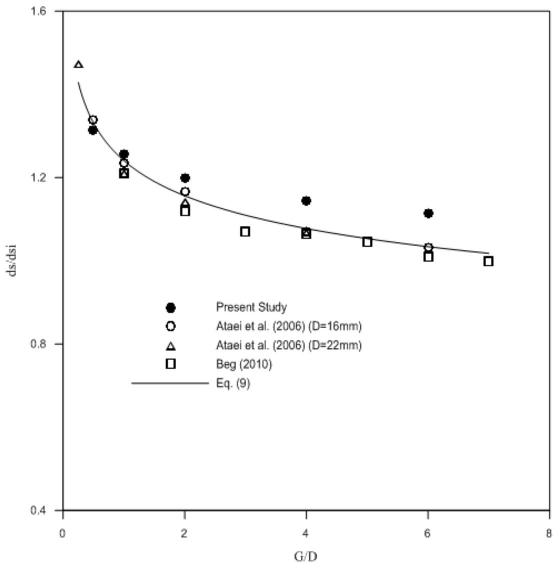


Figure 4. The variations of ds/ dsi against G/D

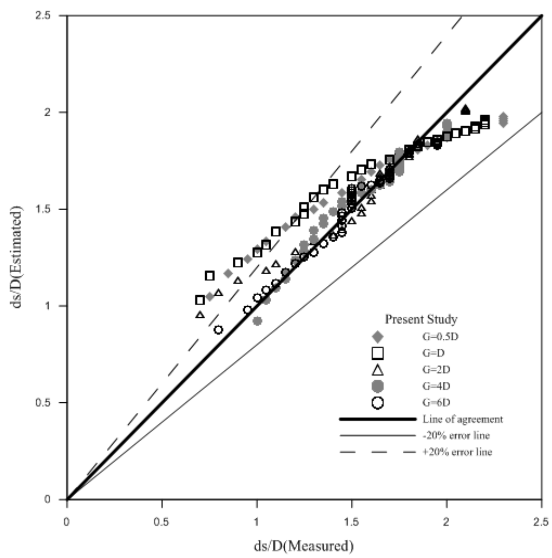


Figure 5. Comparison of the estimated scour depths around side by side piers by using D_{eq} (Eq.10) in Kothyari et al. (2007) equation with measured data

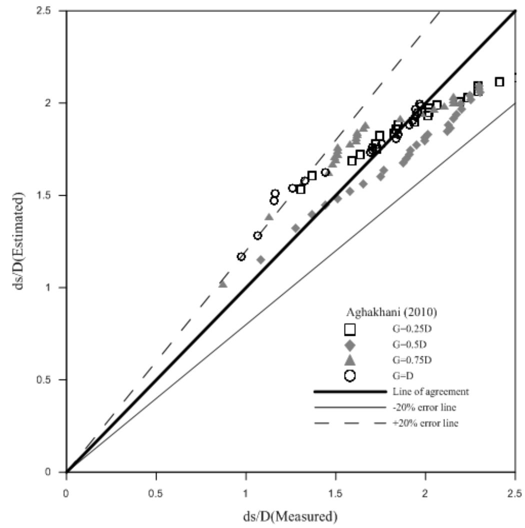
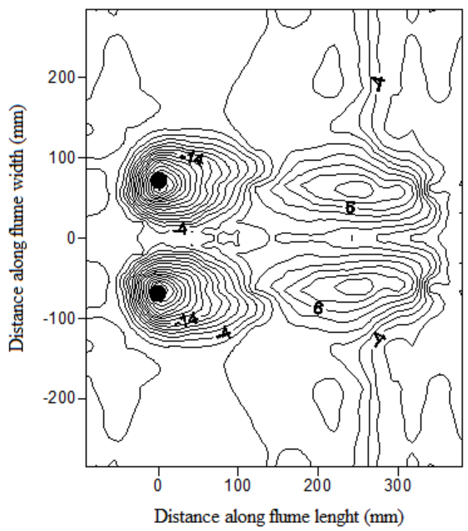
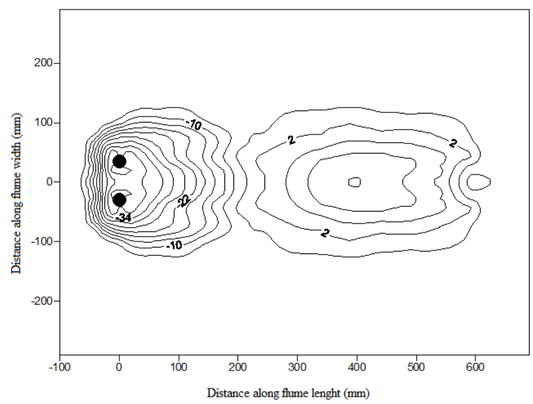


Figure 6. Comparison of the estimated scour depths around side by side piers by using D_{eq} (Eq.10) in Kothyari et al. (2007) equation with measured data of Aghakhani (2010)



(a)



(b)

Figure 7. The variations of bed changes around the side-by-side pier;a) G=2D; b) G=6D (Flow from left to right and units in mm)

The variations of bed changes in equilibrium condition for G=2D and G=6D are plotted in Figure 7. It is clear that, when the piers place close together, the interference between the horseshoe vortices caused the deepest scour depth in front of the piers. The results also

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show that by increasing the space between piers this interference decreases and at G=6D the scour depth became close to the single pier and two scour holes are formed separately.

CONCLUSIONS

An attempt is made to estimate the temporal evolution of local scour depth around side-by-side piers based on the available temporal scour evolution of single pier. The proposed equivalent pier diameter (D_{eq}) can be used in Kothyari et al. (2007) equation for estimating the scour depth evolution in side-by-side piers. An equivalent pier diameter (D_{eq}) is relate to (G/D) and the results show that by increasing the distance between piers, the equilibrium scour depth around side by side piers decreases and closes to values of single pier. Also, the results indicate that for G/D=6, the scour depth reaches to the isolated pier.

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