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Numerical Investigation of Scour around Two Side-by-Side Piles with Different Spacing Ratios in Live-bed

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Abstract. In this study, a previously developed and validated hydro-morphological model is employed for numerically investigating scour around two identical side-by-side piles. The model benefits from a coupled approach between a selected hydrodynamic and a developed morphodynamic model which has been successfully validated for predicting scour around single circular piles. The hydrodynamic model solves Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations in combination with the k-ω-SST turbulence closure model. The model entails bedload and suspended load sediment transport models for non-cohesive sand. The morphological evolution of the bed due to the sediment transport fluxes is expressed by a means of a mass-balance equation. The model is run for two side-by-side piles with three different spacing ratios G/D=1, 2, and 3, where G represents the distance between the piles and D is the pile diameter, under steady-current flow and live-bed conditions. The results of the investigation revealed an inverse correlation between the spacing ratio and the scour hole depth adjacent to piles. The results are generalized and an equation is developed for equilibrium scour hole depth as a function of the spacing ratio.

Keywords: Scour, Side-by-side piles, CFD, Sediment transport.

1 Introduction

The presence of bottom-mounted obstructions such as bridge piers, abutments, offshore wind turbine foundations and oil/gas platforms in marine or riverine environments changes the flow patterns and generates turbulent flow structures in their vicinity [1]. These changes increase the local velocity and the bed shear stress near the structures, which consequently, in an unprotected sea or river-bed condition, enhance the local sediment transport capacity. An increase in sediment mobility leads to erosion of seabed or riverbed sediments around the structures which is known as local scour [2]. Local scour mitigates the insertion depth of the structures and weakens the structural safety which may result in structural failure and financial or life losses.

Despite the significant number of studies that have investigated scour around marine and riverine foundations, the spectrum of parameters that influence the development of scour, brings a high level of uncertainty into the design of safe and feasible hydraulic structure. These factors generally include foundation geometry, fluid and flow parameters, and bed material parameters [3].

In this study, the effect of a group of two identical and side-by-side circular piles with different spacing ratios on flow behavior and local scour is studied. In the literature, few experimental and numerical studies have investigated the impact of a group of side-by-side piles on scouring. Among them, Ataie-Ashtiani and Beheshti [4] experimentally investigated local scour around pile groups including two to eight circular piles with different arrangements and spacing ratios in clear-water steady current conditions. In total, 112 tests were carried out. It was found that depending on pile spacing, scour around a pile group can be different from that of a single pile. In their study, for the case of two side-by-side piles, the maximum scour depth happened for the $G/D \approx 0.25$ which was 50% more than the maximum scour around a single pile. In another work, Kim et al. [1] numerically investigated the progression of scour patterns around two adjacent circular cylinders in side-by-side and tandem arrangements with diverse spacing ratios between 0.25 to 4 in clear-water conditions. Large Eddy Simulation (LES) approach was employed to solve the Navier-Stokes equations which was followed by a Lagrangian approach for sediment transport. They validated their model against the experimental data from Khosronejad et al. [5] for scour around a single circular pile. From their results, they found out that in the case of two side-by-side cylinders when $G/D \geq 1.5$, the local scour patterns are similar to those of a single cylinder. Zhang et al. [2] ran a set of numerical simulations to study local scour around a different arrangement of a group of up to three adjacent piles under steady current flow in clear-water condition. Flow-3D was applied to investigate the local scour. The software used the volume of fluid (VOF) method to capture the water-air interface. RANS equations in combination with the RNG k-ε turbulence closure was applied to solve the hydrodynamic equations. Sediment transport was modelled by both bedload and suspended load models. The model was validated against experimental data from Khosronejad et al. [5] for scour around a single circular pile. Model simulations were conducted for circular piles with D=1.5 m and G/D= 1, 2 and 3. It was observed that with increase in the spacing ratio the pile group effect decreases, as for G/D= 3, there is almost no interaction between the piles effect. Vaghefi et al. [6] experimentally studied the scour pattern around three side-by-side and tandem arrangements of circular cylinders in a 180° bend under clear-water and steady current flow conditions. Circular cylinders with constant G/D= 2 were placed at the positions of 60°, 90° and 120° of the bend. In their study, the maximum scouring depth occurred in the side-by-side arrangement at the position of 90° of the bend and around the pier closer to the outer bank. Qi et al. [7] made a series of experimental tests of local scour at twin piles under combined current and wave. Two pairs of piles with diameters D=12 cm and 8 cm at four different flow skew angles (α_s=0°,30°,60°, 90°) with different $0 \leq G/D \leq 3$ were considered. It is found that with increase in G/D the pile group effects gradually diminished. In their work, the maximum pile group effect on the scour depth was found to occur for side-by-side arrangements with G/D=0. An empirical equation was established to estimate the maximum scour depth around twin piles based on G/D and α_s with maximum error lines in the range of 25%.

In all mentioned studies, ……., and to the author's best knowledge, no numerical investigation on local scour around a pile groups has been carried out in live-bed condition. Therefore, this study aims to bridge this gap with studying the flow behavior and progression of local scour pattern around two identical side-by-side circular piles with different G/D= 1, 2 and 3 in steady current flow. This is important because ….

For this purpose, a coupled hydrodynamic and morphodynamic model is implemented in the framework of OpenFOAM®. The model only solves the water-phase around the piles. Hence, the computational domain is limited to the water-air interface on top. The model is validated against the experimental data of Roulund et al. [8] for scouring around a circular pile under steady current flow in live-bed condition. In this study, the similar flow and bed material condition as Roulund's scour test is used in all simulations.

2 Numerical method

2.1 Governing equation of the flow

In this study, the flow field is governed by incompressible URANS equations. The Reynolds stress terms in equations are modeled by the k-ω SST turbulence closure. k-ω SST is chosen as it has a good capability in predicting adverse pressure gradients and separating flow. The computational domain and boundaries for a case of two side-by-side piles are presented in Fig. 1a. Fig. **1**b shows the dimensions of the computational domain in the xy plane, while the height of the domain is equal to the water depth. The flow and turbulent properties need to be quantified in the boundaries of the computational domain. At the walls, which contain a smooth pile surface and the rough sandy bed, no-slip boundary condition is considered while the near-wall treatment of Cebeci and Bradshaw [9] is imposed on the center of the first layer of mesh cells closest to the wall. This near-wall treatment is valid in the logarithmic region of the boundary layer and can be adapted for both smooth and rough walls to calculate friction velocity u_f. The top boundary of the domain is satisfied with the frictionless slip wall as the model does not consider the water-air interface. The sides are treated with symmetry boundary condition whereas the effects of the side walls on the approaching flow are ignored. The velocity vectors at the inlet are supplied with the curve fitting of the velocity profile provided in Roulund et al. [8] and pressure is treated with the Neumann (wall-normal zero gradient) condition. At the outlet, the flow properties are set as zero normal gradient of all quantities except for pressure, which is equal to zero.

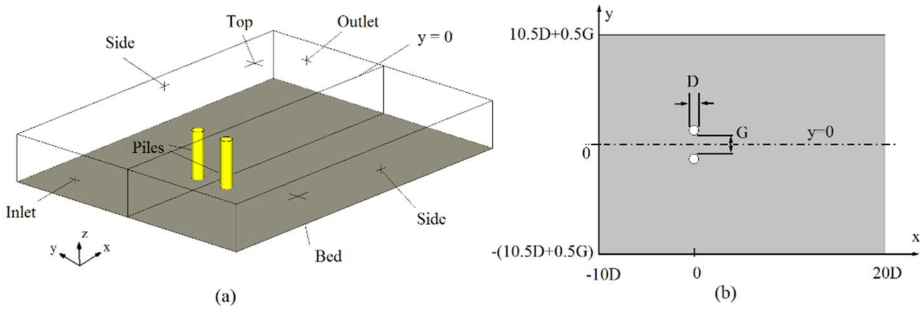

Fig. 1. (a) 3D view of the computational domain and boundaries and (b) top view for a group of two side-by-side piles.

2.2 Sediment transport and morphodynamic models

The sediment transport contains bedload and suspended load. Bedload includes a transfer of sediments that roll, slide or jump along the bed in a thin layer very close to the bed. In contrast, Suspended load includes sediment particles which transfer in the flow over the bedload without continuous contact with the bed and is dominated by fluid turbulence. These two sediment transport modes are separated by a hypothetical layer called the reference level with the height of Δ from the bed. In this study, the bedload rate for each computational grid, q_B, is calculated using a similar approach used by Roulund et al. [8] for a 2D bed. The suspended load is modeled solving an advection-diffusion equation to fulfill the case of a non-uniform and transient flow around structures:

$$\frac{\partial c}{\partial t} + \nabla.[(\vec{u} + \vec{w}_s)c] = \nabla.[D_s \nabla c] + S_\Delta \quad (1)$$

where c is the value of fractional volumetric suspended sediment concentration, $\vec{u}$ and $\vec{w}_s$ are the fluid velocity and sediment fall velocity vectors, respectively, D_s is the sediment diffusivity coefficient and $S_\Delta = E_\Delta$ - D_Δ is the source/sink term for the entrainment E_Δ and deposition rate D_Δ. In the present work, sediment fall velocity is calculated using the method proposed by Soulsby [10]. The entrainment rate, E_Δ, is obtained from:

$$E_\Delta = c_\Delta w_s \quad (2)$$

where c_Δ is the reference level concentration of suspended load which is calculated as suggested by Rijn [11], where Δ is adopted based on the mean particle diameter d_{50} and in the range of $3d_{50}$ to $4d_{50}$. The deposition rate D_Δ is obtained from the approach applied by Liu and García [12]:

$$D_\Delta = c_b w_s \quad (3)$$

where c_b is the sediment concentration at Δ, which here, is equal to the sediment concentration in the center of the first layer of cells closest to the bed. The results of the sediment transport models are reflected as a deformation on the bed boundary of the computational domain. This is achieved by solving a mass-balance equation on a 2D mesh according to the bed boundary of the 3D domain.

3 Model validation

The model is validated against data collected from a physical scour test around a circular pile under steady current flow provided in Roulund et al. [8]. The experiment was carried out in a 10 m length and 4 m width flume. A circular pile with 0.1 m diameter was mounted in a sandy bed at 6.6. m downstream of the inlet section. The depth average of the flow for a test condition was 0.46 m/s with the water depth of 0.4 m. The sandy bed was covered with sand with a mean particle diameter d_{50}= 0.26 mm. For the numerical modeling, a computational domain with 30D length and 20D width with a circular pile placed in the symmetry plane and at 10D downstream of the inlet was considered. The domain height was equal to water depth and equal to 4D. The applied generated mesh included around 400,000 cells while the mesh sensitivity analysis was done. The thickness of the first layer of the grids closest to the bed was 2 mm to satisfy the requirements of the near-wall treatment method and reference level height from the bed. Fig. 2 depicts the progression of the scour hole in terms of scour depth in front and back of the pile which is compared with the experimental and simulation results of Roulund et al. [8]. It is found that the maximum discrepancy in the prediction of maximum scour hole from the present simulation results and Roulund's experimental data is less than 5% during the evolution process.

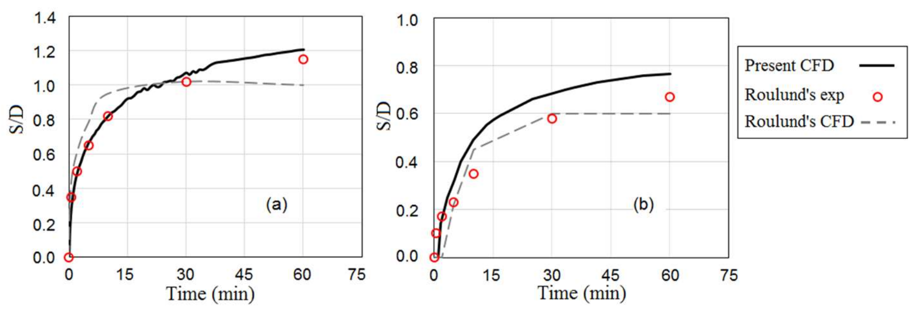

Fig. 2. The evolution of scour hole in terms of scour depth (a) in front and (b) in the back of the circular pile.

4 Results

Two sets of simulations are conducted to investigate the flow behavior and formation of scour hole around a group of two circular side-by-side piles in steady current flow. One is on a rigid bed and the other one is on a mobile bed. A similar geometry (as shown in Fig. 1) and generated mesh is used for each case in both series of tests. The generated meshes include around 600,000 grids. The first series of simulations are run to evaluate the influence of the changes in the spacing ratio in the local flow field and bed shear stress on the rigid rough bed. Fig. 3 shows the contours of flow field in x=0 plane. It is seen that the flow velocity between the piles highly depends on the G/D, while for $G/D \geq 3$ the effect of the pile group in the flow field is small.

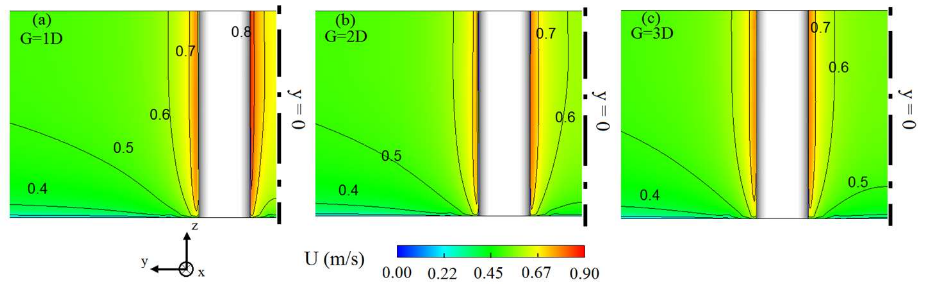

Fig. 3. Flow field adjacent to the two side-by-side piles in plane x=0 with (a) G=1D, (b) G=2D, and (c) G=3D.

The results of the bed shear stress distribution in a dimensionless form for different arrangements of two side-by-side piles are shown in Fig. 4. The dimensionless bed shear stress (BSS) is τ/τ_∞ where τ and τ_∞ are values of local and undisturbed bed shear stress, respectively. The results reveal that decrease in the value of G/D significantly raises the BSS distribution which may result in deeper scour hole in the area between the piles.

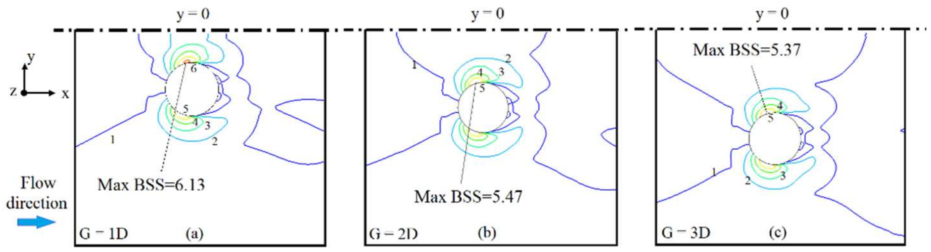

Fig. 4. Bed shear stress distribution around the two side-by-side piles for (a) G=1D, (b) G=2D, and (c)G=3D.

The second series of simulations were conducted on the mobile sandy bed to assess the progression of scour hole pattern adjacent to two side-by-side piles under current flow. Fig. 5 demonstrates the results of the scour hole pattern around piles at t=30 mins of physical time which took around 3 months of simulation time on a 2.3 GHz CPU with 8 MB RAM. The results indicate notable impacts of changes in G/D on scour pattern and maximum scour depth around the piles. The effects mitigate with increase in G/D, as for the case $G= 3D$ the depth in inner and outer sides of the pile group is roughly similar to that of a single pile.

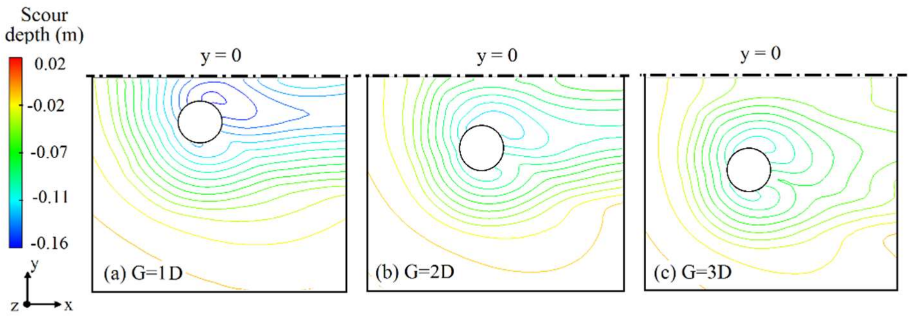

Fig. 5. Scour patterns around two side-by-side piles at t=30 mins for (a) G=1D, (b) G=2D, and (c) G=3D.

It is deemed that the scour development reaches the equilibrium condition after a first one hour of physical time for all cases similar to that of the single pile. Hence, Fig. 6a presents the evolution of dimensionless scour hole depth S/D in time for different spacing ratios of two pile groups and single pile until the equilibrium condition. The equilibrium depth for pile groups is obtained by elongation of the scour depth curves for the first 30 mins with maintaining the ratio with that of a single pile. Fig. 6b displays values of dimensionless equilibrium scour hole depth S_m/D for different arrangements of two pile groups. It is assumed that the pile group effects are completely negligible in G/D=5. Hence, S_m/D equal to that of a single pile is considered for two side-by-side piles with G/D=5. A curve is fitted for the set of data with a formula as following:

$$\frac{S_m}{D} = 1.186 + 1.6\, exp\left(-0.92\left(\frac{G}{D}\right)\right). \tag{4}$$

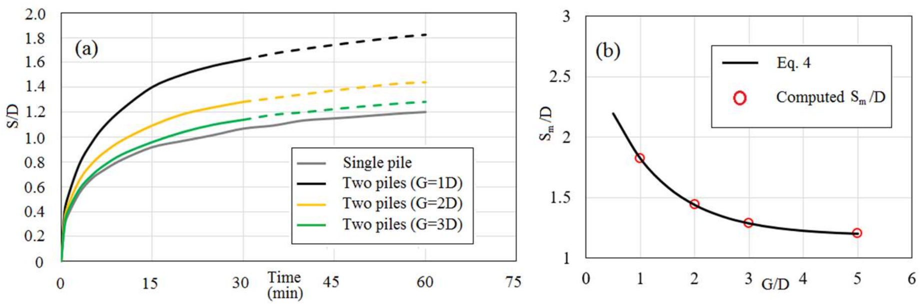

Fig. 6. (a) evolution of scour depth for two side-by-side piles and a single pile and (b) equilibrium scour depth for two side-by-side piles with different spacing ratios.

Sumer et al. [13] inferred that the equilibrium scour depth under current flow and live-bed condition is only proportional to pile diameter D. With considering this, Eq. 4 can be generalized in case of live-bed condition for two identical circular side-by-side piles, however more investigation is needed to understand the impacts of the other factors.

5 Conclusion

In the present study, a numerical model for the prediction of flow behavior and scour pattern around pile groups is implemented. The results for the flow field, bed shear stress and scour pattern for two identical side-by-side piles for different G/D values are provided. The results depict that for $G/D \geq 3$ the pile group effect gradually vanishes. An equation is fitted for the computed equilibrium scour depths for different spacing ratios which can be used for prediction of maximum scour depth adjacent to two side-by-side piles under current steady flow and live-bed condition.

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