Methodology to assess scour development around complex structures

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Abstract. Accurate prediction of scour evolution around fixed offshore foundations is a key parameter for selecting the most appropriate scour mitigation strategy. Various formulations can be used to estimate scour around monopiles. However, non-specific formulations have been developed for more complex foundations. In the case of jacketed offshore substations (OSS), the geometry can be one of the most complex. This paper describes a hybrid methodology (numerical model simulations, semi-empirical approaches and physical experiments) to estimate the scour evolution around OSS. The application of this methodology allows the selection of the most appropriate mitigation strategy from an early stage of the project to the final decision. The methodology is accompanied by some examples. In general, the results obtained from the semiempirical approaches show quite good agreement with the measurements from the physical experiments. Nevertheless, considering the complex geometry of the OSS and the potential nonlinearities associated with the platform geometry, physical experiments are required to ensure the correct estimation of the maximum scour (local and global).

1. Introduction

When structures are supported on the seabed, the presence of the foundation causes an increase in flow velocity, turbulence and vorticity around the structure. All these effects together increase the mobility of the seabed around the structure, leading to what is known as scour ([1] and [2]). The magnitude of the scour depth depends on several parameters such as seabed characteristics, hydrodynamic conditions, water depth or platform geometry.

During the design process of a fixed offshore foundation, an accurate estimation of the scour is critical in order to select the most appropriate scour mitigation strategy [3].

- 1) Free scour development (the maximum scour depth is less than the maximum allowable value or the foundation is designed to allow free scour development).
- 2) Installation of scour protection pads to fix the seabed level to prevent lowering of the seabed around the foundation.

An accurate prediction of the scour around slender cylinders can be estimated using various methods and formulations available in the literature (e.g. [2], [4] or [5] among others). However, when the geometry of the structures is complex, the estimation of the scour along time is more difficult. In many cases reduced scale physical experiments are recommended.

At this point, the Offshore Substation (OSS) is one of the most unique, critical and complex structures to be found at an Offshore Wind Farm (OWF). Although OSS can be monopiles or even gravity foundations, they are often jacket foundations connected to the seabed by multiple piles, groups of piles or suction caissons (Figure 1). For these structures, the development of scour around this type of structure is mainly developed in two phases [1]:

- 1) Local Scour Erosion around elements in contact with the seabed.
- 2) Global scour general lowering of the seabed as a result of the global blocking effect created by all elements of the foundation. The time scale of global scour could take years from the installation of the platform.

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In addition, seabed lowering associated with morphodynamic changes, such as those induced by the propagation of sand waves or megaripples, must also be considered in order to estimate the minimum seabed level at the foundation location.

The correct estimation of scour will provide the platform designers with the necessary information to select the most appropriate mitigation strategy. In general, the design of the scour protection pad is carried out in parallel with the selection of the most feasible mitigation strategy.

This paper focuses only on the presentation of a hybrid methodology to assess the free scour evolution around the jacket OSS, where the connection to the seabed is provided by different sets of pile clusters located around the foundation (Figure 1).

The presented methodology includes the application of semi-empirical formulations, advanced numerical model simulations (openFoam) and reduced scale physical experiments. The first two phases (numerical model simulations and semi-empirical approaches) are carried out to identify the potential scour depth using some simplifications at an early stage of the project. While, the final validation of the equilibrium scour depth will be carried out by performing physical experiments on a reduced scale (the results of Phase I and II will be used to properly design the physical experiments). The results of the physical experiments also provided useful information to derive predictive semi-empirical formulations to improve the prediction of the scour depth in future foundations.

This paper is a methodological paper in which the main assumptions made at each stage of the methodology are presented and discussed. In addition, some examples from previous experience are also included in the methodology section of each stage.



Figure 1. OSS geometry.

2. Methodology

The methodology proposed has been divided in three main phases:

- a) Step I (early project stages): Advance numerical model simulations: Identification of the flowstructure interaction and the amplification coefficient around the foundation.
- b) Step II (early project stages): Estimation of the scour based on the application of semi-empirical formulations.
- c) Step III (final validation): Physical experiments at reduced scale (final validation).

In each section, different examples are presented to facilitate the understanding of the proposed methodology. In addition, the methodology presented has been applied to non-cohesive soils, where the maximum erodibility of the seabed material is expected [6].

2.1. Step I: Numerical Modelling (flow-structure interaction)

Numerical model simulations are mainly carried out to estimate the flow amplification coefficient (ratio of the velocity around the foundation divided by the undisturbed flow velocity) around the CFL interaction is evaluated at this stage of the project.

Various numerical methods can be used to calculate the velocities around a jacketed structure exposed to currents and waves. The numerical method chosen must be able to deal with the viscosity of the water and the free surface. In the present case, a RANS method coupled with the VOF transport equation is used to simulate the water effects over the jacket structure.

The Reynolds Averaged Navier Stokes (RANS) method is one of the most widely used models for simulating fluid physics. This method includes the effects of viscosity and the effects of turbulence. The key point of the method is that the turbulence effects are averaged over time. This means that not all but some of the turbulence characteristics are captured. The time averaging of the equations generates additional terms that require additional equations to close the problem. These additional equations are the models used to simulate the turbulence properties. Depending on the model, the turbulence transport equations are different. In this case, the $k\omega$ -sst model is used. This model uses two transport equations to model the turbulence, one for the kinetic energy and one for the dissipation rate. This model assumes that the turbulence is isotropic.

The Volume of Fluid (VOF) method is used to transport the phase information along the domain. It allows the propagation and interaction of the water waves with the structure to be represented. The VOF method uses an additional equation for the propagation of the phase content along the domain.

There are other numerical alternatives capable of solving the fluid-structure interaction problem with much more detail (i.e. .LES, DNS), but RANS models are identified as a good choice in terms of the accuracy/cost ratio, which is one of the major constraints in most engineering problems.

The mesh is one of the key points in setting up the numerical model. The results of the RANS equations are usually quite mesh dependent. Therefore, in order to increase the accuracy of the simulation, a mesh convergence study is carried out. In this way it is possible to reduce the influence of the mesh properties on the final results. This does not mean that the results are correct, as the model used and the boundary conditions are still in the middle, but it allows the uncertainty of the simulation to be reduced.

Since the RANS equations are time-dependent, it is necessary to integrate the equations not only in space but also in time. To ensure that the time integration is correct, it is necessary to perform an additional convergence study for the time step. In this case, the simulations were performed using an adaptive time step algorithm. It relates the value of the time step to the CFL, which is also related to the mesh size. Therefore, the convergence study is not performed directly on the time step but on the CFL number.

The flow-structure interaction results provide very useful outputs in terms of identifying the maximum flow velocities and the extent of lee wakes (Figure 2) around the foundation. Figure 2 (left side) shows the flow amplification factor around a jacketed OSS under currents (maximum flow amplification factor combining the maximum values at each mesh node for different current directions). The coupling effect between flow amplification waves and jacket elements can lead to the development of global scour.

Based on previous experience with various foundations, the flow amplification factors are around 2 for currents and 3 for waves (in a few specific cases, maximum values have been reached up to 3.5-4 times the undisturbed wave-bottom velocity).



Figure 2. Left: Numerical Model Simulation (CFD, openFOAM). Right: Flow Amplification Coefficient.

2.2. Step II: Estimation of the scour based on the application of semi-empirical formulations.

In this section, both local and global scour around the foundation are estimated based on the application of semi-empirical formulations and the results of the numerical modelling. The total scour expected at the foundation is the sum of both quantities plus the expected seabed subsidence associated with the morphodynamic changes.

2.2.1. Local Scour

Based on previous experience with jacket OSS, local scour is mainly located around the elements in contact with the seabed (mainly pile clusters and mud mats). The contribution to local scour from other elements, such as horizontal and vertical frames, J-tubes and upper foundation elements, can be considered negligible compared to the local scour observed around the pile clusters and mud mats. Given the key assumption described in the previous paragraph, a simplification of the pile cluster

geometry is proposed. The main idea is to replace the real geometry with an equivalent simplified geometry capable of producing an equivalent blocking effect. The pile clusters (elements in contact with the seabed) are simplified as an equivalent truncated vertical cylinder, where:

- Diameter: contour of the pile sleeves and jacket column (based on previous experience the equivalent diameter may vary from 8-16metres).
- Height (stick-up): From the ground to the top of the pile cluster (variable height depending on the pile cluster).

In general, the equivalent diameter of the truncated cylinder (simplified pile cluster geometry) is 3 to 5 times larger than the column diameter. Given these differences, local scour is estimated by considering only the contribution of the equivalent truncated cylinder (simplified geometry around the pile cluster). As the height of the equivalent vertical cylinder does not extend along the entire water column, the application of a height correction factor (Kh) is proposed to account for the limited height of the pile cluster with respect to the entire water column. Different height correction factors have been proposed for vertical cylinders (i.e. [7] and [8]).

The simplified geometry can be seen in Figure 3 (dashed red circles represent the simplified geometry).



Figure 3. Simplified geometry.

Given the simplification suggested above, the equilibrium scour depth can be estimated individually using Equation 1:

$$S_{eq-f} = S_{eq} \cdot K_h$$

Where:

- S_{eq-f} Final Equilibrium scour depth.
- Seq Equilibrium scour depth for vertical cylinders.
- K_h correction factor for a truncated cylinder, stick-up height.

It should be noted that the proposed simplification considers each pile cluster as an individual element, without considering the influence of the horizontal and vertical frames, as well as the clogging effect induced by all the jacket elements. In summary, local scour is estimated for individual elements by attempting to reproduce the clogging effect of a single pile cluster.

Based on the proposed simplification of the geometry, the local scour is calculated under steady-state conditions and the long-term analysis is simulated taking into account the metocean conditions associated with the lifetime of the foundation (different metocean databases are used to take into account the characteristics and duration of the events).

2.2.1.1 Steady Environmental Conditions

Under steady uniform conditions (wave, currents or combined wave and currents), the evolution of the scour is often represented by Equation 2 ([1] and [2]), where, S(t) is the evolution of the scour with time, T_{char} (s) is the characteristic time, S_{eq} (m) is the equilibrium scour depth and t (s) the time.

$$S(t) = S_{eq} \left[1 - e^{\left(-\frac{t}{T_{char}} \right)} \right]$$

Equation 2

Equation 1

In order to estimate the evolution of the scour depth along the time, the application of Equation 1 requires the knowledge of the equilibrium scour depth and the characteristic time:

- a) Steady currents: According to [9], tidal currents are chosen as the driving parameter for scour evolution. The selection of maximum currents associated with the RP of 10y-50yr-100yr may give rather conservative results due to the limited duration of these events and combined with the presence of waves:
 - Live Bed Regime ($\theta > \theta_{cr}$): The parameters of Equation 2 can be estimated using the relationship proposed in [5] or [2]. An additional formulation derived from the physical experiments conducted at IHCantabria has been included in the methodology and will be presented soon.
 - Clear Water condition ($\theta < \theta_{cr}$): The parameters of Equation 2 can be estimated using the relationship proposed at [1] and [5].
- b) Combine Waves and Currents: Formulations proposed at [10] and [2] (design sea states based on [11]).

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In general, the results obtained at this stage are quite good compared to the results obtained during the physical experiments.

2.2.1.2 Long term Analysis

In addition to the steady state, a model based on those proposed in [7] and [12] was also included in the methodology to estimate the final equilibrium scour depth around the OSS, taking into account the geometric simplification described above. The developed model considers the following inputs:

- Platform Geometry simplified (as described in the previous section).
- Metocean Characteristics (Figure 4) IHCantabria metocean databases considering waves, currents and water depth variations. Finally, the database time interval (dt) is 1 hour, so the scour estimated was updated hourly.
- Soil Characteristics (non-cohesive materials).
- Flow amplification coefficient (based on numerical model simulations described in the next section). To estimate the mobility parameter at the foundation.



Figure 4. Example of the metocean characteristics: 1) Wave rose, 2) Time series.

The estimation of the scour depth at each time step follows the equation presented in [10]. The developed model allows the selection of different formulations (steady state) to estimate the scour and backfilling time and the equilibrium scour depth (live bed regime or clear water condition, depending on the sediment transport regime of each time step). Estimation of the backfilling time is not clear for this type of structure. For monopiles, according to [7] and [13], the backfilling characteristic time is often greater than the scour time (variable as a function of the KC number). The evolution model allows the backfilling characteristic time to be varied in order to assess the uncertainties associated with this parameter (variation of the backfilling characteristic time can reduce/increase the final equilibrium scour depth between 0.5-2m). Figure 5 shows an example of the results obtained after applying the evolution model. The blue lines show the evolution of scour over time, while the grey line shows the hourly significant wave height. The main difference between the blue lines is the characteristic time associated with the backfilling events (the backfilling time on the dashed line was considered to be much higher than on the solid line, an accurate estimation of the characteristic time is difficult due to the geometric simplification).



Figure 5. Left: Long term scour analysis. Right: Scour evolution under steady condition.

In general, the equilibrium scour depth reached after applying the long-term analysis gives a lower equilibrium scour depth than the values obtained for tidal steady currents. In many situations, backfilling events combined with the fluctuation of the tidal currents make it impossible to achieve the equilibrium achieved with steady currents.

2.2.2. Global Scour

The estimation of global scour around the jacket foundation is quite difficult to predict. In many situations it may take several years to develop after the OSS has been installed. There is limited information on global scour.

To estimate the evolution of global scour, the formulation proposed in [14] can be used. Additionally, based on previous physical experiments conducted in-house at IHCantabria facilities, the global scour magnitude is estimated to be between 1-2m.

2.3. Step III: Physical Experiments

Physical experiments allow to properly reproduce the interaction between flow, structure and soil, therefore the main objective of the physical experiments is the final estimation/validation of the equilibrium scour depth along the pile clusters, as well as the potential assessment of the global scour around the foundation.

The experimental methodology was developed at IHCantabria facilities (CCOB, equivalent to the basin tests described in [15]). Considering the main characteristics of the basin (CCOB) and the size of the platforms, the scale of the test can vary from 1/35 to 1/45. In addition, since the basin is wider rather than longer, two or even three OSS may be tested simultaneously (Figure 6 shows an example of the proposed setup). Froude scaling laws of similarity [16] and mobility similarity are applied to reproduce the environmental conditions and soil mobility (non-cohesive materials) at laboratory scale.

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Figure 6. General view of the physical tests.

In order to assess the scour evolution over time, physical tests are performed in different steps, which are carried out in sequence. The test sequence is repeated until equilibrium is reached (the duration of the interval may vary depending on the cumulative test time). Between each step, laser scanner measurements are performed to measure the evolution of the scour (depth and extent) over time.

As an example of the results obtained from the basin tests, the next figures summarise the main outcomes obtained during a series of physical experiments around a typical OSS under steady uniform currents (tidal magnitude). Laser scanner measurements are taken around the entire area of the jacket foundation, so that both the local scour and the global erosion pattern can be determined after each time step. Figure 7 shows the laser scanner measurements after three different steps of the test sequences.



Figure 7. Laser Scanner measurements from the physicial experiments

With regard to local erosion close to the jacket piles, Figure 8 shows the evolution of scour along one of the front piles of the jacket foundation (Figure 8 left side, erosion magnitude after each time step, Figure 8 right side, longitudinal profiles from the centre of the pile). Figure 8 clearly shows how, for a single pile, the final equilibrium scour depth was reached by the end of the test.



Figure 8. Left: evolution of the scour around a single pile. Right: Longitudinal Profiles from a single pile after each step of the sequence.

Finally, if the duration of the test is sufficiently long, global scour evolution patterns can also be observed during the physical experiments. For example, Figure 9 shows the global seabed lowering between one of the rows of OSS. This effect was observed when the front erosion wake reached the position of the rear pile cluster (Figure 9). The left side of Figure 9 shows, the longitudinal profiles between the two pile clusters (front and rear) after each time step. From this figure, it can be seen how from step 7 (blue line) to the last profile (black solid line) a general lowering of the seabed is generated along the jacket side. According to different results from physical experiments, the global seabed lowering varies between 1-2 metres.

2745 (2024) 012020

Step #1 Rear Pile Cluster



Based on the methodology and the results presented above, the physical experiments allow us to estimate the global and local scour around complex structures such as the OSS. The execution of the tests in several steps, allows us to identify the global erosion patterns around the different elements of the OSS.

3. Conclusions

The paper summarises the methodology presented to estimate the scour around complex structures such as jacket OSS connected to the seabed by multiple piles. The methodology presented combines numerical model simulations, semi-empirical approaches and physical experiments with the aim of estimating the potential scour around complex structures from the early design stages. The main results are presented below:

- Local scour is mainly located in the elements in contact with the seabed (pile clusters and mud mats). The simplification of the pile clusters as vertical truncated cylinders allows us to estimate the scour depth using some formulations designed for monopiles (under steady conditions and long-term analysis). The application of the semi-empirical approaches allows to get a general idea of the local equilibrium scour depth expected at the pile clusters.
- 3D CFD (openFoam) simulations are performed to reproduce the full geometry of the foundation. Numerical model simulations are performed to estimate the flow amplification around the foundation. According to previous experience with jacketed OSS, the flow amplification factor is around: currents~2, waves~3 (in a few specific cases, the maximum values reached values up to 3.5-4 times the undisturbed bottom orbital velocity). Identification of the flow amplification factor around the foundation provides the potential eroded areas around the OSS. The coupling effect between erosion wakes and jacket elements can lead to the development of global scour.
- Physical experiments allow the identification of the global erosion patterns, the local scour equilibrium depth at the piles and the global scour.
- The comparison between the results obtained with the numerical and semi-empirical approaches and the results of the physical experiments gives quite reasonable results, taking into account the main assumptions made. Finally, the presented methodology has been

satisfactorily applied to various OSS already in operation, under construction or at an early design stage.

List of Abbreviations and Symbols

- K_h correction factor for a truncated cylinder, stick-up height.
- KC Keulegan Carpenter.
- OSS Offshore substation.
- OWF Offshore Wind Farm.
- RANS Reynolds Averaged Navier Stokes.
- S(t) Scour depth in function of the time.
- S_{eq-f} Final Equilibrium scour depth.
- *Seq* Equilibrium scour depth for vertical cylinders.
- t-time.
- T_{char} Characteristic Time.
- VOF Volume of Fluid.
- θ Shields Number.
- θ_{cr} Critical Shields Number.

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