NUMERCIAL WAVE FLUME FOR THE STUDY OF SCOUR PROTECTION AROUND OFFSHORE MONOPILE FOUNDATIONS UNDER CURRENTS LOADING

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Introduction

Offshore Wind Farms are a growing technology in the energy generation market. On one hand, the competitiveness of the energy market, driven by cheap hydrocarbons, is asking from offshore wind turbines for better energetic and economic yields. On the other, climate change, driven by polluting hydrocarbons, is harshening environmental conditions, thus increasing the cost and risks of such turbines. In this context, a better knowledge of the behaviour of offshore wind turbines foundations, can reduce the installations cost, increase/extend its lifetime and prevent failure under extreme weather events. Scour around monopiles has been widely studied, while, scour protection - made of stones - around monopiles has not. De Vos et al. [1] distinguish three main failure modes for scour protection:

- Disintegration
- Edge scour
- Sinking.

Sinking has been studied experimentally in Nielsen et al. [2] for currents, waves and breaking waves. The latter paper hypothesizes that the main reason for the sinking of the scour protection in the case of Horns Rev 1 wind farm, is the pick-up of seabed sediment by the horseshoe vortex - induced by currents - penetrating in the scour protection. Following this hypothesis, a numerical model - based on the Flow 3D software [3]- for the study of current's action on the scour protection was developed. The paper concludes that a porous medium approach of scour protection can be used to determine the bed shear stresses underneath the scour protection, although calibration is needed.

Research objectives

The main objectives of this research is to develop a numerical model able to describe the full depth - from free surface to sand bed - flow characteristics and model the bed shear stresses for a variety of hydrodynamic conditions - current, waves and their combined action - around monopiles and around/inside their scour protection. To the author's knowledge, such a model is not available. This study will try, therefore, to cover this knowledge gap. The current paper focuses on the action of currents on the fluid motion inside the scour protection, the first step in the development of the complete hydrodynamic model. Approaches for macroscopic porous medium and free surface modelling are features readily available in the OpenFOAM framework [4]. These approaches are discussed further later in this paper and have successfully been used by Nielsen et al. [2]. Thus, this study aims to provide a better understanding of the processes involved in the sinking failure of riprap scour protections around monopoles through the use of numerical tools.

Numerical Model

The numerical model used for the study of scour protection around monopile structures is developed in the OpenFOAM framework and uses the foam-extend 4.0 package. In order to model the behaviour of water around the monopile and inside the scour protection, the Volume Averaged Reynolds Averaged Navier Stokes (VARANS) equations are used:

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\frac{\rho \boldsymbol{u}}{n} + \frac{1}{n}\boldsymbol{\nabla} \cdot \left(\frac{\rho}{\boldsymbol{n}}\boldsymbol{u}\boldsymbol{u}\right) - \boldsymbol{\nabla} \cdot \left(\frac{\mu}{\boldsymbol{n}}\boldsymbol{\nabla}\boldsymbol{u}\right) - \frac{1}{n}(\boldsymbol{\nabla}\boldsymbol{u}) \cdot \boldsymbol{\nabla}\boldsymbol{\mu} + \boldsymbol{F_p} = -\boldsymbol{\nabla}\boldsymbol{p_d} - (\boldsymbol{g} \cdot \boldsymbol{x})\boldsymbol{\nabla}\boldsymbol{\rho} + \boldsymbol{\sigma}\boldsymbol{\kappa}\boldsymbol{\nabla}\boldsymbol{\gamma} \qquad (2)$$

Vectorial quantities are shown in bold characters. The derivation and implementation in the OpenFOAM framework of the VARANS equations was done at IH Cantabria [5]. Here, the VARANS equation include a porous media flow model in the last term of the left hand side of eq. (2). The macroscopic porous media flow approach considers the bulk properties of a material by adding drag and inertial terms to the Navier Stokes equations rather than solving the flow in every single pore. The resulting velocity depicts the mean fluid motion in a control volume by averaging the individual interstitial flows. The extended Darcy-Forchheimer equation models inertial and drag forces inside a porous material, and is widely used in the study of coastal structures. The formulation proposed in Higuera et al. [5] for the inclusion of the extended Darcy-Forchheimer equation in the Navier Stokes equations is followed:

$$\boldsymbol{F_p} = A\frac{\boldsymbol{u}}{n} + B\left|\frac{\boldsymbol{u}}{n}\right|\frac{\boldsymbol{u}}{\boldsymbol{n}} + \mathrm{C}\frac{\partial}{\partial t}\frac{\rho \boldsymbol{u}}{n} \qquad (3)$$

A, B and C are coefficients that need to be determined. A variety of formulations exist to determine their values, thus, the reader is referred to Higuera et al. [5], Losada et al. [6], Jensen et al. [7] for more information about their derivation and formulation. For this work, the implementation done by Higuera et al. [5] is used:

$$A = \alpha \frac{(1-n)^3}{n^2} \frac{\mu}{{D_{50}}^2} \quad (4)$$

$$B = \beta\left(1 - \frac{7.5}{KC}\right) \frac{1-n}{n^2} \frac{\rho}{D_{50}} \quad (5)$$

As the flow considered is a steady current, then eq.(5) is reduced to:

$$B = \beta \frac{1-n}{n^2} \frac{\rho}{D_{50}} \quad (6)$$

Coefficient C in equation (3) is set to 0 in order to have a similar formulation of the porous medium to Nielsen et al. [2]. Here again, for coefficient α and β, in equations (4) and (6), a large variety of values can be found in literature and consensus has not been reached upon their values. Nielsen et al.[2] set α to 180 and calibrate β to 2.9, those values will be used in this paper. Eq.(2) is an equation solving multiphase incompressible flow where the Volume of Fluid Method is used. This method has the advantage of allowing the use of a sole set of equations for the water and the air phase and is implemented as depicted by Berberović et al. [8]. If the volume fraction of liquid is $\gamma_{l=}\gamma$ and the volume fraction of gas is $\gamma_{g=}\gamma$-1, then the fluid properties are determined as a weighted average of γ:

Averaged density:

$$\rho = \rho_l \gamma + \rho_g (1-\gamma) \quad (4)$$

Averaged viscosity:

$$\mu = \mu_l \gamma + \mu_g (1-\gamma) \quad (5)$$

The transport of the volume fraction γ is defined as:

$$\frac{\partial \gamma}{\partial t} + \nabla \cdot (\gamma \boldsymbol{u}) + \nabla \cdot (\boldsymbol{u_r} \gamma (1-\gamma)) = 0 \quad (6)$$

Where $\mathbf{u_r}$ is defined as the “compression velocity”. The velocity is active at the interface of the two fluid and reduces numerical dissipation.

Experimental set up and model parameters

Nielsen et al. [2] present velocity measurements inside the scour protection. During these experiments, a plastic plate was placed at the bottom of the flume, this was done in order to obtain a rigid smooth bottom. For a more detailed description of the experimental setup, the reader is referred to Nielsen et al. [2]. Hereafter, are presented some of the key parameter for the test and modelling of scour protections under currents.

Table 1: Experimental and numerical parameters

Physical parameters	**Value**
Flume Width [m]	2
Flume Length [m]	23
Flume Heigth [m]	0.5
Pile diameter (D_p) [m]	0.14
Scour protection diameter (W)[m]	0.8
Mean armour layer stone diameter (D_{50})[cm]	4.3
Number of armour layers [-]	4
α[-]	180
β[-]	2.9
Porosity (n)	0.5 (Numerical model) 0.43 (Measured for experiments)
Water depth (d) [m]	0.45
Current velocity (U) [m/s]	0.4
Water density (ρ_w) [kg/m^3]	1000
Air density (ρ_a) [kg/m^3]	1
Kinematic viscosity of water (ν_w) [m^2/s^{-1}]	1e-6
Kinematic viscosity of air (ν_a) [m^2/s^{-1}]	1.48e-5
Numerical domain parameters	
Length [m]	4.5
Width [m]	2.0
Height [m]	0.65
Number of cells [-]	~1.3 * 10^6
Δt [s]	0.001

Computational domain

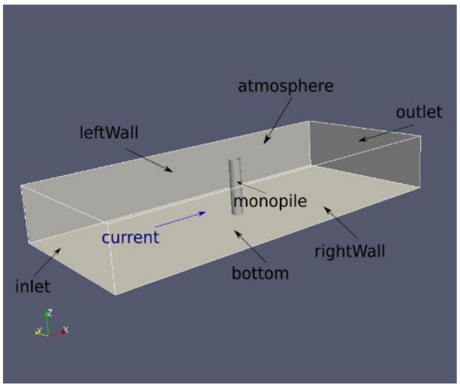

Figure 1:Numerical domain, boundaries and direction of propagation of current

In Figure 1 are presented the boundaries and the numerical domain. The monopile, the bottom and the sides of the computation domain are treated as non-slip wall boundary conditions. For the inlet, outlet and atmosphere (upper boundary) conditions, it is make use of the generation, absorption and atmospheric boundary conditions provided by ihFoam, see Higuera et al. [6]. At t=0, the velocity of the liquid phase in the interior of the domain is set to the current velocity - $\boldsymbol{u}\ [m/s] = (0.4, 0, 0)$ - except in the porous medium where the velocity is set to 0 - $\boldsymbol{u}[m/s] = (0, 0, 0)$. These initial condition are clearly not divergence free, the solver reaches a quasi-steady state and the results are taken at t = 50s.

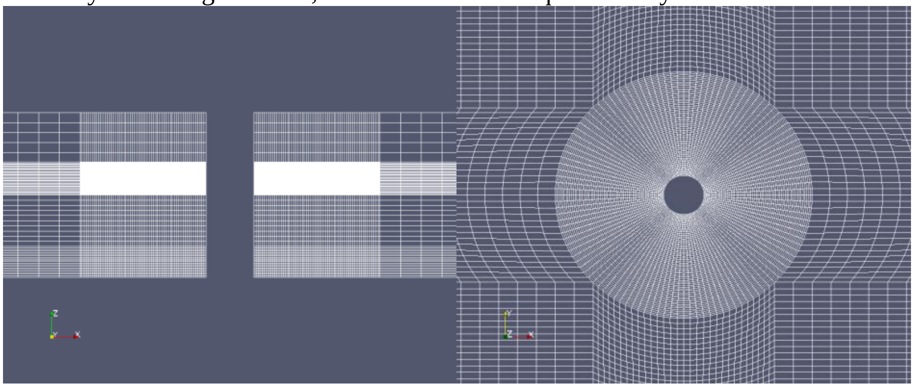

Figure 2: Side (left) and top (right) view of the meshing strategy

As can be seen in Figure 2, the mesh chosen to solve the flow around the monopile and the scour protection is an hexahedral structured grid around the monopile. Special consideration to the free surface, the zone close to the sea bed and around the monopile is given. Those zones are object of a refinement of the control volumes. Mesh generation is performed using the blockMesh utility provided along with the foam-extend 4.0 package. In order to parse the blockMeshDict file, the Python library PyFOAM is used, providing the versatility needed for the comparison to a large variety of test setups.

Results discussion

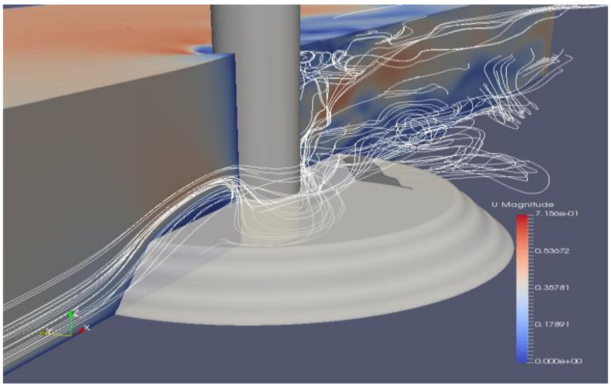

Figure 3: Velocity magnitude and streamlines around a monopile and scour protection for a 4 layer scour protection with a mean stone diameter of 4.3 cm

Figure 3 shows the velocity magnitude and streamlines of water; upstream, around and downstream of the monopile and its scour protection at t=50s. Upstream (left of Figure 3) of the monopile, the streamlines are parallel to each other with a constant velocity. At the approach of the scour protection, the flow is directed upwards as this is the path with least hydraulic resistance. In front of the monopile, inside the scour protection, water is 'hitting' the monopile with a lower velocity than outside the scour protection. A pressure gradient is created leading to a downward flow penetrating the scour protection. The latter phenomenon can be seen by the streamlines entering the scour protection in front of the monopile. Downstream the monopile, streamlines become chaotic showing evidence of turbulent structures produce by the disturbance of the flow by the monopile. In fact, the Reynolds number of this experiment is 56000, therefore, a fully turbulent behaviour of the fluid at the wake of the monopile is expected. At the sides of the monopile, higher tonalities of red indicate an acceleration of the fluid due to the presence of the monopile. Finally, a slight set up of the fluid can be seen in front of the monopile.

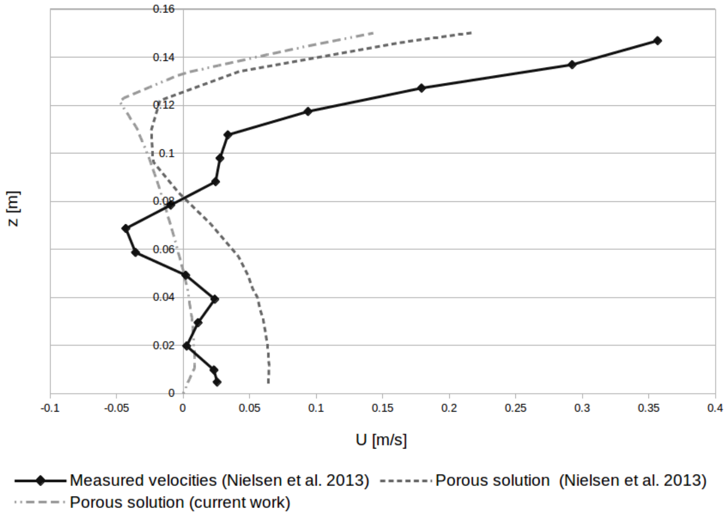

Figure 4: Comparison between measured and numerical solution from Nielsen et al.[2] and current work for a 4 layer scour protection, with a d_{50} of 4.3 cm, 12cm upstream the monopile centre.

In Figure 4 are plotted the velocity measurements (black solid marked line) and numerical model's results (dark grey dashed line) presented in Nielsen et al. [2], 12cm upstream the monopile centre. Also in Figure 4, the numerical results from our developed model are plotted at the same location (light grey dot dashed line). The sea bed is located at z=0m. The scour protection composed of four armour layers has a measured height of z = 12.3cm in the experiments. The current model shows a good agreement with the measurements until 8 cm above the sea bed. From z=8cm to z=12cm, the two numerical models (not marked grey lines) deviate from the measurements. From there on, with increasing z, the three lines seem to become parallel. The difference in the formulation of the porous medium between Higuera et al. [5] and Nielsen et al. [2] certainly plays a role in de difference between the two numerical results. This will be studied further and updated results will be presented at the 13th OpenFOAM Workshop.

Further work

In order to expand the present model, waves and a combination of waves and current will be implemented. Furthermore, a mesh analysis is on the way to quantify the mesh size impact on the results. An approach to model the disintegration failure mode of the scour protection is under study.

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