Numerical Modeling of the Effect of Pile Geometry and Pile Cap Leveling on the Local Scour under Inclined Pier Group

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Abstract

In this research, due to the importance of identifying the mechanisms affecting the scouring on this types of bridge piers, the effect of the geometric shape of the piles that installed under the inclined piers and also the effect of the pile cap leveling in the sedimentary bed have been investigated and the properties of the scouring around the inclined pier group was studied numerically and using the FLOW-3D software.The study of total shear stress in the flow bed at different leveling of the pile caps shows that of the highest shear stress was created when the pile cap position is at the same level with the river bed and by installing the pile cap at a lower level than the river bed, the maximum shear stress decreases. This may be due to the fact that in this case the distance between the pier group increases and the presence of the second pier decreases the flow rate in the pier group and different pier in the one pier group act as the two Independent piers in the formation of flow pattern.By comparing the final longitudinal sections of the scouring at different leveling of the pile cap, it is concluded that the largest reduction in scouring depth occurs in aerofoil-shaped pile caps and pile caps with the sharper nose and better aerodynamic shapes are good options to control the horseshoe vortices and will reduce the scouring depth around the inclined pier group.

Keywords:Scour, Pile geometry shape, Inclined pier group, FLOW-3D

1- Introduction

In fact, scouring is a natural process that is created by the erosion caused by the flow of water on the river bed and also formed near the bridges' piers and supports [1]. Scouring around the head of the piles and the pier of the bridges is one of the major problems of structures such as bridges whose piles are in the water of rivers with erosive flows. The erosion around the bridge piers causes the complete or local failure of some of the bridges. Once a river is in equilibrium state, the amount of input and output sediment is equal to each other. Naturally, a river, in order to achieve such an equilibrium state, shows the behaviors that ultimately leads to reach a physical equilibrium. Of course, annual floods are one of the most important factors in the destruction of this system and cause annual erosion in the river path.

Scouring occurs when the shear stress between the water passing through the river bed and the wall of the stream is increased from the amount of stress necessary to move the particles forming the river cross section [1]. Research indicates that the local scouring phenomenon around the piles of bridges is the main cause of the failure of the piles. In fact, the flow pattern affects the processes of erosion and sedimentation around the pile. Therefore, one of the important points to be taken into account in hydraulic designing of the bridges is the design of the pile and foundation geometry with regard to scouring. In terms of economic and geotechnical reasons, the inclined pier group is used in design of the piers of the bridges [2]. The first fundamental studies on scouring were made by Engels at the beginning of the 20th century and at the Zooner Laboratory in Germany (rouz-Inn) [1]. After this research, many studies were conducted by Chabert and Engeldinger at the Chago Lab. The results of this research show that the amount of scouring in different types of transparent waters and flood with live bed.

At the beginning of the 20th century, Larsen et al published their studies at the Iowa Hydraulic Research Center on the phenomenon of scouring around the bridges' piers. Other investigations on scouring in lateral walls of bridges abutments were conducted by Shen et al and Lane et al at the University of Colorado [1]. In 1931, Lee et al stated that the pier shape is one of the important factors that greatly affects the depth of scouring, due to the dependence of the power of the horseshoe vortex to the shape of bridge piers. The square, circular, rectangular, rounded and elliptical rectangular shapes, have the highest depth of scouring compared to the elliptical piers, respectively. If the cross-sectional shape of the bridge matches the lines of the water flow, the flow separation has been reduced that will have a great effect in reducing of scouring, so that, if the shape of the bridge pier is parallel to the water flow lines, the power of the horseshoe vortex power is reduced significantly which leads to decrease of scouring [3].

In 1996, Melville and Radwicky stated that in the real conditions, bridge piers were designed and constructed with different geometric shapes, and the cross-section of many piers have been changed with increasing the height [4]. In addition, Melville and Chiv in 1999 studied the effects of hydraulic flow conditions such as velocity and depth of flow on scouring. Their research showed that the effect of the flow depth on the maximum value of scouring is depend to the diameter of the aggregate particles in the river bed. This effect varies from relative depth of 1 for fine grain particles to a relative depth of 6 for coarse grain particles (relative depth is equivalent to the depth of water flow relative to the pier diameter).

Ataei et al. (2010) investigated the methods that presented by HEC-18 and Kollman, which were used to estimate the depth of the scouring around the bridge piles, and presented corrective equations for scouring depth estimation [6]. Amini et al. (2012) also investigated the effect of different distances between the pile and the foundation level on the scour depth, and provided a relationship for assessing the depth of scouring under different conditions [5]. Esmailivaraki et al., in 2012, conducted studies in this field, showed that the inclining of the pier to the upstream direction relative to the parallel plane with the water flow would increase the maximum amount of scouring [6].

In 2012, Zhou Chi Wen and Liu Geng King, conducted a numerically calculations and stated that CFD techniques, with the help of powerful water flow image processing method, are capable of displaying flow during scouring, which helps to detect the scouring mechanism and increase scouring over time. By performing these experiments, it was concluded that one of the important parameters for designing the bridge pier is the maximum depth of the scour hole, but the position where the maximum depth of the hole is located and the shape of the hole is different from the experimental results [7].

2-Material and Methods

The erosion model is used to simulate the transfer, erosion, sedimentation and displacement of sediments by fluid (can be defined for all materials with different physical properties). In this model, two concentration fields are used, one associated with suspended load, and another with the bed load. The displacement of suspended sediments occurs as a result of the localized pressure gradient change. The flow of input particles which contain suspended particles and particles that resulted from erosion of the river bed causes the formation of suspended sediments. The adjacent particles block the sediments in the river bed, that leads to fix these sediments and do not move simply, and they can be moved only if they become eroded at the fluid-bed interface and become suspended load. Also, the suspended load is converted to bed load if the deposition rate of the sediment is higher than the erosion rate of the bed. The part of the control volume in which solid particles are filled in it, represented by the symbol fs and the part filled with fluid is represented by the symbol f_L and the following Equation is written for it:

Equation 1)

$$f_s + f_L = 1$$

The suspended load increases the actual fluid viscosity, and this increase occurs as long as the volume fraction of the solid particle (fs), reaches to the cohesive volume fraction (f_{ace}). From this step onwards, the increase in suspended load does not increase the viscosity of the fluid, but also triggers the solid behavior of the particles. In these conditions, the fluid average viscosity is obtained from the following equation:

Equation 2)

$$\mu^* = \mu_f \left[1 - \frac{\min(f_S, f_{SCO})}{f_{SCR}}\right]^{1.5}$$

In Equation 2, μ_f is the molecular viscosity of the fluid, and f_{scr} is the critical solid fraction with a default value of 0.67. The parameter μ* is the increased amount of viscosity due to the presence of suspended load in the fluid and the maximum value of which is obtained in the critical solid fraction and is equal to 5μf. If the volume fraction of the sediment is greater than or equal to fscr, the density of the dense sediment is equal to the $f_{scr} \times \rho_s$ product. This relationship is one of the initial conditions of the model. The apparent density represented by the parameter $\bar{\rho}$ is represented as a linear function of the sediment volume.

Equation 3)

$$\bar{\rho} = \rho_L + f_s(\rho_s - \rho_L)$$

The parameters ρ_S and ρ_L are the apparent density of the sediment particles and the apparent fluid density, respectively. The drift phenomenon is defined as the deposition of sediment particles due to the inducing of buoyancy forces on them. In the simulated scouring model in Flow-3D software, sediment particles are considered as spherical shapes and are affected by fluid viscosity. Therefore, the sedimentation coefficient D_f is obtained from the following equation:

Equation 4)

$$D_f = \frac{d_{50}^2 \times (\rho_s - \rho_L)}{18\mu}$$

Therefore, the sedimentation rate is calculated by the following equation:

Equation 5)

$$u_{drif} = D_f \times f_L \frac{\nabla P}{\bar{\rho}} = \frac{f_L \times d_{50}^2}{18\mu} \frac{\nabla P}{\bar{\rho}} (\rho_s - \rho_L)$$

In equation (5), the parameter d50 is equal to the average diameter of the sediment particles, the parameter μ equals the fluid (water) viscosity, the parameter ∇P / ρ is equivalent to the mechanical potential gradient or the body acceleration or sediment particle acceleration. The value of ∇P / ρ can increase up to ten times the acceleration of gravity that leads to eliminate the numerical effect of the pressure fluctuation. By closing to the free surface of the fluid, the particle body acceleration is replaced by gravity acceleration (g). Sedimentation is a process that occurs only in the presence of solid particles, and if the control volume is completely filled with sediment, the coefficient fL will be zero and $U_{drif} = 0$

relationship will be formed. Also, in the Flow-3D model, the sedimentation coefficient required to calculate the buoyancy force is computed from the following equation:

Equation 6)

$$D_f = \begin{cases} Equation\ (17) and\ (18) \\ \left[\frac{f_s - f_{SCR}}{f_{SCO} - f_{SCR}}\right]^{-2} \left[1 - \frac{f_s - f_{SCR}}{f_{SCo} - f_{SCR}}\right]^3 \\ 0 \end{cases}$$

At the surface of sediments in the river bed, there is a shear stress that causes erosion and movement of sediment particles in the bed. This erosion is a function of fluid shear stress at the bed surface, critical shear stress, and the density of the fluid and sediment. The minimum shear stress required to lift the sediment particles from the fluid-active bed surface using the critical shields parameter is shown in the following equation:

Equation 7)

In the above equation, θcr is the critical shields parameter, and τ_{cr} is the shear stress that is applied by the water stream to the sedimentary particles at the beginning of motion. The purpose of this model is to estimate the amount of sediments that have been eroded from the bed surface. Hence, the shear velocity parameter $\sqrt{\frac{\tau}{\rho}}$ is defined for measuring the power of water flow that needs to lift the sediments from the bed surface, and the rate of removal of sediment from the bed (u_{lift}) can be obtained using the follow equation:

Equation 8)

$$u_{lift} = \alpha n_s \sqrt{\frac{\tau - \tau_{cr}}{\bar{\rho}}}$$

Where, ns is the normal vector of the bed surface, α is a dimensionless parameter indicating the possibility of the lifting of the sediment from the bed, and is usually equal to or less than 1. In this model, the equation (9) is used to obtain the natural angle of sediment placement in the river bed. In equation 22, n and g are the normal vector of the surface and gravity vector, respectively. If the flow is constant, the minimum slope where the scouring hole walls can be stable can be determined according to the internal friction angle of the sediment particles. If the internal friction angle of the sediments is high (such as clay), that is, the stability of the wall at a steep slope is high. In materials where the angle is low (like sand), the scouring hole wall has a lot of tendency to failure and move forward.

Equation 9)

$$\theta = \frac{n}{|g|}$$

The critical shear stress that required to erosion the inclined surface in Flow-3D software, can be calculated with considering the effect of the internal friction angle of the sediments, which is one of the input variable of the model, and calculated using the following equation:

Equation 10)

$$\tau_{cr} = \tau_{cr}^{0}\sqrt{1 - \frac{sin^2\varphi}{sin^2\xi}}$$

According to the above equation, if the natural slope of the sediments is equal to their internal friction angle (ξ= φ), the critical shear stress will be equal to zero ($\tau_{cr} = 0$). This condition
means that the bed surface will be eroded due to any shear stress which applied on it. Also, if the relation φ>ξ is established, the relation ($\tau_{cr} < 0$) will be established, that is, the sediments will erode even if shear stress does not exist. This relationship also indicates that as the internal friction angle of the sediment particles increases, if the wall slope (φ) is increased, the scouring hole wall will also be eroded without any shear stress ($\tau_{cr} = 0$) [10]. The motion of suspended sediments in the system is expressed by the equation called the convection-diffusion equation. By adding expressions that related to drifting and lifting of the sediments, equation (23) can be written as follows:

Equation 11)

$$(\cdot$$

In Equation 11, U is a fluid velocity and the parameters u_lift and u_drift are equal to the sum of the lifting and sedimentation rates of the particles, respectively. In general, the Flow-3D erosion model uses a simple and direct method to simulate erosion and sedimentation in three-dimensional flows. The simulation results indicate that the models created in three-dimensional state are in good agreement with the experimental conditions. In previous versions of this software, there were limitations in creating the correct scouring model, which in the new version (v. 11.2), these limitations have been resolved. For example, in the previous version it was not possible to simulate the coarse aggregate particles, and if this type of particles were simulated, the hypothesis governing the sedimentation in the model was ignored. In general, the bed load should be simulated in a model in which sediment particles should slipped or rotated on dense bed (or suspended in fluid flow). Also, in the case of erodible beds, it was only possible to define a specific type of particle in the model [8]. According to the preliminary studies carried out in this field, it is possible to simulate the scouring model of the inclined bridge pier with the help of the erosion equations provided in this section of the paper.

Exprimental Data

In this research, flow and scouring modeling around the inclined pier of the bridge is performed on the group of the pile with different geometric shapes. One of the most important parts of the numerical studies is to measure the precision of the simulation model. In this study, to determine the precision of the model, the scouring depth around the inclined pier of the bridge, which is located on the cubic foundation, has been compared in two cases; one was the simulation by the Flow-3D software, and the other was the empirical tests conducted by EsmailiVaraki et al. [1] in the Hydraulic Lab of the University of Guilan.

Due to the fact that the laboratory model is at a scale of 1.190 compared to the actual sample of the 8th bridge of Ahvaz, this study simulates and investigates the flow in a channel with the length of 6 m, the width of 0.92 m and the height of 0.6 m. The channel profile simulated in this model is shown in Fig. 1. Also, the geometric characteristics of the models of the bridge piers that located on the pile group with different geometric shapesare represented in this figure. In Table 1, the hydraulic parameters of the flow used in this study are written.

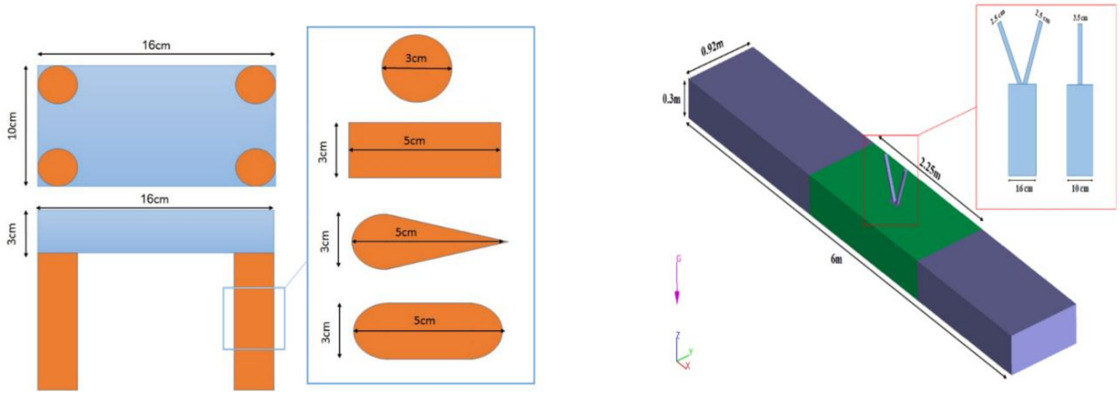

Figure 1: Geometric characteristics of the inclined bridge pier and the group of the pile placed beneath the pier

Table 1: Geometric characteristics and hydraulic flow parameters used in current research models

Model	Relative Velocity (U/U_c)	Relative Depth of Flow (y/D_*)	Relative Foundation Leveling (Z/T_{pc})
Inclined bridge pier on the cubic foundation	0.95	1	At the same level with the bed
Inclined bridge pier on the cylindrical pile group	0.95	1	-2, -1, 1
Inclined bridge pier on the rectangular pile group	0.95	1	-2, -1, 1
Inclined bridge pier on the rounded rectangular pile group	0.95	1	-2, -1, 1
Inclined bridge pier on the aerofoil-shaped pile group	0.95	1	-2, -1, 1

The amount of scouring around the piers depends on many parameters and each of these factors has a special and different effect on the scouring mechanism that may increase or decrease the erosion of the river bed around the bridge piers. These parameters include the type of fluid and the amount of bed sediment, the pier geometry and the hydraulic specifications of the flow, and they can be expressed in the form of the following equation:

Equation 13)

$$f_1 = (y, d_s, D, D_p, T_p, d_p, l_m, l_n, D_{50}, Z, U, \rho, \mu, \alpha, t, t_e)$$

Where y is the depth of flow, ds is the scour depth, D is the bridges' pier width, Dp is the width of the pile cap, Tp is the thickness of the pile cap, dp is the pile diameter , lm is the distance of the piles in a row, 1n is the distance of the piles in a column, D50 is the diameter of 50 percent of particles which have a smaller diameter compared to it, Z is the leveling of the pile cap, U is the average velocity of the flow, ρ is the density of the water, μ is dynamic viscosity, g is gravity acceleration, α is the angle of piers inclination in the parallel plane with the flow, t is the time since the start of the scouring and t_e is time to reach the scouring equilibrium. Fig. 2 shows the important geometric parameters of the inclined pier group.

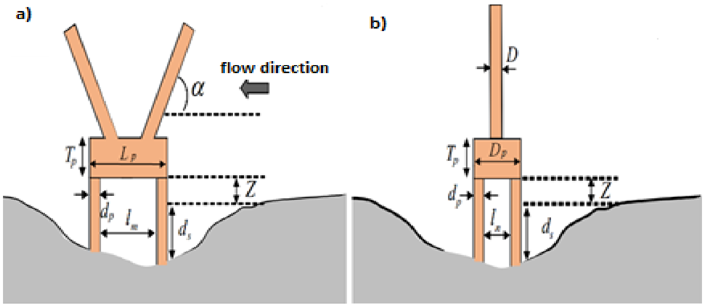

Figure 2: Geometric Parameters of the inclined pier group
A) In direction of the flow, b) Against the flow

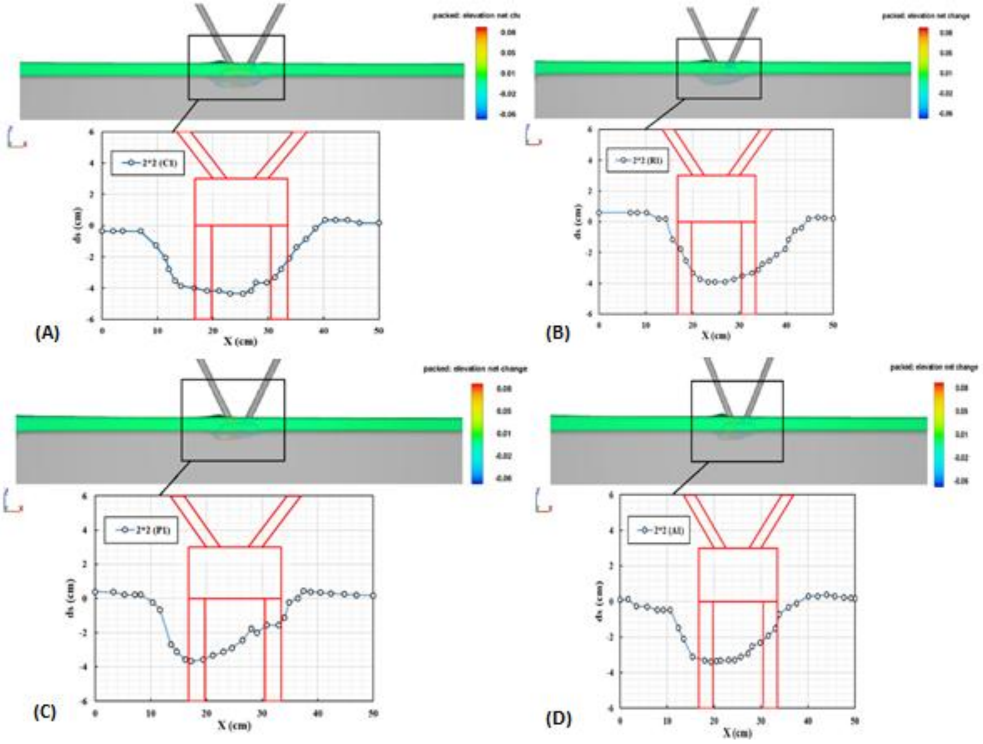

Figure 3: Longitudinal profile of scouring around the inclined pier group with piles that have different geometric shapes

A) C1(Circular) B) R1(Rectangular) C) p1(Rounded Rectangular) D) A1(Aerofoil)

As shown in Fig. 3, the aerofoil-shaped pile has a better effect on reducing scouring than other geometric shapessuch that the maximum scouring depth around the inclined pier group using an aerofoil shaped pile is 36.3 cm, while the maximum scouring depth for cylindrical (circular), rectangular and rounded rectangular piles is equal to 18.4, 2.91, 3.59 centimeters, respectively. The greater effect of the aerofoil pile is related to its geometric shape, which reduces the lifting vortices. Figures (4) show the scouring hole around the inclined pier group and the column diagram of the reduction of the maximum scouring depth percent using piles with different geometric shapes than the cylindrical pile, respectively.

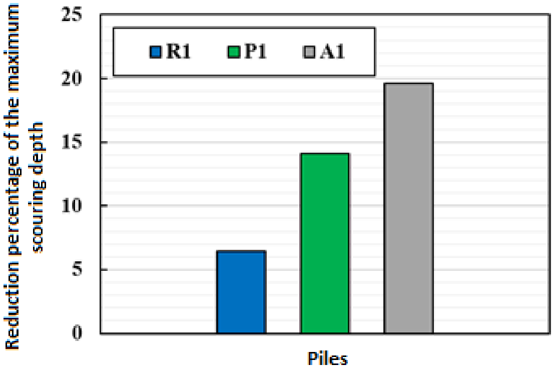

Figure 4- Reduction percentage of the maximum scouring depth with the piles which have different geometries than a cylindrical pile

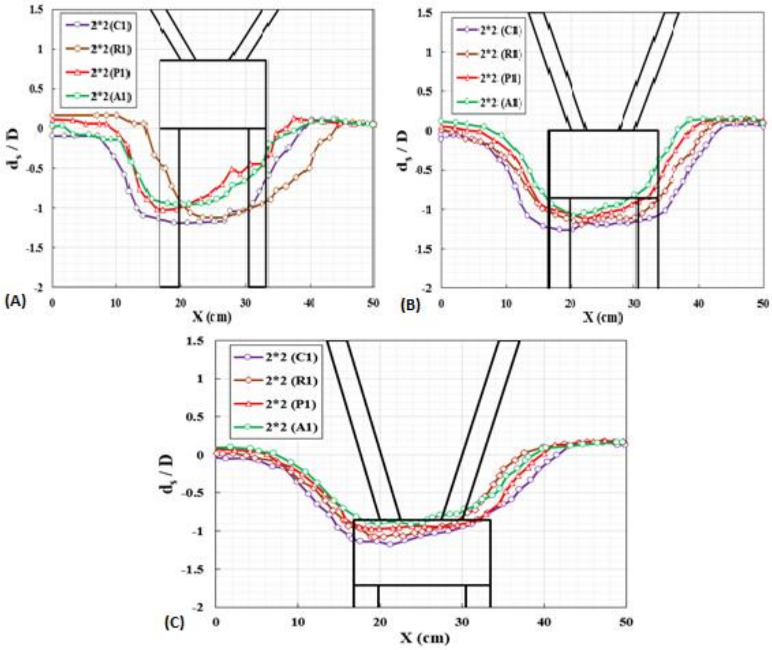

Figure 20: Final longitudinal sections of the scouring at different pile cap leveling

A) Above the bed ($Z/T_p=0$); B) in the same level as the bed ($Z/T_p=-1$); C) lower than the bed ($Z/T_p=-2$)

By comparing the results of the maximum scouring depth at different leveling of the pile caps, it is concluded that the largest reduction in scouring depth occurs in aerofoil-shaped pile caps and pile caps with the sharper nose and aerodynamic shape are good options to control the horseshoe vortices and will reduce the scouring hole depth. Also, when the pile cap is at the same level with the bed, the penetration power of the flow into the space below the pile cap has been increased, which increases the power of the flow erosion and the maximum scouring depth occurs at this level.

In this research, the geometric shape of the piles installed under the inclined piers and pile cap leveling on the sedimentary bed has been studied and the effects of them on the properties of scouring around the inclined pier group have been investigated numerically by the FLOW-3D software.

5-Conclusion

1- The study of the longitudinal sections of the scouring around the inclined pier group shows that the aerofoil-shaped pile has a better effect on reducing scouring than other geometric shapessuch that the maximum scouring depth around the inclined pier group using an aerofoil shaped pile is 36.3 cm, while the maximum scouring depth for cylindrical (circular), rectangular and rounded rectangular piles is equal to 18.4, 91.3, 59.3 centimeters, respectively. The greater effect of the aerofoil pile is related to its geometric shape, which reduces the lifting vortices.

2- The greatest amount of scouring occurs when the pile cap is at the same level as the river bed (Z / Tp = -1). In this condition, the empty space below the pile capgradually increases and some of the water flow penetrates it, causing erosion and scouring around the pile groups. One of the important points is that in this case, the geometric shape of the pile group is effective in reducing erosion and scouring that occurs under the pile cap. Under the same conditions of the pile cap leveling, the aerofoil-shaped pile caps have the lowest size of scouring hole and erosion amount.

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