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CFD Modelling of a Bio-Filter Artificial Reef

PHOENICS Application

Introduction: Artificial reefs are man-made structures that are typically deployed on the seabed, and often constructed in areas with a featureless bottom surface to promote marine life, control erosion, restrict the passage of ships, or improve the conditions for surfing. These structures tend to increase the local current and wave motions. Fast-flowing water can stir up the fine particles of a sand/clay/silt type of seabed and transport them away from the structure, creating a hole. This phenomenon, called scouring, has the potential to weaken the support structure and cause it to sink or tilt. CFD simulation provides a fast and cost-effective method for evaluating the on-set of such scouring of the seabed. The following example describes how CHAM's Consulting Team employed PHOENICS to predict the initiation of scouring due to the influence of an artificial reef.

CFD model description: The artificial reef shown below consists of 200 arrays of thin angled plates hanging from the top of a steel frame attached to a concrete slab submerged in the seabed. Each array contains 20 angled plates spaced vertically 30mm apart. Several million computational cells and extensive computational resources could be employed to model all of these plates in detail. Alternatively, a pragmatic approach is to represent each stack as a *porous blockage*, replicating the resistance to the flow and generation of turbulence. Coefficients of pressure drop and turbulence for the porous blockage are obtained from smaller sub-models and their values calibrated to achieve the equivalent pressure drop and turbulence properties for both the detailed and porous geometries.

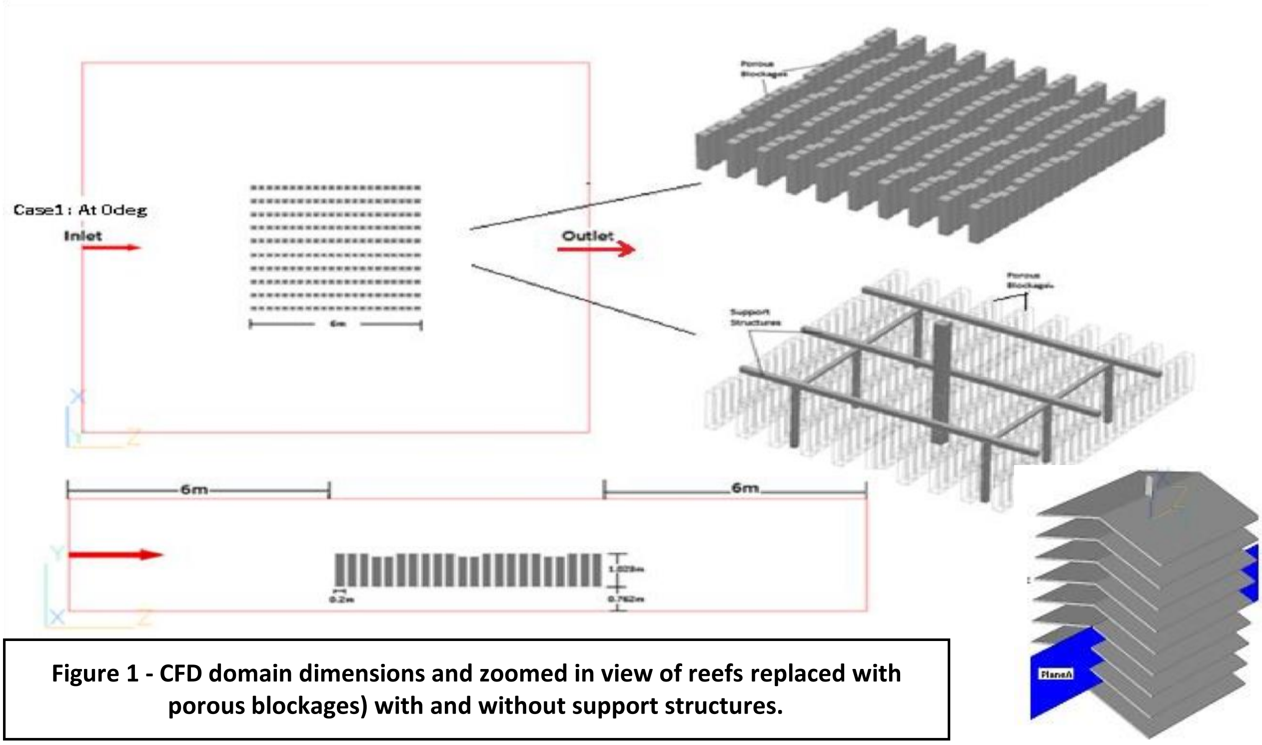

Figure 1 - CFD domain dimensions and zoomed in view of reefs replaced with porous blockages) with and without support structures.

In this case, an additional investigation was performed using a *hybrid model* to verify that the reef, modelled as a porous object, produced similar pressure drop and shear stresses near the sea bed. The hybrid model consisted of a single row of detailed angled plates covering the bottom 10% of the array (i.e. closest to the sea bed), with the remainder represented as porous blockages. Two simulations were performed at 0^o flow, one using just porous objects and the other with the hybrid model. The results for full porous and hybrid models compared well, giving very similar pressure drop, turbulent viscosity and shear stresses near the seabed; thus confirming the validity of the porous approach.

CFD model setup: In Figure 1 (above), each array of plates is represented as a porous blockage within a computational domain surrounding the reef, and a grid of 0.8million cells. Simulations are performed for the three flow directions - at 0^o, 20^o and 40^o - with and without the support structures in place to assess their effect. The water velocity at the inlet varies with height using a logarithmic relationship, setting the reference velocity to 0.33m/s at a height of 3.5m, with an effective roughness height of 0.005mm (based on silt clay seabed material.) The surface of the seabed is flat and represented as 'fully-rough' with the same effective roughness height.

Calculation of threshold shear stress for scouring to occur:

- ***Bed Roughness:*** *The predicted flow field and the local shear stresses are influenced strongly by the type of seabed material present and its surface roughness height, which is a primary input for the CFD simulation. Sediment size and type, as well as the bed grain, influence the transport rate and the induced stresses at the surface. For the case described, the seabed material is taken as 'silt clay' with a bed-roughness height of 0.005mm, based on published data [1]. The grain size is calculated from bed-roughness height using correlations presented in [2].*
- ***Threshold of motion:*** *The scouring process involves a threshold of motion defined as the criticalbed shear stress, or the critical velocity beyond which significant amount of grains begin to move. By*

calculating the threshold of shear stress, one can identify where the sand grains are more susceptible to movement. This investigation uses the critical shear stress correlations for sediment transport given by Guo [3], based on the Shields-Rouse equation.

Dimensionless grain size

$$d_* = \left[\frac{g\left(\frac{\rho_s}{\rho}-1\right)}{\nu^2}\right]^{\frac{1}{3}} d_{50}$$

Threshold shields parameter

$$\theta_{cr} = \frac{0.23}{d_*} + 0.054\left[1 - \exp\left(-\frac{d_*^{0.85}}{23}\right)\right]$$

Threshold of motion

$$\tau_{cr} = \theta_{cr} * g(\rho_s - \rho)d_{50} \;\rightarrow\; \tau_{cr} = 0.15\,\text{Pa}$$

Where, τ_{cr} = critical shear stress; ρ_s = density of sediment (2650kg/m3); ρ = density of water (1000kg/m3); g = acceleration due to gravity (9.81m/s2); d_{50} =grain size; d_* = dimensionless grain size. The calculated threshold shear stress value (τ_{cr} =0.15Pa) is compared with the predicted shear stress at the seabed surface. Any location with a shear stress value higher than the threshold is more likely to undergo scouring. In the event of scouring, the region with higher wall shear stress is more likely to form a pit, whereas a nearby region with lower shear stress might undergo accumulation.

Results: The predicted shear stress near the seabed for the 0^o and 20^o flow angles was higher than the critical shear stress near the support structures (RST values >1 see Figure 2). The maximum shear stress was adjacent to the central column for 0^o flow, and then more-evenly distributed for 20^o. Some scouring was predicted without the support structure for the 40^o flow due to the angled plates alone. With the support structure, no scouring was evident for the upstream triangular region. Conversely, the most scouring of any case was predicted for the downstream region.

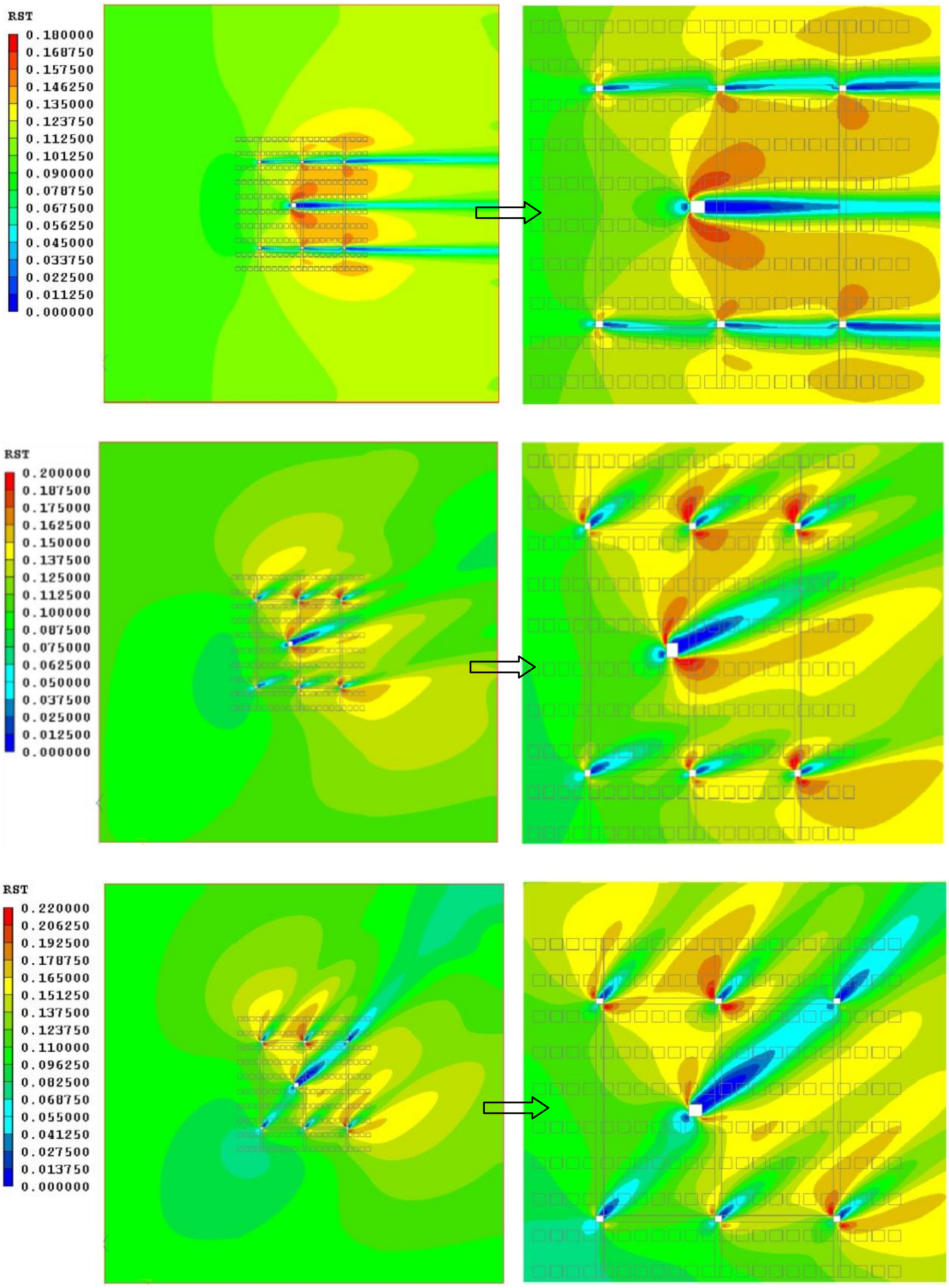

Figure 2 - Comparison of full geometry contours of shear stress taken near sea bed at three different angles of attack (0^0, 20^0 and 40^0).

Estimation of scour depth: The aim of this project was to predict the *initiation* of scouring rather than the actual transportation of particles. Therefore the depth of scouring was not established directly from these CFD results. Instead an empirical relationship for estimating the depth of the scour hole was used (S_c=2*D, where D is the pile diameter) based on a single pile in open water.

Predicted contours of shear stress showed maximum scouring behind the support structures. Therefore, the scour depths based on the central column (0.2mx0.2m) and other columns (0.1mx0.1m) were estimated to be 0.4m and 0.2m respectively using the analytical approach. However, CFD analysis of a single centre support (0.2m by 0.2m) in open water indicates that the maximum predicted shear stress (0.13pa) is less than the critical shear stress (0.15pa) indicating that no scouring should occur for a single pile of this size. Therefore, it should be emphasized that the maximum scour depth values estimated for the support columns are based only on the analytical equation and do not utilise the predicted shear stresses from the CFD models.

Conclusion

The study demonstrates the capability of PHOENICS to predict the initiation of scouring due to the presence of an artificial reef on the seabed by comparison of the predicted shear stresses at the seabed against the critical/threshold levels above which scouring should occur. For all flow angles modelled, some local scouring was predicted to occur adjacent to the support structures. However, for the largest flow angle simulated (40^o), scouring was predicted across a wider region (even without the support structures) with shear stress levels near the seabed greater than the critical shear stress.

References:

[1] DET NORSKE VERITAS AS, On-Bottom Stability Design of Submarine Pipelines, OCTOBER 2010, DNV-RP-F109.

[2] Richard Soulsby , Dynamics of marine sands: a manual for practical applications, page 47-48

[3] Guo, J., Hunter Rouse and Shields Diagram, Advances in Hydraulic and Water Engineering, Vol. 2, 2002, pp. 1096-1098

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