Numerical Simulation of Scouring Around Four Cylindrical Piles with Different Inclination Angles Arrangements

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Abstract: One of the most frequent probable reasons for bridge pile foundation collapse, scouring can result in fatalities as well as economic and environmental consequences. However, in the local scour simulation, there are few thorough numerical investigations around pile groups consisting of front, middle, and rear piles with various inclination degrees of flow attack. The maximum depth of local scour and its mechanism surrounding groups of four cylinders with various arrangements of inclining angles were determined by numerical simulation using Flow-3D software. A validation using the experimental investigation as a comparison was carried out to verify the numerical model. Compared with experimental results, good conformity is shown in the numerical results of scour depth and bed elevation contour using the Van Rijn transport rate equation and RNG k-ε turbulence model. Numerical simulations of four cylinders in different alignment angles were carried out with pile spacing ratios, G/D of 2.5, 3, and 3.5. The deepest maximum local scour always obtained at the rear pile. The trend of maximum local scour depth is consistent with experimental studies, which demonstrated the reliability and capability of the numerical model used to simulate pile groups in estimating sediment scour depth.

1 INTRODUCTION

Scouring is the main cause of bridge failure due to the reduced foundation resistance strength in the soil. "Scouring is a natural phenomenon that occurs because the presence of bridge pile foundation affects the flow pattern and increases turbulence around the pile foundation then removes and erodes the bed material around the pile" (Ghaderi & Abbasi, 2019; Jia et al., 2018; Zhang et al., 2017). The impact of scouring around the pile foundation can cause damage to the bridge structure, economic impact, and loss of life (Tang & Puspasari, 2021). Therefore, the study of scour becomes important during design, operation, and maintenance (Kayser & Gabr, 2013; Storey & Delatte, 2003), especially to monitor and assess the scour depth obtained to reduce the adverse impact on the hydraulic structure. There are three methods used to estimate the scour depth, including conventional, experimental, and numerical. The difference is that the conventional or so-called traditional method uses depth measuring instruments depending on the high cost of installing and maintaining the underwater monitoring, which has a risk of damage during high floods (Lu et al., 2008), whereas, in recent decades, experimental and numerical methods have been used to study about scouring around pile foundations. However, several issues with the experimental method, such as limited data output and inconsistent laboratory results depending on environmental conditions, meaning the results cannot be directly applied to guide design practice or to field applications (Deng & Cai, 2010). Hence, the numerical method is most suitable for use in studying scour with low cost and time-efficient as well as high accuracy and is effective for predicting the probability of failure (Zhang et al., 2017).

Many researchers have studied the numerical study of scour with various problems to comprehend the scour mechanisms around pile foundations. However, many numerical studies simulate the scour depth around the pile group with the direction of water flow in line with the pile position. In fact, there are also conditions where the water flow is not in the

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same direction as the pile position but forms an inclination angle. Several studies have discussed the scour depth around the pile foundations with inclination angle, including (Kim et al., 2017) conducted a numerical study of two cylinders with different alignment angles ranging from 0º – 90º which resulted in the finding of increased scour depth around the rear pile as the alignment angle increased until it reached about 45º – 60º. (Zhang et al., 2017) simulated a numerical study of sediment scour depth around three cylindrical piles arranged at an angle of 45º from the direction of water flow with several pile spacing ratios, G/D of 2, 3, and 4 using Flow-3D software. This study found that the scour hole pattern and G/D significantly impacted the contour of bed elevation. Besides, the maximum scour depth obtained increased from the front pile to the rear pile. (Hamidi & Siadatmousavi, 2018) modeled the depth of sediment scour around two cylinders in an alignment arrangement with various angles of attack (0, 15, 45, 60, and 90º) and G/D equal to 5 using Sediment Simulation In Intakes with Multiblock option (SSIIM) software. Compared to the experimental results, the SSIIM model underestimated the sediment scour depth obtained at the front pile, while the good fit was at the rear pile.

Based on the literature review above, few studies still discuss local scour simulation around pile groups consisting of more than two piles with varying inclination degrees of flow attack and pile spacing ratio numerically. Meanwhile, a comprehensive study including the scour mechanism is needed to understand in determining the appropriate design. So, numerical simulations of the scour depth around four cylinders will be carried out with different inclination angles arrangement and various pile spacing ratios using Flow-3D software in this study. Further, to confirm the applicability and accuracy of the numerical model, a verification simulation was validated by comparing the experimental result before modeling the main case of the pile group.

2 MODEL VERIFICATION

A numerical model was set up similar to the experimental study of (Khosronejad et al., 2012) to validate applicability and accuracy using Flow-3D software. “Flow-3D is a commercial Computational Fluid Dynamics (CFD) software created by Flow Science Inc., which can solve Navier-Stokes equation for free-surface flow and solve complex meshing geometries using Volume of Fluid (VOF) and Fractional Area-Volume Obstacle Representation (FAVOR) methods” (Flow Science, 2008). Reynolds-Averaged Navier Stokes (RANS), which is given below, is the equation that represents the three-dimensional motion of a viscous fluid and governs the motion of an incompressible flow around a bridge pile foundation.

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x}+G_x+f_x \tag{1}$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial v}{\partial x}+vA_y\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial y}+G_y+f_y \tag{2}$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial w}{\partial x}+vA_y\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial z}+G_z+f_z \tag{3}$$

where u, v, and w are the fluid velocity sections for the x-, y-, and z-coordinates, V_F is volume fraction, A_i is area fraction, ρ is fluid density, p is average hydrodynamic pressure, and G_i is body acceleration and f_i is viscous acceleration.

There are several parts of the model setup must be considered in the Flow-3D software which is divided into three stages including general, physics, then meshing and geometry.

2.1 General Setup

In the general setup, the finish time and units are defined according to the length of the simulation time and the units used in the experiment. In this study, the finish time was set to 3000 seconds with simulation units of SI.

2.2 Physics Setup

In the physics setup, there are two important parts to be assessed that will directly affect the simulation results, namely the turbulence and sediment scour models.

2.2.1 Turbulence Model

The renormalized group (RNG) k-ε turbulence model was employed in this study utilizing the Flow-3D software among several other models such as the

Prandtl mixing length model, the one-equation model, the two-equation model (k-ε), the two-equation model (k-ω) and the large eddy simulation (LES) model because it more precisely and properly characterizes low-intensity turbulent flow with the stronger shear area (Zhang et al., 2017). Several studies (Jalal & Hassan, 2020; Nazari-Sharabian et al., 2020; Omara et al., 2018; Tang & Puspasari, 2021; Zhang et al., 2017) have proven by conducting simulations to assess the accuracy of the RNG k-ε turbulence model and produced a good agreement.

2.2.2 Sediment Scour Model

Several important parameters must be set to model the sediment scour using Flow-3D software. First, critical shields number $\theta_{cr,i}$ corresponding to the critical bed shear stress τ_{cr} required for removing sediment from the packed bed interface (Brethour, 2003) was calculated using the Soulsby-Whitehouse equation with a default value of 0.05 (Wei et al., 2014). Second, bed load transport Φ_i as the sediment transport mode by rolling on the packed bed sediment's surface was calculated using the Van Rijn equation with a bed-load coefficient value of 0.053 (Van Rijn, 1984). The maximum packing fraction has a default value of 0.64 and the bed shear stress has a recommended value of 2.5 (Wei et al., 2014). At last, the sediment characteristics, including entrainment coefficient and angle of repose have values of 0.005 (Omara et al., 2018) and 32º (Wei et al., 2014) for sediments with a diameter size of an average particle d_{50} of 0.00085 m and the depth of 0.2 m (Khosronejad et al., 2012).

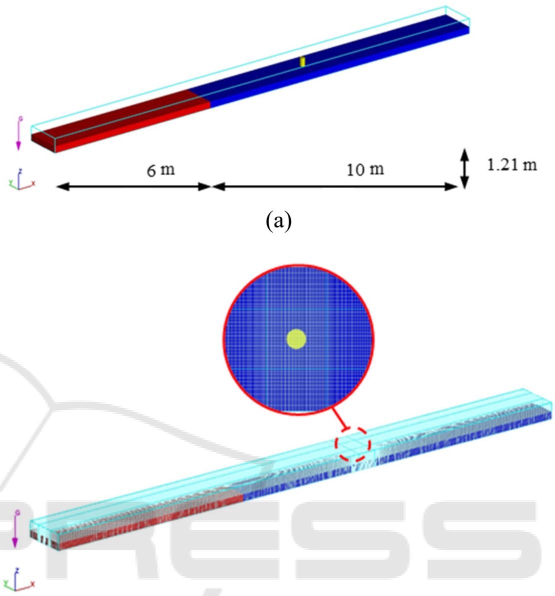
2.3 Meshing and Geometry Setup

At this stage, the steps that must be completed are modeling the geometry of channel flow then proceed with adding the mesh and determining the boundary conditions.

2.3.1 Meshing and Geometry

The geometry of the numerical simulation for verification was modeled the same as the experimental by (Khosronejad et al., 2012) with channel dimensions 10 m long, 1.21 m wide, 4.5 m high and 0.1651 m pile diameter D positioned 4 m downstream from the inlet. A hydrodynamic entry length L_h of 6 m was added to develop the fluid velocity before entering the sediment packed bed which is modeled by solid red color in Figure 1 (a).

The flow depth and inflow velocity were 0.186 m and 0.25 m/s. To improve the precision of the model surrounding the pile, 400,000 cells total, made up of 400 × 50 × 20 cells in the x, y, and z axes were produced using mesh planes of the x and y directions at a finer resolution as shown in Figure 1 (b). To obtain the best geometry shape and surface model, all meshing setups meet the requirements for maximum adjacent and aspect ratios.



(a)

(b)

Figure 1: Numerical model for verification with the display of (a) geometry and (b) meshing.

2.3.2 Boundary Conditions

The applied boundary conditions correspond to the physical conditions in real life including the specified velocity for the inlet, the wall for the front, rear, and bottom sides, the specified pressure for the top boundary, and the outflow for the outlet. Details of boundary conditions is shown in Figure 2.

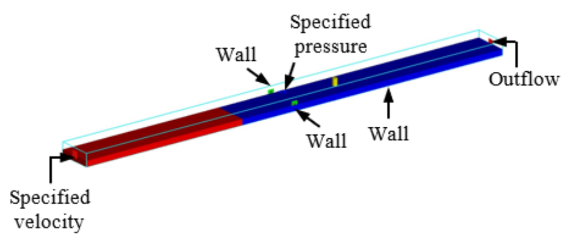


Figure 2: Boundary conditions.

2.4 Verification Result

The numerical simulation run for 50 minutes produced the depth of sediment scour around the single pile compared to experimental results, as plotted in Figure 3. Moreover, the bed elevation contours obtained from the numerical results represent scour and deposition depths in various colors compared to the experimental results.

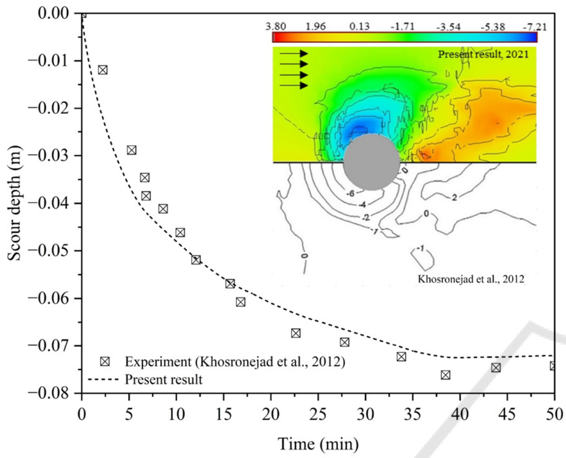
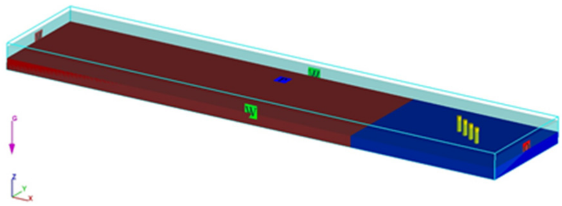


Figure 3: Validation results of the sediment scour depth.

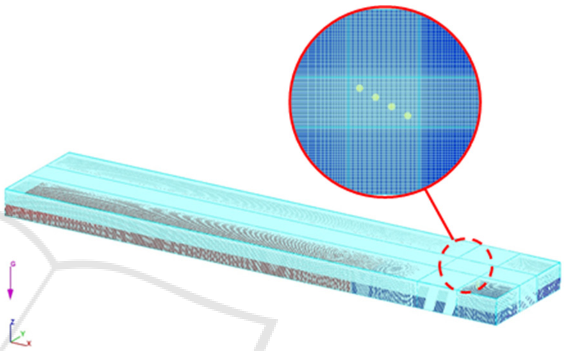
The greatest sediment scour depth obtained was 0.0725 m after running for 38 minutes which showed a good agreement when compared to the experimental result of 0.0762 m at the same time. This numerical model can be used for simulations in alignment angle arrangement.

3 NUMERICAL SIMULATION OF ALIGNMENT ANGLE ARRANGEMENTS

The simulations of scour around four cylinders were numerically performed using Flow-3D software with inclination angles arrangements of 30°, 45°, and 60° and various pile spacing ratios, G/D of 2.5, 3, and 3.5 to estimate the depth of sediment scour and assess the mechanism. All simulation processes are the same as before in the verification stage. The channel geometry was modeled as 42 m × 30 m × 7 m (L × W × H) with an entry length of 100 m before the inlet. The pile diameter of 1.2 m was located 18 m downstream from the inlet on a 3 m deep sediment bed with mean particle diameters d_{50} of 0.002 m, 0.018 m, 0.022 m, and 0.024 m. The numerical setup at the validation stage is used for modeling several alignment angle arrangements with the sizes of minimum and maximum cells are 0.12 m and 0.60 m. The boundary conditions were also adopted from the previous setup with an inlet velocity of 2 m/s. The numerical model of geometry and meshing for inclination angle arrangements are shown in Figure 4.



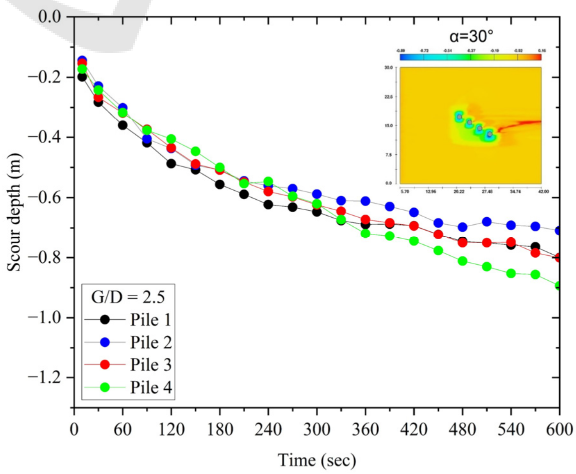
(a)



(b)

Figure 4: Numerical model for angle arrangements with the display of (a) geometry and (b) meshing.

A total of 9 numerical simulations were carried out and run for 600 seconds using Flow-3D software, resulting in the depth of sediment scour as shown below.



(a)

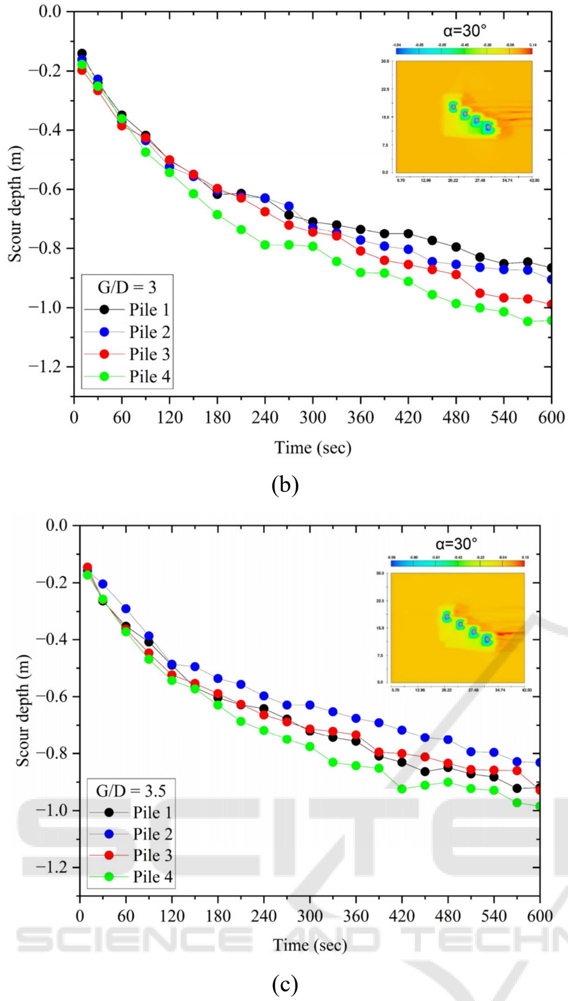


Figure 5: Sediment scour depth with α = 30° and different G/D (a) 2.5 (b) 3 (c) 3.5.

As seen in Figure 5, the greatest depth of local scour produced around four piles, respectively from piles 1 to 4 with an incline angle of 30° for G/D = 2.5 are 0.7999 m, 0.7091 m, 0.8010 m, and 0.8940 m. For G/D = 3 and 3.5, the greatest depths of local scour are 0.8658 m, 0.9046 m, 0.9887 m, 1.0429 m, and 0.9195 m, 0.8319 m, 0.9283 m, 0.9845 m, respectively. Almost all the results indicate that the maximum depth of scour increases gradually from the front pile to the rear pile under various G/D, which is also marked with the darkest blue color in the scour hole area. However, when compared between the pile spacing ratios, the deepest local scour is generated by G/D = 3. At the same time, the smallest is obtained by G/D = 2.5 due to the influence of interference between piles and changes in pile spacing.

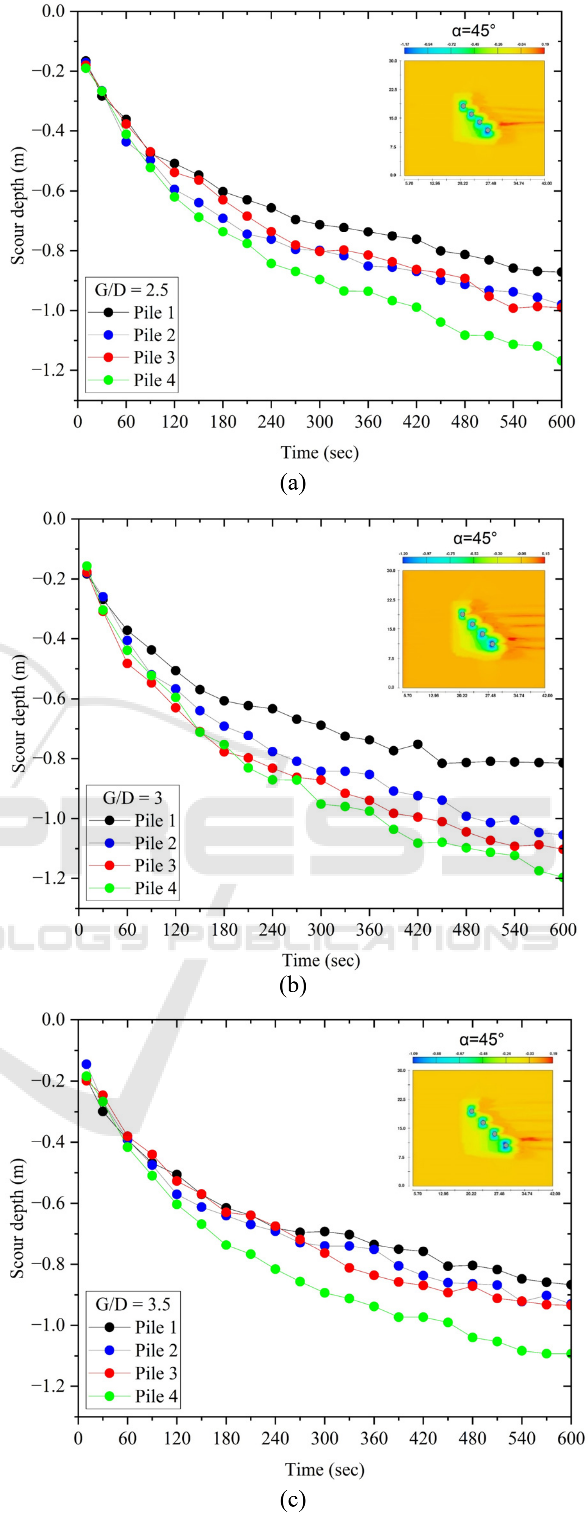
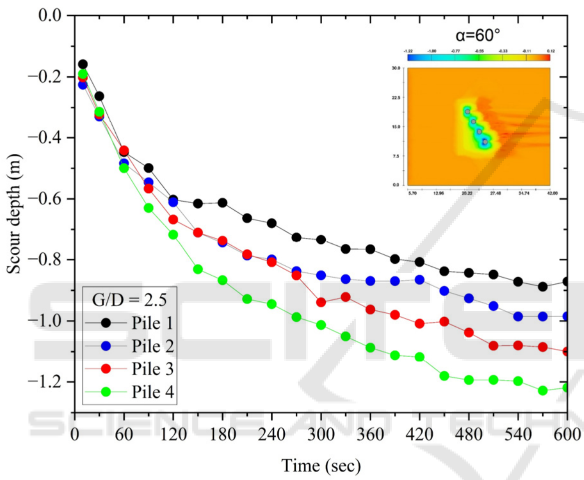
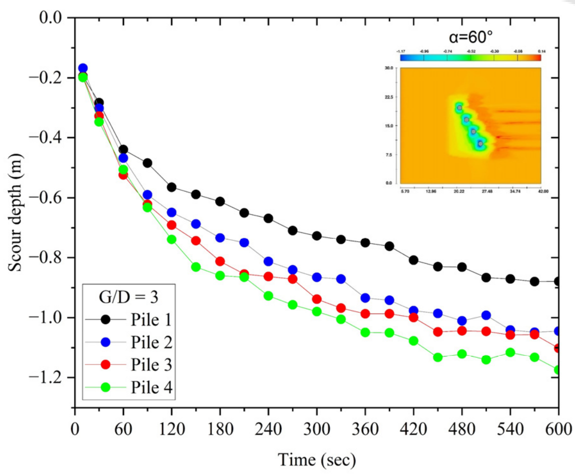


Figure 6: Sediment scour depth with α = 45° and different G/D (a) 2.5 (b) 3 (c) 3.5.

The maximum local scour depths obtained around four piles from piles 1 to 4 with an incline angle of 45° for G/D = 2.5 are 0.8713 m, 0.9799 m, 0.9903 m, and 1.1682 m. For G/D = 3 and 3.5, the maximum depths of local scour are 0.8153 m, 1.0544 m, 1.1026 m, 1.1966 m, and 0.8670 m, 0.9300 m, 0.9342 m, 1.0930 m, respectively. Same as the previous results for α = 30°, because of the accelerated flow and elevated turbulence, all the results indicate that the maximum depth of scour increases gradually from the front pile to the rear pile for all G/D. Compared between pile spacing ratios, the maximum depth of local scour is obtained by G/D = 3, and the smallest is obtained by G/D = 3.5 due to the influence of interference between piles along with changes in pile spacing.



(a)



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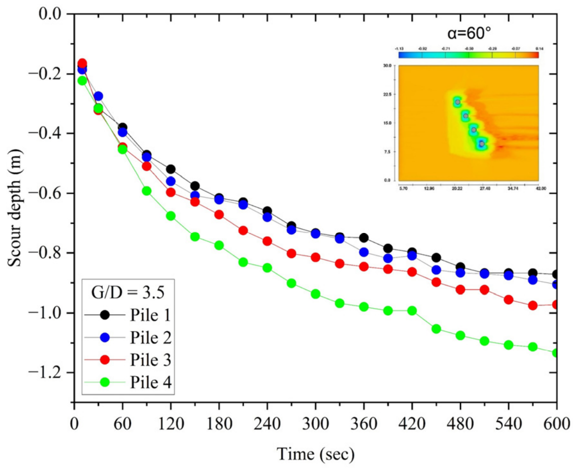

(c)

Figure 7: Sediment scour depth with α = 60° and different G/D (a) 2.5 (b) 3 (c) 3.5.

The maximum local scour depths obtained around four piles from piles 1 to 4 with an incline angle of 60° for G/D = 2.5 are 0.8713 m, 0.9848 m, 1.0995 m, and 1.2188 m. For G/D = 3 and 3.5, the maximum depths of local scour are 0.8792 m, 1.0449 m, 1.1017 m, 1.1745 m, and 0.8717 m, 0.9056 m, 0.9720 m, 1.1336 m, respectively. As seen in Figure 7, the maximum depth of scour increases gradually from the pile in front to the rear for all G/D. Compared between pile spacing ratios, the maximum depth of local scour is obtained by G/D = 2.5. In contrast, the smallest is obtained by G/D = 3.5, which is slightly different from G/D = 3 due to the influence of interference between piles and pile spacing changes. Compared between angles of attack, the maximum local scour depth gradually increases with increasing angle of attack, as stated by the experimental study of (Zhou et al., 2020). However, some results have different trends because the maximum scour depths are not obtained at equilibrium conditions.

4 CONCLUSIONS

The study of sediment scours around four cylindrical piles with inclination angles arrangements of 30°, 45°, and 60° and pile spacing ratios, G/D of 2.5, 3, and 3.5 has been performed numerically to estimate the depth of local scour and investigate its mechanism. Based on the results, Flow-3D software is an effective tool for calculating the depth of sediment scour using the bed load transport rate equation of Van Rijn and the turbulence model of RNG k-ε. The greatest depth of local scour obtained for all inclination angle arrangements at each pile spacing ratio has the same trend of increasing gradually from the pile in front to the back due to accelerated flow and elevated turbulence. However, when compared between pile spacing ratios, the smallest maximum scour depth is obtained by G/D = 2.5 for α = 30° and G/D = 3.5 for α = 45° and 60° because of the interference effect between adjacent piles. Although most numerical results are linear experiments, further studies in the alignment angle arrangements still need to determine and obtain the maximum scour at the equilibrium depth.

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