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Three-dimensional CFD modeling of wave scour around side-by-side and triangular arrangement of piles with REEF3D

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Abstract

Sediment transport and resulting local scour in marine and coastal environments can lead to the failure of structures. The knowledge and understanding of erosion and sediment transport mechanisms and the correct prediction of the local scour magnitude is crucial for the structural design. In the current paper the complex physics of local scour under wave conditions are modeled. The numerical results are compared with experimental data, showing good agreement. The three-dimensional computational fluid dynamics model REEF3D is used to calculate the detailed flow field and the resulting sediment transport pattern around the vertical pile. The location of the free surface is represented using the level set method, which calculates the complex motion of the free surface in a realistic manner. For the implementation of waves, the CFD code is used as a numerical wave tank. In order to provide an accurate prediction of propagating waves, the convection terms of the Navier-Stokes equations and the level set method are discretized with the 5th-order Weighted Essentially Non-Oscillatory scheme. The pressure is solved on a staggered grid, ensuring tight velocity-pressure coupling. The numerical model employs a Cartesian grid and complex geometries are treated with an immersed boundary method based on ghost cell extrapolation. Sediment transport is implemented through standard bed-load and suspended load formulas. The resulting sediment discharges and concentrations are evaluated with the Exner equation, giving the local erosion and deposition pattern for each time step. For the geometric representation of the moveable sediment bed, the level set method is used.

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Keywords: Local scour; level set method; numerical wave tank; CFD; REEF3D

1. Introduction

Sediment transport in coastal environments is highly influenced by wind waves. In general, the waves stir up sediments due to the non-oscillatory motion of the fluid near the bed. Studies suggest that the non-oscillatory behavior of the fluid particles intensifies in the presence of a pile and results in relatively high turbulence near the sediment bed [1]. Most marine structures are supported by a group of piles, which further increases turbulence near the sediment bed. The arrangement of the piles is another parameter that may affect bed stress patterns around the group of piles. The mechanism of scour under waves is defined as follows: when a cylinder is exposed to the waves, non-

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uniform oscillatory fluid motion, called the streaming effect, is formed around the cylinder [2]. Streaming effect is the magnification of randomness and fluctuation of the water particles around the piles. It develops high bed stresses around the cylinder and stirs sediments into suspension. Studies suggest that steady streaming effect magnifies bed stress by a factor of 7 to 11 compared to the undisturbed value [3].

Olsen and Melaaen (1993) [4] studied local scour under a steady current, using a three-dimensional flow and sediment transport model to calculate fluid behaviour and scour development. A similar study was extended by Olsen and Kjellesvig (1998) [5] to study local scour in detail. The finite volume method (FVM) is used to discretize the domain and the Reynolds Averaged Navier-Stokes equation and the $k - \epsilon$ turbulence model is used to calculate the dynamic behaviour of the fluid flow. The semi-implicit method for pressure-linked equations (SIMPLE) is applied to calculate the non-hydrostatic pressure. The bed shear stress reduction on sloping beds was assessed using a sediment-slide algorithm. The results showed good agreement with the experiment and empirically calculated maximum scour depth values. Roulund et al. (2005) [6] carried out a study using a 3D model with the $k - \omega$ model. The simulated results from the model matched well with experimental observations. Though, hydrodynamic and sediment transport around the hydraulic structures were researched considerably, the free surface was assumed to be a rigid lid. Liu and Garcia (2008) [7] employed a three-dimensional numerical model with free water surface and mesh deformation for local sediment scour using the VOF method. Afzal et al. (2014) [8] carried out the three dimensional numerical analysis of pier scour using the level set method. Different tests were run to simulate the scour evolution and free surface under the currents and wave respectively. Results showed good agreement with experimental observation made by Sumer and Fredsøe (2001) [1]. The current study numerically investigates scour under the wave conditions. Two different arrangements are used in the study. The first arrangement consists of two piles in a side-by-side arrangement. In the second test, the number of piles is increased to three with the same gap ratio as in the side-by-side arrangement. The temporal development of the local scour and the final scour contour are plotted. Finally, the simulated scour depth is compared with the laboratory observation.

Nomenclature

d_{50} mean diameter of particle
ρ fluid density
p pressure
ν kinematic viscosity
ν_t eddy viscosity
g acceleration due to gravity
D diameter of the cylinder

2. Numerical model

The fluid domain is simulated using the three-dimensional continuity and the momentum equations (Reynolds Averaged Navier-Stokes equations) to define the velocity and pressure field under combined wave and current action.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + g_i \tag{2}$$

where u is the velocity, ρ is the density of the fluid, p is the pressure, ν is the kinematic viscosity, ν_t is the eddy viscosity and g the acceleration due to gravity.

The advection and diffusion terms of the RANS equations are discretized with the WENO scheme by Jiang and Shu (1996) [9]. It uses adaptive stencils to improve the accuracy and can handle large gradients right up to the shock very accurately. In order to get further accurate approximation, the Hamilton-Jacobi version of the WENO scheme [10] is used for the variables of the free surface and turbulence algorithms. Chorins Projection method [11] is used to model the pressure. A staggered grid is used which avoid odd-even decupling between the pressure and the velocities. Turbulence is modeled with the k- model [12]. The third-order Total Variation Diminishing (TVD) Runge-Kutta scheme [13] is used for time discretization. In order to optimize time steps, an adaptive time stepping approach is used. The free surface is captured using the level set method proposed by Osher and Sethian (1988) [14]. It uses a continuous signed distance function ϕ (x,t) to define the interface between two immiscible fluids. It is defined as follows:

$$\phi(\vec{x},t)\begin{cases} >0 & if\ \vec{x}\ is\ in\ phase\ 1 \\ =0 & if\ \vec{x}\ is\ at\ the\ interface \\ <0 & if\ \vec{x}\ is\ in\ phase\ 2 \end{cases} \tag{3}$$

where ϕ (x,t) is calculated using convection equations with externally generated velocity field U_j from RANS equations.

$$\frac{\partial\phi}{\partial t} + U_j\frac{\partial\phi}{\partial x_j} = 0 \tag{4}$$

3. Sediment transport model

As water flows over the sediment bed, the sediment particles are exposed to the bed shear stress. If the magnitude of the resulting stress exceeds the critical value, sediment transport takes place. In this study van Rijn (1984) [15] formulas are used to calculate bed load and suspended load under the combined current and wave action.

$$\frac{q_{b,i}}{d_i^{1.5}\sqrt{\frac{(\rho_S-\rho_W)\cdot g}{\rho_W}}} = 0.053\cdot\frac{\left(\frac{\tau-\tau_{c,i}}{\tau_{c,i}}\right)^{2.1}}{\left(d_i\left(\frac{\rho_S/(\rho_W-1)\cdot g}{\nu^2}\right)^{1/3}\right)^{0.3}} \tag{5}$$

where, $q^*_{b,i}$ is the dimensionless bed load transport rate, $\tau^*_{c,i}$ is dimensionless critical shear stress, $\tau^*$is dimensionless shear stress, τ_c is critical shear stress, g is gravitational acceleration and is particle diameter. The suspended load is calculated using convection-diffusion equation.

$$\frac{\partial c}{\partial t} + u_j\frac{\partial c}{\partial xj} + w_s\frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j}\left[\Gamma\frac{\partial c}{\partial x_j}\right] \tag{6}$$

$$c_{bed,suspload,i} = 0.015\frac{d_i}{a}\frac{\left(\frac{\tau-\tau_{c,i}}{\tau_{c,i}}\right)^{1.5}}{\left(d_i\left(\frac{\rho_s/(\rho_w-1)g}{\nu^2}\right)^{1/3}\right)^{0.3}} \tag{7}$$

Here ρ_s is the density of the sediment, ρ_w is the density of the water and d_i the sediment particle diameter. Bed level changes are computed by using the Exner formula, which is based on the mass balance of sediments being transported by the flow. It states the temporal variation of scour considering the sediment porosity, the divergence of bed load with erosion and deposition caused by suspended sediment particles. Exner formula is given below:

$$(1-n)\frac{\partial z_b}{\partial t} = -\frac{\partial q_{b,x}}{\partial x} - \frac{\partial q_{b,y}}{\partial z} - E + D \tag{8}$$

where q_b is the bed load, n is porosity, z_b is local bed surface elevation, E is the erosion rate caused due to suspension and D is the corresponding deposition rate.

4. Experimental setup and numerical wave tank

The experimental tests were carried out in a wave flume at the Department of Hydrodynamics and Water Resources (ISVA), Technical University of Denmark by Sumer and Fredsøe (1997) [2]. The flume was filled with fine sediments d_{50} = 0.16 mm and density = 2650 kg/m^3) and a 90*mm* diameter cylinder was placed at the center location. The time development of the local scour was recorded after imposing the waves on the cylinder. The still water depth of d = 0.39m was maintained throughout the experiment and it was run until equilibrium conditions were achieved.

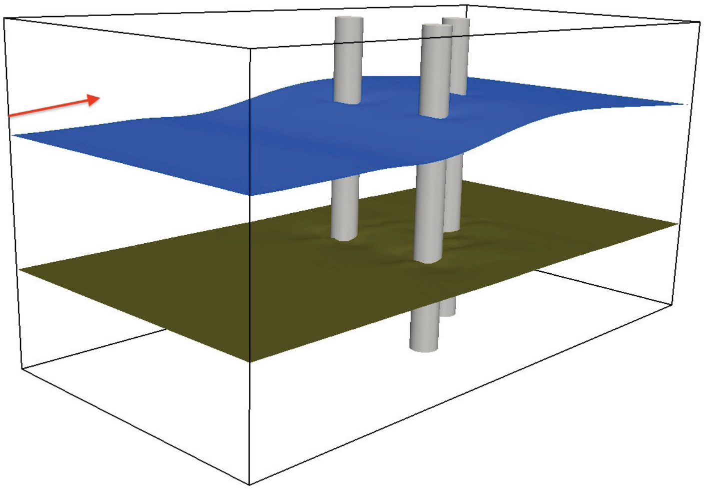

Fig. 1: Numerical wave tank, triangular arrangement with three piles

In this numerical study, the emphasis is on the local scour around the pile. The numerical wave tank is used to simulate wave action on the movable bed. The cylinders have a diameter of D=90 mm are placed in the center of a 2m long and 1 m wide tank in either a side-by-side or triangular arrangement. The cell size is kept 2 cm throughout the domain. In order to avoid unnecessary reflections from the outlet, first order cnoidal waves are generated using the active wave absorption method [16]. The test conditions and chosen parameter for experimental and numerical simulation are shown below in table 1.

5. Numerical results and discussion

5.1. Comparison of simulated results with experimental observation

In the study, a side-by-side arrangement with two piles and a triangular arrangement with three piles are simulated. The other parameters for the wave and sediment properties are the same for both tests. The numerical simulation is run under the cnoidal wave action until equilibrium condition is achieved. The simulated scour depths with the input parameters are listed in table 1. The results match well with the experimental observations [2]. The experimental value of the maximum scour for side-by-side arrangement is 39.6*mm*, while the REEF3D simulated scour depth is 36.6*mm*. Similarly for the simulation with triangular arrangement a scour depth of 18.0mm is predicted, which is close to experimental scour depth of 20.0 mm. The comparison of numerical results with experimental data is shown below in Table. 1.

Table 1: Details of the setups used in the different simulations

Parameters	Test 1(Side by side arrangement)	Test 2 (Triangular arrangement)
Cylinder diameter D (mm)	90.0	90.0
Wave period T (s)	4.0	4.0
Maximum bed orbital velocity U_m (cm/s)	26.0	26.0
Wavelength L (m)	8.8	8.8
Amplitude (cm)	5.30	5.30
Keulegan Carpenter number	13.0	13.0
Experimental scour depth (mm)	39.6	18.0
REEF3D scour depth (mm)	36.6	20.0

The temporal development of the local scour for both scenarios is shown in Figure 2. It is recorded every 5.0 s until the equilibrium state is achieved. It is clearly seen that for both the cases, the scour depth increases with the time and attains an equilibrium state after 6 hours. The time taken to reach the equilibrium state is almost the same but the scour magnitudes are different. Local fluctuations in scour depth are also seen in the graph, which represents the sediment backfilling process with backward and forward wave action.

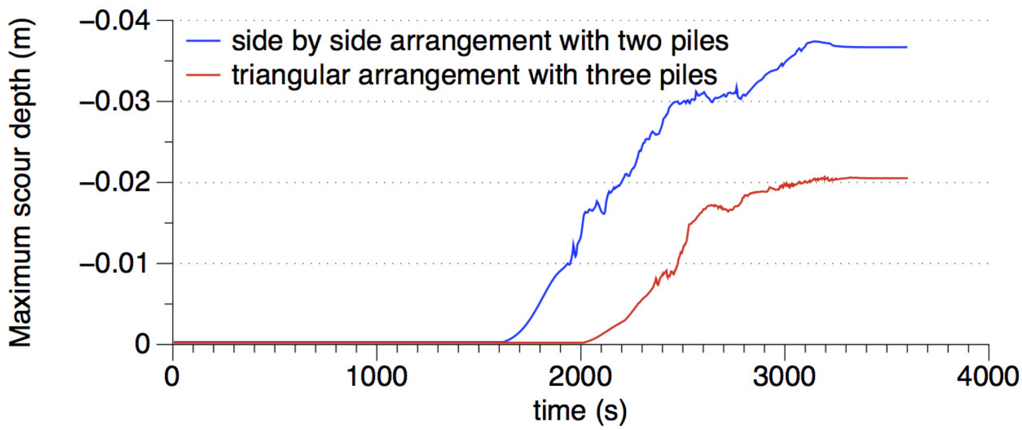

Fig. 2: Comparative temporal variation of the local scour around the side-by-side and triangular arrangement of the piles

5.2. *Side-by-side arrangement with two piles*

At first a simulation is run for the side-by-side arrangement where both piles are directly exposed to the incident waves. The area between the two piles creates a contraction effect. The magnified velocity due to the contraction results in higher bed stresses and higher sediment transport rates than for a single cylinder. The equilibrium scour and the free surface location around the piers is shown in figure 3. It is observed that maximum scour is taking between the individual piles while outer edges of the cylinder are also equally affected.

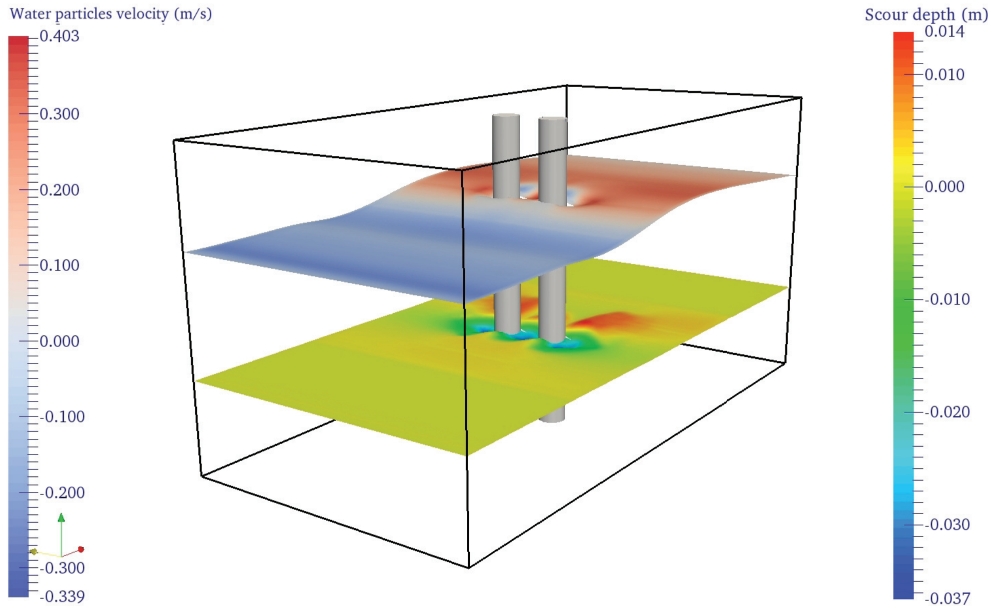

Fig. 3: Local scour with free surface velocity profile around the side-by-side piles arrangement

5.3. Triangular arrangement with three piles

In the second simulation the number of piles is increased to three with a triangular arrangement while keeping the center to center distance of the piles the same as in the previous section. The third additional pile is placed in perfect triangle arrangement as shown in figure 4. Keeping all other input parameter unchanged, the simulation is run until equilibrium conditions are achieved. It is found that the simulated scour depth is 20 mm and it matches well with experimental scour depth of 18 mm. As shown in figure 4, in comparison to side-by-side arrangement, the magnitude of the local scour decreases with negligible scour around the additional third pile. The final scour pattern with the free surface velocity is shown in figure 4.

It can seen that the placement of the third pile in front of the gap is reducing the jet effect in the contraction area. Therefore relatively less velocity is observed, which results in less scour. Moreover, the sides of the piles are also less affected by scour. It is interesting to note that in comparison to the side-by-side arrangement, scour is reduced by 45% and the area affected by the scour is also smaller. In addition to that, there is no observed scour at the downstream side the piles and the stirred up sand from the higher bed stress zone is the deposited there.

6. Conclusion

Numerical simulations of local scour around cylinders in a side-by-side and a triangular arrangement are performed using the REEF3D. Cnoidal waves are generated in the numerical wave tank and the free surface is captured using the level set method. The local scour simulations are run until equilibrium condition is achieved. Finally, the simulated results are compared with experimental observations and well agreement is seen. The following conclusions are drawn from the results:

- Scour under wave action increases with time until equilibrium state is achieved.
- The side-by-side arrangement of the piles develops a contraction effect and results in higher scour
- The triangular arrangement with same spacing between the piles develop less scour
- Compared to the side-by-side arrangement, the triangular arrangement results in a reduced scour depth

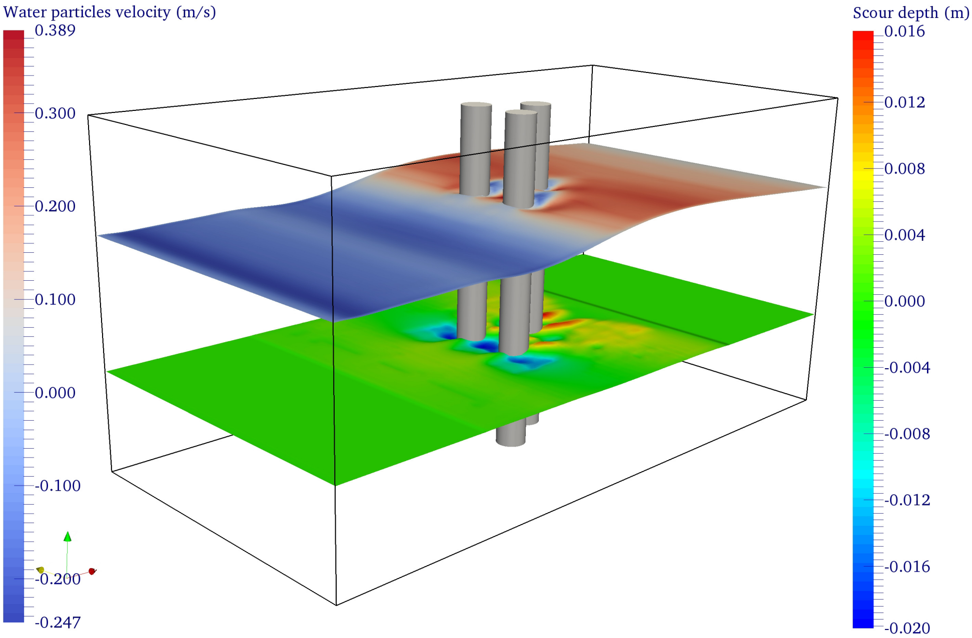

Fig. 4: Local scour with free surface velocity profile around the triangular arrangement with three piles

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