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A numerical approach for determining equilibrium scour depth around a mono-pile due to steady currents

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ABSTRACT

In this work, we propose a first approximation approach to obtain the equilibrium scour depth around a mono-pile using a numerical scour model. This is achieved by modelling the turbulent flow around the cylindrical pile to obtain the bed parameters driving the sediment motion. Using the bed parameters obtained and a Torczon optimization algorithm, the simulation model attempts to deform the bed boundary towards the equilibrium scour depth in the shortest path possible. The predicted scour depth from simulations using this approach correlated reasonably well with experimental observations.

1. Introduction

Local scouring is a process whereby bed materials are removed around a marine structure due to the disturbances of the uniform flow which typically results in a higher degree of turbulence and erosion capacity. When not managed properly, scouring can result in a significant reduction in the stability of foundation and a premature failure of the hydraulic structure.

Modelling and predicting the scour process is already challenging in laboratory environment, let alone in complex offshore applications. This complexity has resulted in coastal engineers being generally conservative when predicting scour of offshore structures. Looking at the oil and gas industry, the approach taken to tackle scour is typically to overdesign, have real-time monitoring systems or have a regular inspection programme setup to mitigate these problems. While such strategies work reasonably for this sector, less can be said for the offshore wind industry. For an offshore wind farm, the cost of protecting the large number of foundations of the wind turbines can be significant. In addition, the financing of such projects are typically lower and more complex, hence, the need for higher certainty in analysing scour is more critical to ensure its profitability. This has resulted in scour prediction research gaining significant interest, especially so with the recent increase in the number of offshore wind farms installations.

Scour analysis has typically been done empirically which has led to the derivation of numerous equations to determine the time-varying scour hole development and its eventual equilibrium scour depth [1]. For offshore wind installations, the industry currently relies heavily on these empirically derived equations and past experience to estimate bed level changes and local scour around the offshore structure. Focusing on local scour, the only classification society which provides recommendation is the Det Norske Veritas (DNV), DNV-OS-J101 [2]. In this guideline, it is suggested that the estimated scour depth is approximately 1.3 times the pile diameter, based on the equation derived by Sumer et al. [3]:

$$\frac{S}{D} = 1.3\{1 - \exp[-0.03(KC - 6)]\} \quad (1)$$

where S is the scour depth, D is the pile diameter and KC is the Keulegan–Carpenter number which describes the relative importance of drag force over initial force for oscillatory flows around a structure. Eq. (1) has been validated for smaller lab-scale structures by Sumer et al. [3]. While this equation holds for slender piles, uncertainty arises when it is applied to large foundations

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larger than 5 m (diameter calculated based on the wave periods in the North Sea [4] as described below) which are the typical pile diameter for new offshore wind turbine foundations. For large piles ($D/h > 0.5$, where h is the water depth), wave diffraction and reflection around the structure become important, especially when $D/L > 0.2$ [5] where L is the wavelength. Likewise, physical tests have shown that scour depth around large piles scale differently from that of slender piles [5,6]. Furthermore, the location of the maximum scour depth moves from the upstream face of the pile to 45° along the pile [7] as its size increases. Personal communication with various geotechnical practicing engineer reveals a general sentiment that current scour prediction tools are overly conservative for large piles. In addition, the cost implication of providing 1.3D scour allowance for large piles (5 m and greater) can be high and this has motivated wind farm owners to place more emphasis on obtaining more detailed analysis of the potential scour around each foundation.

With the rapid advancement of numerical capabilities and the significant reduction in computational cost, performing scour analysis numerically is increasingly more feasible. Likewise, from an industrial perspective, the confidence in using computational modelling is increasing with numerical models being used more widely as an engineering design tool. Thus, the potential of performing scour analysis numerically could be realized in the near future and current developments should be geared towards that direction.

For full numerical scour models, there are a number of developments being done currently in various research institutions. These models simulate the scour around a range of structural configuration including mono-piles [8,9], pipelines [10] and tripod structures [9]. In most of these investigations, the codes were developed in-house and hence, generally unavailable for public use.

For a mono-pile [8,9], the numerical work done so far is able to capture the key flow features of the scouring processes and the simulated equilibrium scour depth results agreed reasonably well with experimental observations. For a pipeline configuration [10], both the scouring and backfilling processes were modelled and the equilibrium scour depth was consistent with experiments for the different KC values they tested. For the pipeline backfilling process, while the order of magnitude of the equilibrium scour depth and time-scale were consistent with experiments, there were qualitative differences between the two results. For the simulation backfilling time series, it had a downward concave profile as it evolves towards its new equilibrium scour depth as compared to the upward concave profile observed in experiments. However, the time-scale magnitude of the simulation and experimental observation agreed well.

While these numerical investigations have shown good correlation with experimental results, we are of the opinion that full numerical scour models are more of an academic field development and are yet to be able to be practically applied to industrial applications. This is primarily due to the high computational time required for each simulation (about 2–4 weeks simulation time for a typical lab scale model) and the uncertainty of the results, given the complex environmental conditions experienced by the offshore structures. While the application of a full numerical scour model has not reached a level which can be readily adopted by the industry, the hydrodynamics portion of the model has reached a matured level and is trusted by the industry. Hence, this is an area we will focus on in understanding the potential of developing a numerical scour model based on a hydrodynamics approach.

In practical engineering, a 'quick' scour analysis that is able to take into account the complexity and uncertainty of the process is needed before it can be adopted for industrial use. As such, there are recent works on developing 'hybrid numerical scour model' for industrial applications. One of the most significant development is by Danish Hydraulic Institute (DHI). The DHI approach performs simulations around the structure based on fluid dynamics calculations and predefined scour rates derived from full scour model simulations done earlier [11]. This concept has since been developed into a commercial tool called WiTus [12]. In this work, we aim to adopt a similar path to develop a 'hybrid numerical scour model' which is based on a hydrodynamics approach.

The objective of the current work is to develop a hybrid numerical scour model based on a hydrodynamics approach to predict the equilibrium scour depth around an offshore structure for industrial application. The offshore structure configuration in this work is limited to a cylindrical pile experiencing a uni-directional steady current load case without wave loading. While a cylindrical pile was adopted in the current work, the method developed aim to be sufficiently generic to be applicable to more complex structures in the future. To allow for industrial applicability, consideration will be made to ensure that the computational time/requirements remain low so that the model can be adopted easily by the industry. The key novelty in this work is in approaching the scour process as an optimization problem of the sediment driving forces (e.g. Shields parameter) around a structure. Hence by employing an established optimization algorithm, the proposed numerical model aims to bypass the 'iterative' scour mechanism and estimate the equilibrium scour depth within a shorten period.

2. Theory

The scour around an offshore structure is primarily due to the changes in the sediment mobility within its vicinity. These changes in sediment mobility are due to the increase in bed shear stress caused by the constriction and amplification of the flow and the increase in turbulence around the structure. As such, these are the key areas to be modelled well in order to predict the equilibrium scour depth.

In a full numerical scour model [8], the approach is typically: (1) model the turbulence flow around the structure, (2) determine stress amplification and Shields parameters on the bed and (3) utilizing these bed parameters as inputs into the sediment transport equations to solve the sediment transport and morphological evolution of the bed. This approach provides a significant amount of details into the scour process. However, the computation time required is significantly high.

In this work, a hybrid/modified approach is proposed to reduce the computational requirement for each simulation. This approach is quite similar to the process described above, i.e. first, the turbulence flow around the structure is calculated, then the shear stress amplification and Shields parameters on the bed are determined. Subsequently, instead of determining the sediment transport behaviour and bed morphology, an objective function and mesh optimizer will be used to guide the bed morphology to an equilibrium scour depth of a predefined shape. This modified approach reduces the computational requirement of the scour simulation model by estimating the equilibrium scour depth within a limited numbers of iterations.

2.1. Turbulence modelling

Due to the large domains considered, the full governing equations cannot be solved as in fluid flow investigations of small and simple geometries (see further references in e.g. [13]), although the averaged equations can still be utilized together with a suitable turbulence model. Hence, to model the turbulence of the flow, a Reynolds Averaged Navier Stokes (RANS) approach was utilized in this work. In a RANS approach, when a Reynolds decomposition is