WAVE-CURRENT INTERACTION EFFECTS ON MONOPILE SCOUR USING THREE-PHASE EULERIAN MODEL

Nishchay Tiwari, Junior Research Scientist, HR Wallingford, United Kingdom, OX10 8BA, n.tiwari@hrwallingford.com
Michiel Knaapen, Principal Scientist, HR Wallingford, United Kingdom, OX10 8BA, m.knaapen@hrwallingford.com
Sina Haeri, Technical Director, HR Wallingford, United Kingdom, OX10 8BA, s.haeri@hrwallingford.com

INTRODUCTION

Scour around monopile foundations is a primary design driver for offshore wind assets because seabed erosion can compromise geotechnical capacity, inflate maintenance, and shorten design life (Sumer and Fredsøe 2002). Scour arises from flow separation, an upstream horseshoe vortex, and lee-side wake vortices that elevate near-bed shear and entrain sediment (Roulund et al. 2005). Offshore sites rarely experience current-only conditions; combined waves and currents modulate vortex strength and persistence, producing scour geometries that differ from steady currents. A consistent trend in flume studies is that co-directional wave-current forcing intensifies horseshoe vortices and deepens scour, whereas opposing waves weaken phase-averaged near-bed flow and reduce scour extent (Sumer and Fredsøe 2001; Qi and Gao 2014). This work presented in this abstract examines these mechanisms with a three-phase Eulerian CFD approach, focusing on how alignment (current-only, co-directional, opposing) controls sediment transport, vortex dynamics, bed shear, and the resulting scour shape.

METHODOLOGY

A three-phase Eulerian formulation (air-water-sediment) is adopted using sedInterFoam (Mathieu et al. 2025). The free surface is captured with a volume-of-fluid (VOF) method; incident waves are generated and absorbed with relaxation zones (waves2Foam) (Jacobsen et al. 2012). Turbulence is modelled by the two-phase $k-\omega$ RANS closure, solving phase-averaged transport with interphase-consistent eddy viscosity; this choice is standard for the SedFoam/sedInterFoam stack and robust in adverse-pressure-gradient flows (Chauchat et al. 2017). The sediment phase is treated as a dense granular continuum with collisional/frictional stresses; $\mu(I)$ rheology provides rate-dependent friction at high concentration (Jop et al. 2006). Bed evolution is obtained from the sediment continuity and momentum equations, so scour morphology is resolved as part of the multiphase dynamics.

The computational setup imitates the Fast Flow Facility (FFF) at HR Wallingford: a $1.75\,m$ monopile $(h/D = 0.8)$ in a $0.3\,m$ sand bed $(D/d_{50} \approx 8.8 \times 10^3)$ with $1.4m$ water depth, meshed at about 2 million hexahedral cells; baseline current-only runs at $0.2\,ms^{-1}$ for $600\ seconds$ are extended to $0.3-0.4\,ms^{-1}$ $(Re_D \approx (3.5-7.0)\ \times 10^6)$ and to combined wave-current cases (Figure 1).

Model outputs are compared with FFF measurements collected using (i) free-surface elevation probes processed via power spectral density (PSD) and incident/reflection analysis, and (ii) laser-based bed surveys of scour morphology.

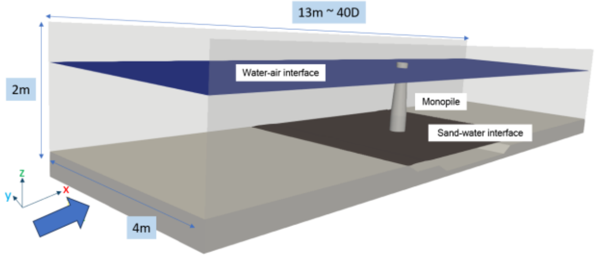

Figure 1 - Computational domain setup, showing monopile, sand bed, and numerical wave-current flume used in sedInterFoam simulations.

Domain and boundary forcing

Three alignment cases isolate wave-current effects on vortex dynamics and scour shape:

- Current-only (benchmark)
- Co-directional waves + current (wave orbital velocity reinforces the current at crest)
- Opposing waves + current (orbital velocity counteracts the current at crest)

Irregular JONSWAP waves (Figure 2) are imposed at the inlet with active absorption at the outlet. Lateral walls are slip or weakly reflecting; the bed is mobile. Relaxation zones are applied to prevent wave re-reflection at the open boundaries. Mesh refinement is concentrated within a few pile diameters (D) of the monopile and in the near-bed layer to resolve separation, the horseshoe-vortex core, and shear layers. Time stepping respects a combined Courant criterion over water, air, and sediment volume fractions.

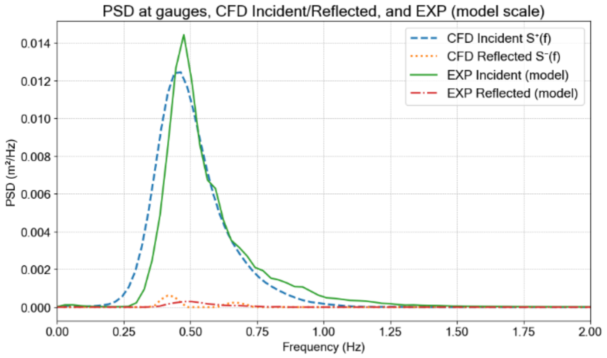

Figure 2 - Incident and reflected free-surface waves validated against experiments using PSD-based reflection analysis at probe locations in front of the monopile.

MECHANISTIC INTERPRETATION

- Near-bed vorticity (magnitude/sign) identifies formation, strengthening, detachment, and destruction of the horseshoe vortex through the wave phase and tracks wake vortex shedding (Roulund et al. 2005).
- Bed shear stress (water-phase wall shear at the mobile interface) locates erosion at the upstream toe, flanks, and lee reattachment line; crest-trough modulation is contrasted between co-directional and opposing alignment (Sumer and Fredsøe 2001; Qi and Gao 2014).
- Morphology metrics: maximum depth S/D, upstream/downstream asymmetry, and downstream elongation; interpretation is tied back to the KC-based regime view for piles under waves and combined forcing (Sumer and Fredsøe 2002).

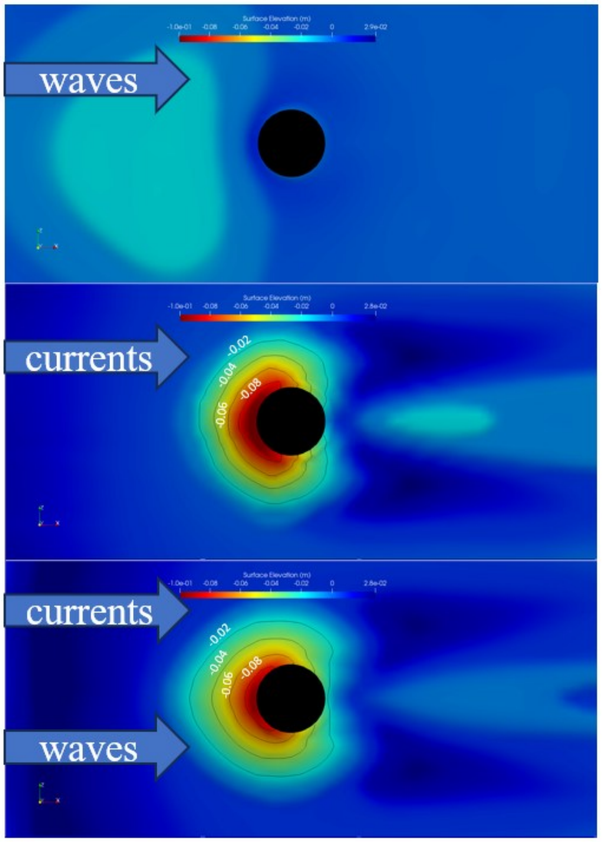

Figure 3 - Evolution of local scour patterns around the monopile at $t = 180\,seconds$, highlighting erosion in co-directional wave-current forcing compared to current-only alignment.

RESULTS

Figure 3 shows that although the bed is mobile for the present conditions ($U_\infty = 0.4\,ms^{-1} > U_{cr} = 0.3\,ms^{-1}$); with $d_{50} = 0.2\,mm, \rho_s = 2650\,kgm^{-3}$, the combined wave-current case produces a shallower but broader scour cavity compared to the current-only run at $t = 180\,seconds$. The velocity ratio indicates a Shields parameter above the mobility threshold ($\theta \approx 0.085 > \theta_{cr}$), confirming that sediment is in motion. In the diagrams, wave-induced orbital motions periodically intensify and relax the horseshoe vortex: crest phases excavate the upstream toe, while trough phases favour partial backfilling of the scour hole and promote redistribution of suspended sand onto the lee bar. This cyclic infill reduces the maximum depth (S/D) but extends the lateral scour footprint, with a more diffuse lee-side deposit than in the current-only alignment. Hence, it highlights that in these runs waves act primarily as a mixing and redistribution mechanism, yielding a less-deep but wider scour hole while still evidencing active sediment mobility and phase-controlled vortex dynamics.

CONCLUSION

The three-phase Eulerian technique, combined with $\mu(I)$ rheology, proves effective in simulating wave-current induced scour around monopiles. The approach captures both sediment mobility and the phase-dependent dynamics of the horseshoe vortex, reproducing realistic scour patterns. By resolving cyclic excavation and infill processes, it not only provides reliable morphological predictions but also offers valuable insights into the underlying flow physics that drive scour development.

ACKNOWLEDGMENTS

The project has received funding from Horizon Europe Marie Skłodowska-Curie Actions, Grant Agreement no. 101072443 - SEDIMARE. Experimental data is taken from the Fast Flow Facility at Froude Modelling Hall, HR Wallingford Ltd.

REFERENCES

Chauchat, Cheng, Nagel, Bonamy and Hsu (2017): SedFoam-2.0: a 3-D two-phase flow model for sediment transport, Geoscientific Model Development, 10, 4367-4392.

Jacobsen, Fuhrman and Fredsøe (2012): A wave generation toolbox for the open-source CFD library OpenFOAM, International Journal for Numerical Methods in Fluids, 70, 1073-1088.

Jop, Forterre and Pouliquen (2006): A constitutive law for dense granular flows, Nature, 441(7094), 727-730.

Mathieu, Kim, Hsu, Bonamy and Chauchat (2025): sedInterFoam 1.0: three-phase numerical model for sediment transport with free surfaces, Geoscientific Model Development, 18, 1561-1573.

Qi and Gao (2014): Local scour around a large-diameter monopile in combined waves and current, Coastal Engineering, ELSEVIER, 83, 72-81.

Roulund, Sumer, Fredsøe and Michelsen (2005): Flow and scour around a circular pile, Journal of Fluid Mechanics, 534, 351-401.

Sumer and Fredsøe (2001): Wave scour around a large vertical cylinder, Journal of Waterway, Port, Coastal, and Ocean Engineering, 127(3), 125-134.

Sumer and Fredsøe (2002): The Mechanics of Scour in the Marine Environment, World Scientific.