Numerical Modelling of Scour Around an Offshore Jacket Structure Using REEF3D

Nadeem Ahmad, Hans Bihs, Arun Kamath and Øivind A. Arntsen

Abstract In the present paper, a numerical investigation of the scouring around offshore jacket structure is carried out. The open-source CFD model REEF3D is used for the numerical modelling. The model solves the Reynolds-averaged Navier–Stokes equations with k-ω turbulence closure to calculate the flow hydrodynamics. The simulated flow field is coupled with sediment transport module in the model to calculate the scouring process. The scouring calculations are based on the Exner formula. The free surface and sediment bed topography are captured with the level set method. Results discuss the numerical modelling of an in situ local scour around the jacket foundations at the C-power wind farm Thornton bank. The key finding from the paper is the local scour around the individual jacket foundations and the global scour which takes place in form of a saucer-shaped. Additionally, the hydrodynamics and the temporal evolution of the scouring process under the wave and current action are discussed. The implication of the study is to set up a CFD model for the hydrodynamics and the scour calculations around offshore jacket foundations.

Keywords Jacket foundations · Local scour · Global scour · Wave and current
Free surface · CFD · REEF3D

1 Introduction

Increased renewable energy generation and the development of the larger offshore turbine generators are one of the prime tasks, the offshore industry has to deal with. In this context, the stability of jacket structure is an important concern and needs to be analysed thoroughly against the possible scour around the jacket structure foundations.

N. Ahmad (✉) · H. Bihs · A. Kamath · Ø. A. Arntsen
Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway
e-mail: nadeem.ahmad@ntnu.no

K. Murali et al. (eds.), *Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018)*, Lecture Notes in Civil Engineering 22,
https://doi.org/10.1007/978-981-13-3119-0_40

There is a limited knowledge about the scouring process around the offshore platforms such as the jacket foundations, tripods and the other type of wind turbine foundations [15][?, ?]. This is due to the fact that the field measurement of the flow hydrodynamics and the temporal variation of the erosion process are challenging and time-consuming process. Thus, the estimation of the maximum scour around the jacket foundations is carried out by using the scour formula for the group of the vertical foundations [14], developed for vertical foundations and does not account for the effect of the scouring process around the horizontal and the tangential bracings assembled with the vertical foundations, i.e. the jacket structure. The calculation of the maximum scour depth around the jacket foundations using the formula might be ambiguous and consequently unexpected expenditure on the scour protection measures [9]. CFD modelling of the scouring process around the jacket foundations could be a suitable approach to analysing scour problems more accurately. A growing body of literature has investigated sediment transport under the local flow field. These studies discuss the 2D and 3D numerical modelling of local scouring process around the single horizontal foundation and vertical foundations [1, 2, 4, 13]. However, there is still a need for a discussion on the scour process around the jacket foundations, which comprises an assembly of the horizontal and the tangential bracings attached with the vertical foundations.

Hence, the primary objective of the present study is to investigate 3D scour around jacket foundations. The numerical model is implemented for the modelling of an in situ local scour case around the jacket foundations at the C-power wind farm Thornton bank, which is a sandbank. According to the available field data [7], the storm of the significant wave height $H_s = 3.5$–4.5 m occurred during the period of December 2011–January 2012 and resulted in the scour around the jacket foundations. To study the same case, two case scenarios are run. The first case discusses the scour calculations for the waves of $H = 4.5$ m; the Keulegan–Carpenter number KC = $\pi H/D = 14$. The second case shows the scouring process under the typical steady current flow, i.e. the $KC = \infty$. The simulated results discuss hydrodynamics, the maximum scour depth and the temporal variation of the scour process around jacket foundations.

2 Numerical Model

2.1 Hydrodynamic Model

The open-source CFD model REEF3D [5, 6, 12] is used for the numerical modelling of the wave hydrodynamics and the sediment transport. The model solves the incompressible Reynolds-averaged Navier–Stokes (RANS) equations, along with the continuity equation to calculate the velocity field in the numerical wave tank. The k-ω model is used to calculate the eddy viscosity by solving for the turbulent kinetic energy k and the specific turbulent dissipation ω. Details of the equations and the method can be found in [6].

2.2 Morphological Model

Sediment transport is calculated based on the flow field simulated by the hydrodynamic module in REEF3D. The bed shear stress is determined considering a logarithmic velocity profile near the sediment bed. The bed shear stress τ is defined as follows:

$$\tau = \rho u_*^2 \tag{1}$$

where u_* is the shear velocity and is defined as:

$$\frac{u}{u_*} = \frac{1}{\kappa} \, ln\left(\frac{30z}{k_s}\right) \tag{2}$$

here u is the velocity at a height z above the bed, $\kappa = 0.4$ is the von Karman constant, $k_s = 3d_{50}$ is the equivalent sand roughness and d_{50} is the median grain size. The bed-load calculations are made with the formulation proposed by [16]. It is based on the sediment particle mobility which suggests that when the bed shear stress just exceeds the critical bed shear stress, the motion of the particles is initiated. The formulation for the bed-load transport rate q_b [16] is defined as follows:

$$\frac{q_b}{d_{50}^{1.5}\sqrt{(s-1)g}} = 0.053\,\frac{T^{2.1}}{D_*^{0.3}} \tag{3}$$

Here, T is the transport stage parameter and D_* is the particle parameter. The critical bed shear stress calculated with the Shields diagram leads to underestimation of the sediment transport because it does not account for the effects of a sloping bed. This problem is handled with the modified critical shear stress formulation on sloping beds proposed by [8]. The effect of the sloping bed is accounted for by considering the longitudinal bed slope θ, the transverse bed slope α, the angle of repose of the sediment φ and the drag and lift forces, yielding to the expression for the critical bed shear stress reduction factor r. Thus, the modified critical bed shear stress τ_{cr} is calculated by multiplying the Shields critical bed shear stresses τ_0 with the reduction factor r [8]. The change in bed elevation is calculated with Exner's formula. The method is based on the conservation of sediment mass where the horizontal spatial variation in the bed load is conserved with the spatial change in the vertical bed elevation. The morphological evolution occurs as a nonlinear propagation of the bed-level deformation in the direction of the sediment transport. The transient change in bed level is defined as follows:

$$\frac{\partial z_b}{\partial t} + \frac{1}{(1-n)}\left[\frac{\partial q_{b,x}}{\partial x}\right] + E - D = 0 \tag{4}$$

where z is the bed level, $q_{b,x}$ is the bed load, n is the sediment porosity, D is the deposition rate and E is the entrainment rate from the suspended load. The sediment surface is modelled with the level set method approach which is an implicit representation of the sediment bed as the zero level set. The driving velocity $F = \partial z_b/\partial t$ moves the interface in the vertical direction to represent the change in the sediment bed due to the scouring action.

3 Model Validation

The model has already been validated for the scouring under the steady and unsteady flow conditions. Results from these validation cases discussed the scour around the vertical piles, horizontal piles and the piles in a group. Details of the papers can be found in [1, 3].

4 Scour Around the Jacket Foundations

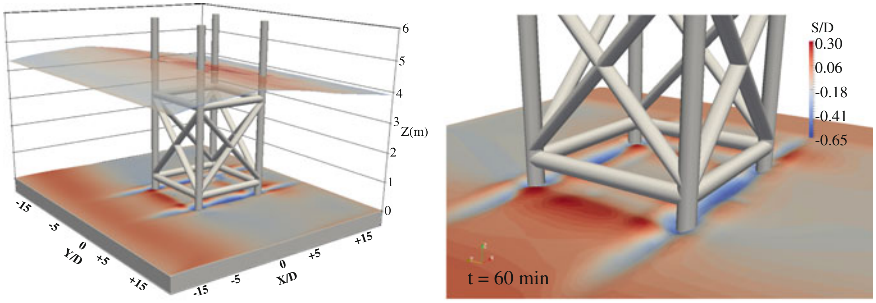
The model is implemented to simulate the scour around the jacket foundations at the C-power wind farm Thornton bank, which is a sandbank. The height of the jacket foundations on the site is between 40 and 50 m. The jacket foundations comprise of the four vertical foundations connected with horizontal and the diagonal bracings. The diameter of the vertical foundations is $D = 2$ m, and the gap between the individual foundation is $G/D = 10$. The jacket foundations are located in water depths ranging from 12 to 30 m. According to the hydrodynamic measurements available from the Flemish banks monitoring network [7], only two storms of the significant wave height $H_s = 3.5$–4.5 m occurred during the period of December 2011–January 2012 and resulted in the major scour.

The numerical modelling is carried out by the scaling the in situ incident waves and sediment characteristics. The selected scaling factor satisfies two scaling criteria. First is the Froude criterion for hydrodynamics that arises when the ratio of the inertia force to gravity force is held constant between prototype and model. The second criterion maintains the speed parameter of the sediment particles between prototype and model. Thus, the calculated scaling factor for the sediment bed material is 2.7 and the incident wave characteristics are scaled down by a factor of 7.5. The details of the scaling method and calculations can be found in the article by [10]. After the scaling, the height of the jacket foundations is considered to be 6 m. The diameter of the vertical foundations is $D = 0.26$ m, and the diameter of the diagonal bracings is 0.13 m. The gap between the vertical foundations is $G/D = 10$ which replicate the actual gap ratio between the foundations on site. The still water level is $d = 4$ m. The fifth-order Stokes waves of wave height $H = 0.6$ m; assuming the wave period of $T =$ 4.5 s are generated in the NWT. The bed material consists of non-cohesive sand with median particle diameter $d_{50} = 0.13$ mm. The sediment density is $\rho_s = 2700$ kg/m^3, and the angle of repose of the sediment is $\varphi = 35°$. The Shields parameter for the bed material is $\theta_c = 0.047$. The wave generation in the numerical wave tank is managed with the active wave absorption method (AWA). The method is considered to be a good choice to manage both the wave generation and the absorption in a relatively shorter numerical domain [11].

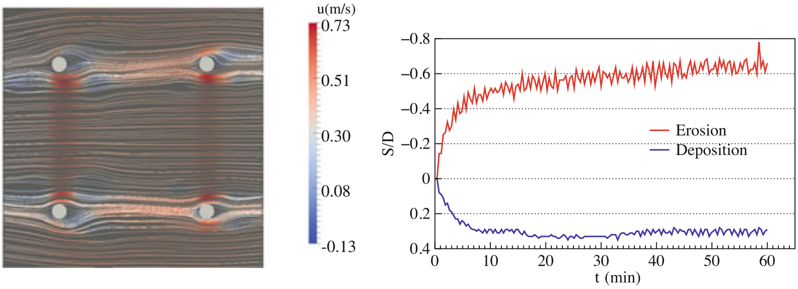
4.1 Scour Under Waves

In this section, results of the scouring process around the jacket foundations for the observed waves are discussed. The foundations are exposed to the regular waves of wave height to water ratio H/d = 0.15 and the KC = 14. The simulation is run for $t = 60$ min. Figure 1a shows a 3D view of the simulated maximum scour depth with the free surface profile, and Fig. 1b shows a zoom-in view of the simulated scour around the jacket foundations. It can be seen that the maximum scour is taking place around the vertical foundations and the area under the longitudinal bottom bracings is equally affected. However, the foundations at the downstream side and the area under the lateral bracings show relatively less scour. Figure. 1c demonstrates the velocity profile at XY-plane to elaborate on the change in the velocity around the jacket foundations. The higher velocity around the vertical foundations and under the lateral bottom bracings indicates a flow contraction and the formation of the flow jet, respectively. In addition, despite being the shadow region, there is significant flow velocity under the longitudinal bottom bracings which indicate a converging flow into the shadow region for the KC = 14. Thus, the presence of relatively higher velocity due to the flow contraction around the vertical foundations, the formation of the flow jet under the lateral bracings and a converging flow regime under the longitudinal bracings results in the higher local scour, the wake erosion and the tunnel erosion, respectively, consequently a global scour around the jacket structure [15].

Figure 1d shows the temporal variation of the erosion and the deposition process. The spikes in the graphs represent the change in the maximum scour depth or deposition changing with the back-forth action of the waves. It is seen that temporal variation of the maximum scour and the deposition is almost the same, and it grows rapidly in the beginning and slows down as it approaching an equilibrium state after $t = 60$ min. The magnitude of the maximum scour depth is $S/D = 0.65$ that is almost double of the maximum deposition. The result agrees with the field observation [7] of the average scour depth measured after the storm, compared to the expected value of S/D = 1.3 for high foundations calculated using the empirical formula [9, 14].



(a) Full view (b) Zoom-in view, scour after t=60 min



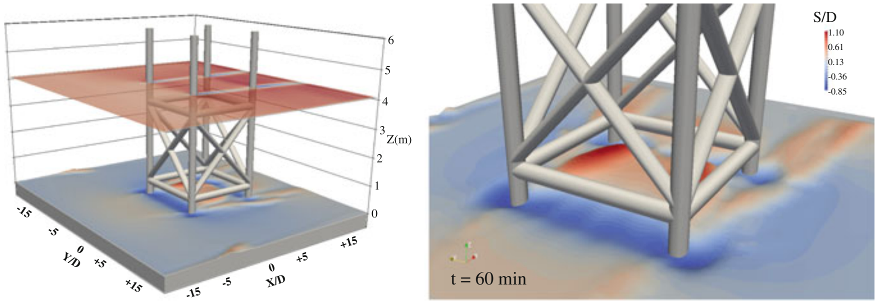
(c) XY-plane, Z/D = 0.25 (d) Temporal variation of the process

Fig. 1 Scouring under the wave action around the jacket foundations

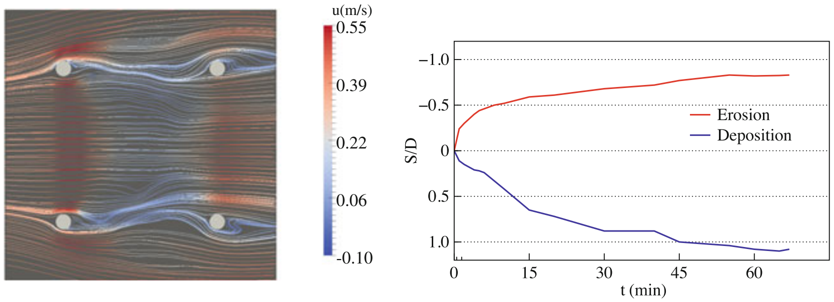
4.2 *Scour Under the Steady Current*

In this section, scour under the steady current is discussed. The incident flow velocity is $u = 0.6$ m/s which represents a typical flow condition on the field [7].

The simulation is run for $t = 60$ min, and the results of the hydrodynamics and the resulting scour around the jacket foundations are discussed. Figure 2a shows a 3D view of the simulated maximum scour depth with the free surface profile, and Fig. 2b shows a zoomed view of the simulated scour around the jacket foundation. It can be seen that the maximum scour is taking place around the vertical foundations connected with the lateral bottom bracings at the upstream side of the structure. The foundations at the downstream side of the structure show relatively less scour. However, the area under the longitudinal bottom bracings seems safe against the erosion. Figure 2c shows the velocity profiles at XY-plane. Results show a higher velocity around the vertical foundations, relatively low velocity under the bottom lateral bracing and the lowest velocity under the longitudinal bottom bracings. Consequently, the higher local scour around the vertical foundations, relatively strong tunnel erosion and almost no wake erosion. In addition, It can be seen that the sediments eroded from the upstream side foundations and are depositing in low-velocity regime inside the jacket. Figure 2d reveals that both the scour depth and the deposition grow rapidly



(a) Full view (b) Zoom-in view, scour after t = 60 min



(c) XY-plane, Z/D = 0.25 (d) Temporal variation of the process

Fig. 2 Scouring under the current flow around the jacket foundations

and attain equilibrium state with an almost equal magnitude of the maximum erosion and the deposition. The magnitude of the maximum deposition is $S/D = 0.85$. The result supports the field observation that under the typical conditions of the steady current, the averaged scour depth ranges between $S/D = 0.7$–0.95.

5 Conclusion

The main objective of the study was to implement a CFD model to predict the scour around the offshore jacket structures in the deep water. The open-source CFD model REEF3D is successfully implemented and the results of the maximum scour under the waves and current action predicted satisfactorily with a good agreement with the field measurements. The following conclusions can be drawn from the study:

- Model provides sharp capturing of 3D scour featured with the free surface profile for the large domain, the problem encountered around the deepwater offshore jacket structure.

- The study revealed the scour pattern under the waves ($KC = 14$) and the steady current ($KC = \infty$).
- In case of the wave flow, the maximum scour takes place under the longitudinal bottom bracings attached with the vertical foundations, which indicates significant wake scour compared to tunnel scour.
- In case of the steady current flow, the maximum scour takes place under the lateral bottom bracings attached with vertical foundations, which indicates significant tunnel erosion compared to wake erosion.
- The current approach will help to solve the hydrodynamics and the associated scour problems, combining the reliable design of protection measures.

Acknowledgements This study has been carried out under the POL- NOR/200336/95/2014, and the authors are grateful to the grants provided by the Research Council of Norway. This study was supported in part with computational resources at the Norwegian University of Science and Technology (NTNU) provided by NOTUR, http://www.notur.no.

References

1. Ahmad N, Bihs H, Chella MA, Arntsen ØA, Aggarwal A (2017) Numerical modelling of arctic coastal erosion due to breaking waves impact using REEF3D. In: The 27th international ocean and polar engineering conference. International Society of Offshore and Polar Engineers
2. Afzal MS, Bihs H, Kamath A, Arntsen ØA (2015) Three-dimensional numerical modeling of pier scour under current and waves using level-set method. J Offshore Mech Arctic Eng 137(3):032,001
3. Ahmad N, Bihs H, Alagan Chella M, Arntsen ØA (2017) A numerical investigation of erosion around offshore pipelines. In: MekIT'17—9th national conference on computational mechanics, Norway
4. Ahmad N, Bihs H, Kamath A, Arntsen ØA (2016) 3D numerical modelling of pile scour with free surface profile under wave and current using level set method in model REEF3D. In: 8th international conference on local scour and erosion, ICSE 2016, Oxford, UK
5. Bihs H, Kamath A (2017) A combined level set/ghost cell immersed boundary representation for floating body simulations. Int J Numer Methods Fluids 83(12):905–916
6. Bihs H, Kamath A, Alagan Chella M, Aggarwal A, Arntsen ØA (2016) A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. Comput Fluids 140:191–208
7. Bolle A, Winter JD, Goossens W, Haerens P, Dewaele G (2012) Scour monitoring around offshore jackets and gravity based foundations. In: 6th international conference on scour and erosion
8. Dey S (2003) Threshold of sediment motion on combined transverse and longitudinal sloping beds. J Hydraul Res 41(4):405–415
9. DNV (2014) Design of offshore wind turbine structures. Offshore standard DNV-OS-J101. Det Norske Veritas AS
10. Hughes SA, Fowler JE (1990) Technical report CERC-90-8: midscale physical model validation for scour at coastal structures. Technical report, Coastal Engineering Research Center Vicksburg, MS
11. Jacobsen NG, Fuhrman DR, Fredsøe J (2012) A wave generation toolbox for the open-source CFD library: openfoam. Int J Numer Methods Fluids 70(9):1073–1088
12. Kamath A, Alagan Chella M, Bihs H, Arntsen ØA (2016) Breaking wave interaction with a vertical cylinder and the effect of breaker location. Ocean Eng 128:105–115

13. Olsen NRB (2010) A three-dimensional numerical model for simulation of sediment movements in water intakes with multiblock option, users manual
14. Sumer BM, Fredsøe J (1998) Wave scour around group of vertical piles. J Waterw Port Coast Ocean Eng 124(5):248–256
15. Sumer BM, Roulund A, Fredsøe J, Michelsen J (2002) Three-dimensional numerical modeling of flow and scour around a pile. In: Proceedings of 1*st* international conference on scour of foundations, pp 795–809 (2002)
16. van Rijn LC (1984) Sediment transport, part I: bed load transport. J Hydraul Eng 110(10):1431–1456