The Behavior of Scouring Around Multiple Bridge Piers Having Different Shapes

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Abstract. In this research, a numerical simulation was conducted to study the behavior of the scouring pattern and the effect of spacing between bridge piers at specified hydraulic conditions such as velocity, depth of flow, and the sediment effective diameter. Moreover, the cross-section shape of piers and their effect on the scouring depth around bridge piers was studied, using Computational Fluid Dynamics (CFD), ANSYS (Fluent) software. A comparison of the simulation results obtained with previous laboratory investigations was done to verify the validity of the numerical model. Generally, the scour pattern using the CFD software gave good agreement with the experimental study. A reversed proportion between scour depth and the spacing between piers were noticed, as pier spacing increase the scour depths decrease, for the spacing ratios were 2, 3.5, 4.6, 5.5, and the maximum scour depths were 32, 34, 37, 50 mm respectively. The results show that the minimum scouring depth happened with triangle-noise pier, then with oblong pier, and the maximum was with pier having a circular section. Moreover, results show that the maximum scouring depths at the center pier are 22, 29, and 36 mm for these shapes respectively.

1. Introduction
The problem of scouring is usually complex and difficult to be evaluated especially when the flow conditions were inclusively turbulence. Erosion caused by the flow around bridge piers in alluvial streams is one of the important hazardous problems in the field of river engineering. In many respects, bridges interfere and/or affect the natural function of the river, and special attention is adopted during the design of a bridge. Many bridge failures have occurred due to an undermining of their foundations. Therefore, in order to minimize the risk of failure, many requirements must be recognized and considered, such as site selection, hydraulic analysis (backwater effect, mean velocity, depth of scour at the piers), channel adjustment, hydrologic analysis (stage-discharge curve, maximum flood of record and frequency of occurrence), and the design and dimensions of the bridge itself [1]. The major scour depth usually occurs during floods with unsteady-state flows which may even have multi currents directions compared with the normal flows. Therefore, the economical design with safe consideration of bridge piers must depend on accurate estimation of expected maximum scouring depth for the stream bed around bridge piers during its anticipated life, so that the foundation can be taken deeper to prevent threatening the stability of the structure.

The scour depth in the turbulence flow conditions was of considerable complexity and it was difficult to be evaluated. The interaction between flow properties and sediment characteristics is not easy to be...
quantified. Therefore, there are as many theories and formulas that were investigated. And there are many investigators and researchers have been directed toward the study of scour at a single pier, while not that much information is available which concerning the more complex nature of local scour around adjacent piers or group of piles. Theoretical developments for scouring problems are limited, many investigators tried to solve the complicated flow field interaction with the transportation of sediment, the physical model seems to be promising pursued estimating the expected depth of scouring [2, 3] but they are usually at high costs. As well as the use of numerical models will provide more flexibility, and avoiding limitations of physical models. So numerical analysis using CFD techniques was an adequate alternative for the physical model.

The length of a bridge and minimum span between piers (in addition to structural considerations, pier geometry and type, pier loading, and the soil bearing capacity) is hard to decide. That decision requires an estimation of the backwater effect and the acceptable scour that will scour in flood flows that have various magnitudes. The exception being that the shorter bridges will cost less, but will create more backwaters. The rise in stage upstream of the bridge must be restricted because of increased damage to the riverine area which would result from more frequent floods.

Although design criteria suggest that the spacing between piers and piles should be kept as far as possible from each other, and must cause minimum disturbance and obstruction to the streamflow. Reduction of scour can be achieved by utilizing auxiliary protection structures [1, 4] such as the placement of additional smaller piers upstream the main piers, this will reduce the scour near the main piers by breaking the incident current and weaken the strength of the vortex system. As well as, the scoured material will be deposits downstream at the main pier.

The aim of the present research is to achieve the following objectives:

- Developing a numerical model for simulating the depth of scouring using ANSYS CFD software.
- Investigating the spacing influence between the bridges piers on the maximum scouring depth.
- Defining the feasible shape of bride piers that produce the minimum scouring depth.
- Checking the validity of the CFD model compared with results obtained by laboratory investigations.

2. Theoretical Aspect of Scouring Phenomenon

Many investigations have been implemented to carry out and estimate the scouring depths around bridges piers concerning different flow conditions, piers shapes or geometry, and bed material, herein general review and definition will be presented.

2.1. Shape of Piers

[5] has classified the shapes of the pier into two types; First pier with blunt-nosed, which sufficiently induces an extended field of pressure that produces a hydraulic separation of the boundary layer in three-dimensions. Thus, the occurrences of maximum scouring depth will be at the nose of the pier, moreover a minimum influence on the depth of scouring will be produced if the pier of blunt-nosed shape is aligning with the direction of flow. Second the piers having sharp-nosed shape, no vorticity would be created at the edge of such piers. The maximum scouring depth would occur at the end downstream of the pier since the system of vortex always exists around the pier.

2.2. Type of Scour

Scour that can occur at the site of bridge piers can be classified as; natural scour of the stream bed is due to the river morphology, progressive degradation, which occurs over relatively long reach and long time. General scour that may occur due to the contraction of the cross-section and rebuilding the levees of the channel due to resistance produced by the presence of the bridge piers and earthen approaches. And an increase in flow velocity resulted from the reduction in the flow area that will
cause an increase of shear stress at the bed, so there is an increase in the power of stream and turbulence at the constriction causing the transportation of the bed materials. That movement will cease when the depth has increased and the velocity has reached the condition that the boundary shear is equal to critical tractive force. The second type is the local scouring is defined as an abrupt lowering of bed elevation, especially at the obstruction vicinity as a consequence of local non-uniform three-dimensional flow field deflections and disturbance around piers. It should be considered that various scour types may occur simultaneously, so the ultimate scour depth must be determined by appropriately combining these effects [1].

2.3. Bed Conditions
General and local scouring occur under two conditions of bed; Scouring occurs under the clear-water condition when the sediment upstream the scour site is not disturbed even though the water may contain a heavy suspended material finer than bed material. The scour depth gradually increases with time, the sediments are transported from the scour site but not replaced by the inflow load, and the erosion continues until maximum limiting value is reached the equilibrium condition. Live-bed scour is a scour with sediment transport, where the scouring site receives sediment from the inflow load. The depth of scour increases initially and varies with time because of the influence of periodically dumping of sediment in the site of scouring (moving bed form). The condition of equilibrium will be reached when the amount of transported sediment is equal to that removed.

3. Investigation of Scouring around Bridges Piers
The numerical models are characterized by a wide range of flexibility to avoid the critical limitation in physical ones. Many studies have been conducted using numerical models to investigate and cover different conditions of flow and the geometry of piers that affecting the scouring depth around the bridge piers.
Mathematical modeling of flow and Van Rijn formula of sediment transport, (RNG) k-ε model, was used by [6] to investigate the influence of pier cross-section using the model capability of prediction. The study demonstrated that the hydro-morphological model in three-dimensions can be estimated closely the scouring around bridge piers effectively, with different shapes of piers cross-sections. Significantly, the prediction of the depth of scouring located at the pier nose with various cross-section shapes of bridge piers. Also, they were found that the capability of model prediction depends on the characteristics of flow around the circular pier, not only the shape geometry of the pier.
An investigation of Bicon-Cave longitudinal shape of the bridge piers concluded that the bed shear stress has significantly reduced with the use of that shape in their experiments. [7]. For that purpose, multi numerical simulations that have been implemented to carry out the depth of scouring using a Finite Volume approach. The study demonstrates that the shape of longitudinal Bicon-Cave bridge piers causes a reduction in bed shear stress with a percentage of 10 % to 12 % at the conjunction site where the pier and bed are connected.
[8] developed a new method to estimate the transitory variation of scouring depth and final scour extension around the bridge pier. Accordingly, they used the rules of physical modeling for rivers, a simple method was established for physical modeling of local scouring around bridge piers. Depending on the sediment density scale, low-density sediment with \( \rho_s = 1.05 \text{ kg/m}^3 \) was considered in the model for scouring experiment. The results of the experiment including a temporal variation of scour depth, equilibrium time and scour depth and final extension of the scour hole were then scaled up to the prototype. Finally, empirical equations were utilized to predict maximum scour depth for the typical prototype. Results showed that the value of equilibrium scour depth from the present method was in the range of empirical equation prediction.
[9] studied the effect of using the circular and the square collar types which used on a pier having a cylindrical shape. A reduction in the scouring depth was achieved, when using the two types of collars, especially under the bed elevation. The research also showed that a significant reduction in the scouring depth was determined when the square collar used compared with the use of a circular collar.
The obtained percentage of reduction in the rate of scouring was 70% for the square collar, while for the circular collar was 50%, those percentages as a comparison with the simple pier having no collar. [10] implemented an experimental study to demonstrate the influence of the distance between bridge piers. As well as he studied the influence of the cross-section shape of piers on the scouring depth around the bridge piers. Moreover, an empirical equation has been derived to predict to estimate the scouring depth for the hydraulic conditions which have been adopted in a laboratory study conducted using laboratory canal having 0.6 m wide, 0.2 m depth, and effective length of 5.6 m. The experiments were conducted under a flowrate of 2.443 l/sec. The predicted equation has acceptable results compared with the laboratory measurements.

4. Parameters Influencing Local scour
Various parameters contribute to the local scour phenomenon, some of which are difficult to quantify, however, they may be grouped under the following categories; First, parameters relating to structure (bridge and piers geometry), including piers geometry (shape and size), absolute size compared with channel width, pier spacing, piers orientation concerning the flow direction. Second, parameters relating to the stream, including the flow rate, velocity, and depth of flow, alignment of the channel, stream slope, cross-sectional shape, flood characteristics and frequency of occurrence, and overbank consideration. Third, parameters relating to streambed sediment, including shape factor, specific weight, size, and size distribution of sediment.

5. Summary of the scouring formulas
There are numerous common scour formulas used to predict the scouring depth. It should be realized that can be drawn formulas and design graphs can at the best yield only rough estimates of scour depths to be expected around the bridge piers, there is no scour depth predicting formula which enables designers to confidence estimation of the maximum depth of scouring [1]. Prediction of scouring depth must always be tempered with judgment because the field situation is always going to be complex. So, the prediction formulas give widely variation of estimation of scour depths when they applied to a particular site, that lack in the consistency would be due to different reasons, such as the un ability of many studies to distinguish between various hydraulic conditions of the transportation of sediment [11], and beside of depending these formulas upon limited ranged of data. In the present study, the formula predicted by [12] was used to estimate the depth of scouring, according to the governing limitation of the formula that works on.

6. Theoretical Aspect of CFD Model and Description of Mesh (Grid)
Numerical modelling includes the solution of the Navier-Stokes unsteady flow equations. These equations are depended on the conservation of mass, and momentum assumptions for moving mass of a fluid. In the case of absence assumption of sources/sinks of the mass and the momentum, the concept of conservation of mass is described by equation having the following partial differential form of:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \]  \hspace{1cm} (1)

Where; \( \rho \) = density in Kg/m\(^3\), and \( v \) =velocity of the fluid in m/sec. The conservation of momentum similarly described by equation having the following partial differential form:

\[ \frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho vv) = -\nabla p + \nabla \cdot \tau \]  \hspace{1cm} (2)

Where; \( p \) =pressure in (N/m\(^2\)), and \( \tau \) =Stress tensor in N/m\(^2\). The equations of transport are solved with various turbulence quantities to represent the influence of turbulence on the fluid flow.
7. CFD Model Set-Up

The set-up of the computational fluid dynamic model can be defined by the steps described in the following articles:

7.1. Hydrodynamic model

The hydraulic simulations will be described as run using ANSYS (Fluent) software. For the validation study, an open channel flume model which has been proposed by [10] was used in this study, the flume having a width of 0.3 m, water depth is equal to 26.1 cm. Three different shapes of piers were used, two of them (cylindrical with 4.63 cm and the rectangular with round –nosed shape) are done by the experimental study by [10] the third pier shape is rectangular with triangular nosed all the piers have the same width which equal to 0.0463 m. With the 3D model, it will possible to predict a grid that resolves the vertical stream-wise and transverse directions with acceptable accuracy. The k-ω SST turbulence was adopted with standard wall functions. So the range of turbulence models classified as Reynolds-Averaged Navier-Stokes (RANS) models. They are approximations of time-averaged which are used widely in the industrial applications. The k-ω SST model is known with good behavior in separating fluid flow and with adverse values of pressure gradients [7]. And to conduct the description of the CFD simulation: the second-order scheme of discretization schemes was used for the formulation of pressure, momentum, velocity, the kinetic energy of turbulence, and the dissipation equations. A time step of 0.01s was used throughout to keep the simulation stable. Fully developed turbulent fluid flow that was specified was used at the inlet by using a separate RANS simulation upstream of the piers. Fig.1 shows the geometric of the domains used in the modelling. A specified pressure inlet the upstream boundary was used. When a free surface is simulated in FLUENT software, the users have to specify a free surface which is approximated as a flat and rigid with free slip condition. Simulating free slip wall boundary condition has been achieved by using wall boundary condition with zero specified shears. According to results obtained by [13], if the flow velocity is 12 times the pile diameter away from the pile center, it can be considered that the area has an insignificant pile influence. Therefore, to achieve non-reflecting characteristic boundary conditions in the numerical model, the outlet boundary at the exit is placed at 12D downstream of the pier. No-slip boundary conditions are applied on the bottom of the wall, cylinder surface, and the sidewalls of the channel. An O-type about 5 Million grid size has been used for the region close to the cylinder as shown in Fig.2 that produced by FLUENT Software. In this region, the finest grids are closest to the cylinder.

7.2. Morphological model

In addition to the hydrodynamic flow behavior, sediment transportation is considered a significant parameter that should be precisely modeled in the scouring simulation. The transport of sediment is considered to occur immediately when the shear stress at the bed exceeds the critical value of shear stress of the sediment particle, (this is called the incipient motion of sediment) [14]. After the initial motion, the rate of sediment transport will be considered as another criterion key used to describe the quantity of scour development as well as describes the scouring levels at a specified time. So, the incipient motion of the rate of sediment transport and sedimentation must be measured, as they are key parameters that determine the quality of any sediment transport model. The most common method used to predict the sediment inception is based on the excess critical value of shear stress [15].
Fig. 1. The geometric details of the computational domains used in the modelling: (a) Cylinder pier, (b) Oblong pier and (c) Triangle-nose pier.

Fig. 2. Hexahedral grid layout in the computational domain.

The critical shear stress of sediment proposed by [16] is defined by:

$$\tau_{b,cr} = \rho g (s - 1)d_{50} \theta_{cr}$$

(3)

where $\tau_{b,cr}$ = critical sediment shear stress in N/m$^2$; $s$ = relative density of particle in Kg/m$^3$; $d_{50}$ = median diameter of sediments in mm; and $\theta_{cr}$ = critical Shields number (dimensionless), which is determined by:
\[
\theta_{cr} = \begin{cases} 
0.24D_e^{-1}, & D_e \leq 4 \\
0.14D_e^{-0.64}, & 4 < D_e \leq 10 \\
0.24D_e^{-0.10}, & 10 < D_e \leq 20 \\
0.013D_e^{0.29}, & 20 < D_e \leq 150 \\
0.055, & 150 < D_e 
\end{cases} 
\] (4)

Where; \(D_e = \frac{d_{50}(\zeta - 1)g/\theta^2}{3}\); and \(\theta = \) kinematic viscosity coefficient; In reality, the riverbed is not always flat despite Equation 3 being designed for the flat riverbed. The formula used to estimate the critical shear stress in dimensionless form was;

\[
T = \frac{(\tau_b - \tau_{b,cr})}{\tau_{b,cr}} 
\] (5)

Where; \(T = \) dimensionless form of the critical shear stress; and \(\tau_b = \) the sediment shear stress in N/m². Once \(\tau_b > \tau_{b,cr} \), the triggering value of removal in the current simulation model of sediment transport, the incipient sediment motion is immediately taking place.

After the sediment movement begins, the rate of sediment transport will take place as another key parameter that describes the scour process. The rate of sediment transport is characterized as the movement of solid particles, in dissolved and particulate form, that goes over a given transverse cross-section of a stream with a determined fluid flow during a given unit time, and its estimation can be conducted by van Rijn (1986):

\[
\frac{dh}{dt} = 0.00033 \rho_s (\Delta g d_{50})^{0.5} \frac{D_e^{0.3}}{n} T^{1.5} 
\] (6)

In which \(h = \) riverbed elevation in m; \(t = \) time in sec.; \(n = \) sediment void ratio (taken as 0.4 based on (Melville 1975; Melville 1997)); \(\rho_s = \) sediment material density in Kg/m³; \(\Delta = (\rho_s - \rho) / \rho = \) relative density; \(\rho = \) fluid density; \(g = \) acceleration due to gravity; and \(T \) should be obtained following Equation 5.

[17] had been inserted these equations in a computer language written in C++ and embedding it in the CFD code [18] as a UDF. The simulations were conducted for a single circular pier having an oblong shape, and the pier was fixed with different attack angles. The study illustrates that the dynamic mesh technique was coupled with a Large Eddy Simulation method using a High-Performance Computer (HPC) in parallel mode. He proposed that the bed of the river can be updated according to the calculated shear based on the riverbed elevation (h) for each time step of the scour simulation.

8. Results and Discussions

The simulation results will be presented here to show the influence of horizontal distance that apart between the bridge piers, as well as presents the influence of pier cross-section on the scouring depth. Moreover, to demonstrate the accuracy of the CFD simulation model, a laboratory study conducted by [10] was chosen, and the same hydraulic conditions were adopted in the simulation of the numerical model. A comparison was implemented between the results obtained from the numerical simulation and those obtained by the experimental study to check the validity of predicting results of numerical approaches, so it considered as a verification of the CFD model.

8.1. Influence of bridge piers spacing on the scouring depth

In this section, the effects of the horizontal spacing between bridge piers on the maximum depth of scouring have been discussed. The spacing ratio (x/b) in this study is equal to the clear spacing between the piers (x) to the pier width (b). Different ranges of spacing have been considered here (x/b=2.0, 3.5, 4.6, and 5.5). For results validation, a comparison with an experimental study reported by [10] has been done for the circular pier case. Fig.3 shows the maximum depth of scouring for the middle pier in the domain with different ranges of spacing ratios. The general behavior for the maximum scouring depth shows good agreement with the experimental study. From the figure, it also can be seen that the effect of spacing after x/b=4.6 could be neglected since there is no significant change in the maximum scour depth after this ratio.
For a validation purpose, Fig. 4 shows a comparison between the CFD study and the laboratory study done by [10] for the relation between the scour depth at the equilibrium state at a different space to width ratios. It can be clearly notice that for the both studies the behaviour of scour depth is the same, the values of scour depth in case of CFD study are less than in the laboratory study, this deficiency may be because the use of URANS models instead of using resolving models such as large eddy simulation (LES) which is needed very high requirements especially in case of scour around obstacles [17].

Fig 5, and Fig. 6 show the longitudinal and vertical sections of the bed at the deepest scour depth for a circular bridge pier and at a different space to width ratios. It can be clearly noticed that the maximum scour depth increase with decreasing the horizontal distance between piers until space to width ratio equal to 4.6, after this ratio the effect of horizontal spacing between pier has an insignificant effect on the maximum scouring depth of the bridge piers.

8.2. Influence of shape of bridge pier on the scouring depth

In addition to the spacing effect on the scouring depth, the effect of the pier shape has been also investigated in this study. Three types of pier shapes have been considered (circular, oblong and tri-nose pier) all shapes have the same width (b). Fig. 7 illustrates the effect of pier shape on the maximum scouring depth for x/b=4.6. The results show that the circular pier has the maximum scouring depth compared with the other two shapes. Whereas the maximum scour depth seen with the oblong shape is greater than that with the tri-nose shape. In addition to that, Figs. 8, 9, and 10 show the three-dimensional of the equilibrium scour pattern around the circular, oblong and tri-nose pier respectively. Figs. 8,9 and 10 (a and b) show the topography of the scour pattern around the piers and the side view of the maximum depth of scour at the middle piers. It can be clearly obtained that the maximum depths of scouring for all three shapes have been located at the front edge with an angle approximately equal to ±45°. Figs. 8, 9 and 10 (c) show the contour lines of the maximum scour depth after 30 hours of flow time. It was noticed that the maximum scour depth in case of the circular pier is greater than the other shapes (oblong and tri-nose pier) with maximum scouring depth equal to 37mm compared to the maximum scouring depth with oblong shape piers that 30mm, and the maximum scouring depth with tri-nose shape piers that 22mm.
Figure 4. The relation between relative scouring depth and the spacing-width ratio.

Figure 5. Longitudinal profiles of the bed at the side edge of the central circular pier, \(d_{50} = 0.254\) mm, \(y = 26.1\) mm, \(V = 156\) mm/s.

Figure 6. Vertical sections of the bed across the flow at the central circular pier, \(d_{50} = 0.254\) mm, \(y = 26.1\) mm, \(V = 156\) mm/s.
Figure 7. The maximum scouring depth for the different pier shapes for the middle one in the computational domain.

Figure 8. Equilibrium scours pattern around the circular piers. (a) The topography of the scour, (b) Side view at the middle pier and (c) Counter lines of the maximum scour depth.
9. Conclusion
In this research, the effect of the spacing ratio between the piers and the pier shape has been investigated. As a result, there are many outcomes of the present study:

1. In general, the scour pattern using the CFD method gave good agreement with the experimental study that deals with same shapes and that having the same hydraulic conditions.

Figure 9. Resultant equilibrium Scouring pattern around the oblong, (a) Topography, (b) Side view at the middle pier, and (c) Maximum scour depth.

Figure 10. Resultant equilibrium of Scour pattern around the tri-nose piers, (a) Topography, (b) Side view at the middle pier, and (c) Maximum scour depth.
2. The spacing ratio between the piers has a significant effect on the maximum scouring depth. Since it increases with reducing the spacing between the piers.

3. From this study, it concluded that there is no significant effect for spacing ratio $x/b > 4.6$ on the maximum scouring depth.

4. By studying the effect of pier shape on the maximum scouring depth, it can be clearly seen that the circular shape has a maximum scour depth greater than oblong shape and the tri-nosed shape.

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