Effect of Factors Influencing Bridge Scour

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Abstract: Scour has been identified as one of the main causes of bridge failures in Australia and worldwide. Accurate estimation of scour around bridge piers is challenging as it requires a comprehensive analysis of the interactions between fluid, soil and bridge structure. The mechanism of scour is influenced by many factors including geometry of the channel, dynamic properties of the flow, soil conditions, geometry of the bridge piers and abutments. Numerical modeling of flow around bridge pier using computational fluid dynamics (CFD) is fundamental step in determining the effective parameters that control sediment removal around the pier and scouring of the bed. This study aims to investigate the effect of key parameters such as flow velocity, flow depth and sediment coarseness on scour initiation through a sensitivity analysis. A multi-interaction numerical model is developed using CFD package Fluent 16, and prediction of upstream and downstream velocities is validated against experimental data. The developed model is used to generate bed shear stress data for a number of clear water scenarios for sandy bed in order to investigate the effect of different parameters on the scoured area. Results show that the mean flow velocity, characterized by the Froude number, has a dominant effect in controlling scour initiation among the variables considered in the current study. These results also form the basis for development of a closed form analytic model for estimating scour around bridge piers against the wave loading.

Keywords: Bridge pier scour, CFD, Fluent, Sensitivity analysis, Froude number

1. Introduction

Scour has been identified as one of the key drivers for bridge failures in Australia and worldwide. Recent studies reveal that more than 60% of bridge failures in the USA (Deng & Cai, 2009a) are due to scour associated with flood events, whilst a recent study (Owen & Powers, 2014) estimates this number to approximately hits 50% for Australian bridges. Due to the significant role that bridges hold within road infrastructure, the failures of bridges can result significant damage to socio-economic aspects, and hence asset managers are on tremendous pressure mainly due to incurring costly repairs. For example, 70% of annual expenses of bridge maintenance in New Zealand are incurred by scour-related bridge damages (Melville & Coleman, 2000), with USA being cost $30 million annually (Deng & Cai, 2009b; Lagasse, 1997) for scour induced bridge failures. Therefore, it is important to estimate the scour on bridge piers for reliable failure prediction of bridges that can lead to better management of these essential infrastructures.

Scour is defined as the removal of sediment around bridge piers, leading to the loss of soil support and sudden collapse of the bridge without prior warning. The failure mechanism could differ depending on the type and position of the bridge foundation system. Considering bridges on shallow foundation, the scour hole could undermine the spread footings and results in inadequate soil support leading to loss of stiffness (Figure 1.a). For bridges on deep foundation, several failure mechanisms can be identified; penetrating mechanism (Figure 1.b) due to loss of skin friction, or buckling (Figure 1.(c)) or pile tip undermining (Figure 1.d) mechanisms due to loss of soil support. Prediction of scour depth as well as the shape of the scour hole is of critical importance for identifying the bridge failure mechanism and bridge failure risk due to flood events.
Traditionally, scour prediction has been performed using either analytical equations based on sediment transport theories (Miedema, 2008) or empirical equations based on envelop curves fitted over limited field and/or laboratory data. Among those empirical methods, HEC-18 equation (also known as CSU), Sheppard and Melville equations are the most commonly used equations for scour depth prediction. A comparison between these equations has shown that the HEC-18 equation is the most conservative one (Zevenbergen, 2010). Also, Transportation Research Board has performed a comparative study between 23 commonly used scour prediction methods and some modifications have been performed on the selected methods (Sheppard, Melville, & Demir, 2013). The study suggests that melding and modifying Sheppard and Melville equations into a method known as Sheppard/Melville (SM) equations could lead to better prediction of local scour at bridge piers. Despite being popular, most of the empirical equations which have been utilized in almost all of the bridge design codes across the world, provide conservative estimations of scour due to being developed for worst-case conditions (“Bridge Scour Manual”, 2013).

Due to inherent limitations of empirical models for estimating scour, several researchers have estimated scour using numerical modelling during past decades (Liu & García, 2008; Olsen & Kjellesvig, 1998; Richardson & Panchang, 1998; Roulund, Sumer, Fredsøe, & Michelsen, 2005), and the interest for numerical modelling is ever increasing due to the advancement in computing technology (high speed computing and sophisticated software tools). Typically, numerical approach to scour prediction requires coupling the flow and the sediment transport models. The flow model, which can be developed using computational fluid dynamic (CFD) methods, calculates the scour-inducing forces applied to the river bed. The sediment transport model, on the other hand, computes the transport rate of the bed material as a result of the applied forces from the flowing water. When coupling, the flow model is updated based on the new bed elevation calculated from the sediment model. Coupling could be accommodated through either multiphase modelling or mesh-updating
techniques (Xiong, Cai, Kong, & Kong, 2014; Xiong, Tang, Kong, & Cai, 2016). Also, the initiation of the scour can be obtained by comparing the applied bed shear stress, which is induced by the eroding behavior of flowing water, with the sediment critical shear stress (Salaheldin, Imran, & Chaudhry, 2004). This is a simplified method which could help identifying the area where the applied shear stress is greater than the critical shear stress (i.e. the scour initiates).

In this paper, a flow model is developed using the CFD package FLUENT 16 solver. Firstly, the model is validated against experimental data and then a series of analysis was conducted to investigate the effect of key parameters such as flow velocity, flow depth and sediment coarseness on scour initiation. The results of bed shear stress from CFD model is compared with the sediment critical shear stress in order to estimate the generated scoured area, thus to quantify the effects of the flow velocity, flow depth and the median grain size ($D_{50}$) of the bed material on scoured area variation around the pier. The outcome from the current study could lead to better understand the interaction between flow, soil and structure which can be the fundamental step towards developing accurate numerical methodologies.

2. Numerical Model Approach

The main agents of scouring are vortices caused by the turbulent flow past the bridge pier. Computational fluid dynamic (CFD) modelling solves the flow past the pier and leads to the computation of flow variables including flow velocity and shear forces at the river bed. The model predicted bed shear stress could be used to identify the scoured area when being compared with the sediment critical shear stress. It will be explained in more details in section 2.3.

2.1 Flow Model Description

The computational fluid dynamics (CFD) package FLUENT 16, is used to solve the three dimensional Reynolds-Averaged Navier-Stockes equation (RANS) for incompressible turbulent fluid flow. RANS is the time averaged momentum equation (equation of motion) for fluid flow, which is governing the flow past the pier. The solver is programmed based on Finite Volume method. Different turbulence closure models are assessed for accuracy which includes three $K – \varepsilon$ models (Standard, Realizable and RNG) and the SST $K – \omega$ model. The SST $K – \omega$ model is found to produce more accurate for the flow past the pier compare to other models.

Appropriate boundary conditions based on the nature of the flow past the pier is specified at domain boundaries. At all wall boundaries including the pier wall, a non-slip wall boundary condition is assigned. At the inlet and outlet, velocity inlet and pressure outlet boundary conditions were used respectively. Water surface boundary condition was selected as zero gradient boundary condition. It translates to assigning no boundary values (neither pressure nor velocity) at the surface where the solver uses the values of adjacent cells for the boundaries. That is an alternative to volume of fluid method (VOF), which is a free surface modelling technique. It is assumed to be a correct boundary condition for deep flow regime (where the water flow depth is greater than the pier diameter (Fu & Rockwell, 2005)) and the surface wave effect is negligible. A non-slip wall with a roughness equal to the median grain size of the bed material ($D_{50}$) is defined as the bottom boundary condition.

2.2 Model Validation

The numerical model developed is validated against the experimental result of (Dargahi, 1989) for flat bed. Dargahi (1989) conducted physical model tests to investigate the behaviour of the flow past a cylinder. Table 1 shows Dargahi experimental conditions.

<table>
<thead>
<tr>
<th>Flow depth (m)</th>
<th>Pier diameter (m)</th>
<th>Flow Velocity (m/s)</th>
<th>$D_{50}$ of the bed material (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.15</td>
<td>0.261</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 1: Dargahi Experimental condition modelled in the present study
The geometry and mesh discretization of the model is showed in Figure 2. The depth and width of the computational flow domain is chosen to be equal to the depth and width of the flow domain in the experiment. The length of the computational domain is chosen as 12D based on the suggestions in the literature (Salaheldin et al., 2004; Tseng, Yen, & Song, 2000). The mesh resolution near the pier as well as the bed boundary condition is of critical importance since the correct representation of the flow near the wall boundaries could lead to a successful solution of the turbulent flow. A mesh dependence study has been performed in order to ensure the accuracy as well as the cost-effectiveness of the results.

Figure 2. Grid system for the computational flow domain around the circular pier

Flow pattern around the pier, predicted by the flow model, is presented in Figure 3. It shows wake vortices downstream the pier, which contribute to shaping the scour hole by sucking up sediment from the bed. Wake vortices, with a vertical axis of rotation, form downstream the pier as the flow is passing the pier and separating around the sides of the pier. It forms the circulation region which extends a few pier diameters downstream the pier.

Figure 3. Top view of predicted velocity vectors around the pier at Z=0.1 m

The results obtained from CFD model based on SST $K-\omega$ turbulence model in Fluent 16 are compared with the test data as showed in Figure 4. The flow velocity at upstream and downstream of the pier is compared to the experimental data. The results indicate that the model is able to capture...
the flow structure upstream of the pier \((X/D = -0.73)\) along with at locations far downstream from the pier \((X/D = 8)\). Experimental flow velocity reported by Dargahi at \(X/D = 0.57\) is positive indicating there is no flow reversal caused by the re-circulation behind the pier footing. In contrast, almost all of the numerical models predict negative flow velocity just behind the pier. It is an acceptable prediction as the circulation region is believed to extend a few pier diameters behind the cylinder (Salaheldin et al., 2004).

![Comparison between numerical and experimental data](image)

**Figure 4.** Comparison between numerical and experimental data a) upstream the pier, b) downstream the pier

### 2.3 Scour Initiation Control

Scour initiation control is an important step for estimating the flow induced scour depth. The initiation of scour can be defined as whenever the hydrodynamic shear stress \((\tau)\) at the fluid-bed interface exceeds the sediment critical shear stress \((\tau_{cr})\), which is a function of the material properties. The scour area can be estimated by comparing the CFD model predicted fluid-bed shear stress distribution with the sediment critical shear stress (i.e. \(\tau > \tau_{cr}\)) as a simplified approach (Salaheldin et al., 2004). The sediment critical shear stress could be computed from equation 1 which is based on the Scoulby and Whitehouse Critical Shield Parameter for cohesionless soil (Soulsby & Whitehouse, 1997).

\[
\tau_{cr} = \theta_{cr}(\rho_s - \rho_w)gD_{50}
\]

Where \(\rho_s = \text{mineral density of the bed material (kg/m}^3\)

\(\rho_w = \text{density of water (kg/m}^3\)

\(D_{50} = \text{mean grain size of the bed material (m)}\)

\(\theta_{cr} = \text{Critical Shield Parameter} = \frac{0.3}{1 + 1.2d_s} + 0.055(1 - e^{-0.02d_s})\)

\(d_s = \text{dimensionless grain size} = D_{50}\left(\frac{\rho_w - \rho_s}{\rho_w}\right)^{0.3}\)

\(\varrho = \text{kinematic viscosity of water (m}^2\text{/s)}\)

\(s = \text{ratio (density of particle/density of water)}\)
A plot of typical shear stress distribution around the pier for a model in which \( V = 0.28 \text{ m/s}, \ d = 0.2 \text{ m} \) and \( D_{50} = 0.39 \text{ mm} \) is shown in Figure 5. The figure shows a contour of bed shear stress greater than critical shear stress \( (\tau > \tau_{cr}) \) around the pier, which results in the scoured area. As seen in the figure, the bed shear stress is maximum at the sides of the pier where the flow acceleration and the separation occur. It is also of high magnitude at the wake region downstream the pier (shown in Figure 3) where wake vortices develop.

![Figure 5. Top view of scour-inducing bed shear stress; i.e. the scoured area \((\tau > \tau_{cr} = 0.21)\), for \( V = 0.28 \text{ m/s}, \ d = 0.2 \text{ m}, \ D_{50} = 0.39 \text{ mm} \)](image)

### 3. Sensitivity Analysis

Sensitivity analysis is an approach to analyse the behaviour of a numerical model when different parameters change. It enables the quantitative analysis of the scour-inducing factors. A series of analysis is carried out in this study to investigate the effect of various factors influencing scour. Three parameters, including Froude number, flow depth and the \( D_{50} \) of the bed material, were varied at three different levels (i.e. 27 simulations) which are considered within practical limits. The dimensionless Froude number, flow depth and the \( D_{50} \) of the bed material are changing in the range of 0.1 to 0.3, 0.2 to 0.4 m and 0.08 to 0.675 mm respectively. Froude \( (Fr = V / \sqrt{gd}) \) is a dimensionless number dealing with the ratio of inertial forces to gravitational force and, hence, is an important number in open channel flows when it comes to scaling the results. The number is limited in the range of 0.1 and 0.3 in order to achieve the clear-water scour range. In this range, the fluid flow is dominated by gravitational forces and behaves in a stable way. In each of the twenty seven scenarios the model predicted bed shear stress is compared with the critical shear stress calculated from equation 1 and the area where \( (\tau > \tau_{cr}) \) is identified as the scoured area.
The variation of scoured area with the change in flow velocity, flow depth and $D_{50}$ of the bed material is shown in Figure 6. As seen in Figures (a) to (c), increasing the flow velocity results in growing the scoured area. It seems that the scour rate in shallow flows (depth = 0.2m) increases more rapidly with increase in flow velocity compared to higher flow depth conditions. Also, it could be inferred that the increase rate in scoured area is also dependent on the coarseness of the bed material. For the same flow velocity, the percentage of scoured area for $D_{50} = 0.385$ mm is 20% less than that for $D_{50} = 0.08$ mm. The scoured area decreases another 20% for the same flow velocity where $D_{50}$ increase to 0.675 mm. The same trend is observed in figures (d) to (f) indicating that the scour rate decreases with an increase in $D_{50}$ provided that the flow condition doesn’t change. It can be seen that the percentage of scour area is depreciated with the increase in $D_{50}$ of the bed material (i.e. coarser the bed material).

There is a clear dependency of scour area on flow velocity and flow depth as can be seen from graphs (a) to (f). The third series of graphs (g-i) have been designed to evaluate the combined effect of flow velocity and flow depth through Froude number. It is noticeable that for Froude number of 0.1, which translates to more stable flow condition, the scoured area is almost zero suggesting that the scour is negligible at lower-range Froude number ($0 \leq Fr < 0.2$). Also, it is observed that increasing the Froude number results in a growth in the scoured area and the rate of the growth depends on the bed material coarseness ($D_{50}$). For fine grain size (graph (g)), the scoured area increases at a rate of 50% to 80% provided that the flow depth is constant and the Froude number is raised to 0.2, while in the same flow depth and Froude number for medium and coarse grain sizes (graphs (h) and (i)), the
scoured area increases at a rate of 2% to 50% and 0.5% to 20% respectively. This suggests that the scour process is governed by the bed material coarseness at higher range Froude number \((0.2 \leq Fr \leq 1)\).

According to the abovementioned explanations, the scour process is interconnected with all three parameters of flow velocity, flow depth, and \(D_{50}\). Correlation analysis is performed in order to understand the contribution of each factor for the resulted scour. Correlation analysis is a statistical tool that helps identifying how much each changing parameter correlates with the scoured area. Using the results of 27 simulation scenarios, a correlation model has been developed based on the Spearman Correlation method (Spearman, 1904). The percentage of contribution of each parameter to the scoured area shows the sensitivity of the scour process to the selected parameter. As can be seen from the results of the correlation analysis (Figure 7), the percentage of contribution of flow velocity is the highest among other parameters tested, indicating that flow velocity is the dominant factor governing the scour process. The scour process seems to be less sensitive to flow depth even though it is reported as another key parameters of the flow. Taking into account that the Froude number is a ratio of flow velocity to the square root of flow depth, the Froude number could represent the dominant parameter. The sediment condition, on the other hand, seems to have less impact than the flow condition.

4. Discussion and Conclusion

The present study aims to investigate the effect of influencing parameters such as flow velocity, flow depth, and sediment coarseness on scour estimation using numerical modeling. A flow model is first developed using Fluent 16 in order to predict the shear stresses caused by the eroding behavior of flowing water at the river bed, and then it was validated against published experimental data for the upstream and downstream flow velocity around buried bridge piers. The developed model is applied to generate bed shear stress data for a number of clear water scenarios for sandy bed, and the results are analyzed using sensitivity/correlation analysis in order to investigate the effect of the considered factors on the scoured area. The key conclusions from the current study can be summarized as:

- Percentage of scour area is depreciated with the increase in \(D_{50}\) of the bed material (i.e. lesser the scour with increasing coarseness of the bed material).
- The scour process is governed by the bed material coarseness at higher range Froude number \((0.2 \leq Fr \leq 1)\).
- The scoured area is negligible at lower-range Froude number \((0 \leq Fr < 0.2)\).
- Generally, the scour process is more sensitive to the variations of flow velocity, but less sensitive to the sediment condition.

![Figure 7. Sensitivity analysis of twenty seven simulation scenarios](image-url)
• Froude number could represent as dominant parameter affecting the scour as was accounted in empirical methods developed for estimating equilibrium scour depth by Chitale (1962), Froehlich (1988) and the HEC-18 (Arneson, Zevenbergen, Lagasse, & Clopper, 2012; Chitale, 1962; Froehlich, 1988).

The analysis results showed that the utilized SST K-ω model was less effective for capturing the complicated circulation region, especially behind the pier. The current study is being extended by adopting better flow models such as Large Eddy Simulation (LES) which could capture scour induced vortices around subsea/river structures. Further work is required to compute the scour depth by accounting the multi-interaction mechanisms between fluid-structure, fluid-soil and soil-structure.

5. Reference


