Numerical Simulation of Wave Hydrodynamics with a Focus on Wave Structure Interaction

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Wave Structure Interaction: Offshore Energy

Offshore Wind Energy: Wave Force, Local Scour

Ocean Wave Energy: Wave Climate, Wave Forces

Offshore Structures: Wave Force, Green Water

Offshore Structures: Floating, Mooring, Ice
WSI : Transportation & Aquaculture

2. FLOATING BRIDGE

2.1 Recommended priorities

The following alternatives will be developed further.

Crossing the Sognefjord

Because of the great depth of the fjord, more than 1250 metres at the proposed place of crossing, it has been decided not to have any fixed foundations on the fjord bottom.

The width of the fjord, 3700 metres, calls for special measures to ensure sufficient horizontal strength and stiffness of all structures withstanding movements and forces from currents, waves and wind.

The two most promising alternatives for crossing at Lavik-Oppedal are briefly described in the following:

Floating bridge with high bridge mid-fjord for ships passage.

Fig.1 The "bucket handle alternative"

This is a bridge with columns on pontoons, where the bridge is curved horizontally with descending height towards the shorelines. This structure, which is sometimes referred to as the "bucket handle alternative", provides the necessary clearance for future cruise ships.
REEF3D::CFD

- **Solves:**
  - Full 3D Navier-Stokes Equations
  - Free Surface: Two-Phase Flow - Water & Air
  - Turbulence

- **Focus on:**
  - Free Surface Flows
  - Wave Hydrodynamics
  - Wave Structure Interaction
  - Floating Structures
  - Open Channel Flow
  - Sediment Transport

- **The Code:**
  - C++ (modular & extensible)
  - Parallel Computing / HPC
  - Open-Source
  - Developed at the Department of Civil and Environmental Engineering, NTNU Trondheim
REEF3D::CFD: Multiphysics Extensions

- Sediment Transport
- Local Scour
- Arctic Erosion

- Porous Structures

- Floating Structures
- 6DOF
- Mooring

- Vegetation

- Debris Flow
- Granular Flow

- Stratified Flow
Level Set Equation: A Signed Distance Function

\[
\phi(\vec{x}, t) \begin{cases} 
> 0 & \text{if } \vec{x} \in \text{phase 1} \\
= 0 & \text{if } \vec{x} \in \Gamma \\
< 0 & \text{if } \vec{x} \in \text{phase 2}
\end{cases} \quad , \quad |\nabla \phi| = 1
\]

\[
\phi_t + \vec{u} \cdot \nabla \phi = 0
\]
Governing Equations

Incompressible RANS Equations:

\[
\begin{align*}
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} &= -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_t) \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + g_i \\
\frac{\partial U_i}{\partial x_i} &= 0
\end{align*}
\]

- **Temporal Discretization:** RK3
- **Spatial Discretization:** WENO
- **Pressure Solution:** projection method + multigrid
- **Turbulence Modeling:** RANS or LES
- **Mesh:** non-uniform, immersed boundary
Wave Hydrodynamics: 3D Breaking Waves on Reef

Collaboration with Prof. Seiffert, Florida Atlantic

Experiments design based on CFD input
Reef Case 13

$H=0.10, \ L=4m, \ d=0.460$
Reef Case 13 - Close-Up
H_0=0.06 \text{ m}, \quad T_0=1.67 \text{ s}

incident wave at -0.114 \text{ m from the toe}

on the slope at -0.196 \text{ m from the crest}

on flat bed at +0.165 \text{ m from crest}

on flat bed at +0.114 \text{ m from crest}

on leeward slope at +0.196 \text{ m from leeward crest}
Wave Structure Interaction: Non-Breaking Waves

The numerical model is validated with experimental data for regular wave interacting with a slender pile. For the tested cases, waves are non-breaking. The comparisons show that the numerical model is capable of predicting the free-surface, the fluid particle velocity, and the dynamic pressure on the cylinder, provided that the correct incident boundary conditions are applied. The agreement between the experimental data and numerical results for the wave force is reasonable and consistent with the comparisons of other physical variables for the regular cases.

4.2 Breaking wave interaction with the truss structures in shallow waters

Wind turbine foundation structures in shallow waters are subjected to slamming forces, typically caused by plunging breaking waves (Kamath et al., 2017). Since the wave-breaking phenomenon is extremely complicated and involves strong non-linear effects, the breaking wave forces are of major concern in the design of offshore wind turbine substructures. There were not many attempts in the past to estimate the breaking wave forces in the case of jacket type structures. The theoretical description of the impact forces involves the use of several parameters such as slamming coefficients, curling factor, breaker shape and wave kinematics at breaking, which have to be determined through experiments. Compared to monopiles, jackets are more complex structures and the analysis is more complicated, due to the presence of the local members, joints and their different orientations.

Fig. 4.6 presents the velocity profiles at different elevations from the bed, at the horizontal distance $x = 60.4\, \text{m}$. Then numerical results underestimate the troughs of the measured velocities, while it perfectly matches the crests. The velocity probes from propellers record absolute values only, whereas the numerical results show downward drift as can be seen in Figs. 4.4d and 4.4e, suggesting a small opposing current. However, the amplitudes of velocities tend to be of the same range.

The time histories of the dynamic pressures along the perimeter of the pile at water depth $d = 4.23\, \text{m}$ are shown in Fig. 4.5. The numerical results underestimate few of the troughs of the measured pressures slightly, and have a good agreement at the peaks. At the critical region from the view of flow separation (Figs. 4.5c and 4.5d), no significant change of the time history is visible.

The time history of the total inline forces acting on the pile is plotted in Fig. 4.6. In the case of the laboratory data the forces $F_x$ represent the sum of the measured forces in the bearings and in the numerical, the pressure has been integrated over

Experiment: GWK - Mo et al. 2007, JE
Wave Structure Interaction: Breaking Waves

Experiment: GWK - Irschik et al. 2002, ICCE
Jacket Structures: WaveSlam

WaveSlam Jacket in GWK

Slamming Event
WaveSlam : 2D breaking

Fig. 10. Comparison of the free surface elevation (a) and horizontal particle velocities (b) of numerical results with experimental at Gauge 1 location.
WaveSlam: Breaking Wave Forces

Figure 4.18: Breaking wave propagation and interaction with the structure. Side view, case b3: (a) $t = 1.2\,\text{s}$; (b) $t = 1.2\,\text{s}$; (c) $t = 1.2\,\text{s}$; (d) $t = 1.3\,\text{s}$; (e) $t = 1.3\,\text{s}$; (f) $t = 1.4\,\text{s}$.

Figure 4: Comparison of the experimental and numerical normalised breaking wave force time-series for case (a) S1 ($s = 0.033$) (b) S2 ($s = 0.045$) (c) S3 ($s = 0.048$) (d) S4 ($s = 0.051$). Red solid line presents numerical; black crosses for experimental.

$x_b = 0.9\,\text{m}$
$d = 4.3\,\text{m}$
$H = 1.7\,\text{m}$
$T = 4.6\,\text{s}$
$s = 0.05$
WaveSlam: Breaking Wave Forces

Figure 13: Computed wave profile during wave breaking with the velocity variation on the jacket for case D2 (x = 0.5 m, s = 0.035) at t = (a) 34.5 s (isometric-view) (b) 34.5 s (top-view) (c) 35.05 s (isometric-view) (d) 35.05 s (top-view) (e) 35.20 s (isometric-view) (f) 35.20 s (top-view) (g) 35.35 s (isometric-view) (h) 35.35 s (top-view) (i) 35.50 s (isometric-view) (j) 35.50 s (top-view)

(x_b = 1.5m, d = 4.3m, H = 1.6m, T = 5.55s, s = 0.03)

The numerical model is able to compute the total breaking wave loads on the jacket structure with a good accuracy as seen in Figs. 4a, 4b, 4c and 4d. The first and second force peaks are estimated with errors of 2.3% and 2.7% for case S1, 2.9% and 2.5% for case S2, 1% and 1.7% for case S3 and with errors of 0.8% and 2.7% for case S4, respectively.

The breaking waves impact the front face of the jacket first which leads to the first peak. Then, they interact with the rear face, resulting in the second force peak in the force time series (Fig. 5). There are some minor discrepancies in the troughs of the numerical and experimental wave force signal, but since the focus of the present study is to investigate the peak breaking wave loads, further simulations are continued with dx = 0.05 m.
REEF3D: Open-Source Hydrodynamics

REEF3D::CFD

REEF3D::NSEWAVE

REEF3D::FNPF

REEF3D::SFLOW
FNPF Governing equations

\[ \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \]

Laplace Equation

\[ \frac{\partial \eta}{\partial t} = -\frac{\partial \eta}{\partial x} \frac{\partial \Phi}{\partial x} + \frac{\partial \eta}{\partial y} \frac{\partial \Phi}{\partial y} + \tilde{w} \left( 1 + \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) \]

kinematic FSFBC

\[ \frac{\partial \tilde{\Phi}}{\partial t} = -\frac{1}{2} \left( \frac{\partial^2 \tilde{\Phi}}{\partial x^2} + \frac{\partial^2 \tilde{\Phi}}{\partial y^2} - \tilde{w}^2 \left( 1 + \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) \right) - g \eta \]

dynamic FSFBC

\[ \frac{\partial \Phi}{\partial z} + \frac{\partial h}{\partial x} \frac{\partial \Phi}{\partial x} + \frac{\partial h}{\partial y} \frac{\partial \Phi}{\partial y} = 0, \quad z = -h. \]

kinematic bed BC

\[ \sigma = \frac{z + h(x)}{\eta(x,t) + h(x)} \]
Solution of the Laplace Equation

Laplace Eq. for the potential

\[
\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0
\]

\[Ax = 0\]

system of linear Equations

hypre: BiCGStab + PFMG
FSFBC: Spatial Discretization

Convection Discretization: Conservative 5th-order WENO

\[ U \frac{\partial U}{\partial x} \approx \frac{1}{\Delta x} \left( \tilde{U}_{i+1/2} U_{i+1/2} - \tilde{U}_{i-1/2} U_{i-1/2} \right) \]

- can handle large gradient
- high accuracy
- maintains the sharpness of the extrema
Beji & Battjes: Submerged Bar - FNPF vs CFD

Wave Input
- \( H = 0.02 \text{m} \)
- \( T = 2.0 \text{s} \)
- wave theory: linear waves

**FNPF**
- mesh: \( 800 \times 10 = 8.000 \text{ cells} \)

**CFD**
- mesh: \( 6000 \times 160 = 960.000 \text{ cells} \)
Beji & Battjes: Submerged Bar

**FNPF**

![Wave propagation comparison](image1)

(a) wave gauge 1 at $x = 4.0$ m

![Wave propagation comparison](image2)

(e) wave gauge 5 at $x = 14.5$ m

**CFD**

![Wave propagation comparison](image3)

![Wave propagation comparison](image4)

**Figure 1**: The configuration of the numerical wave tank for the wave propagation over a submerged bar, showing the experimental and modelled wave profiles at different wave gauges.

**Figure 2**: The grid convergence study for the numerical wave tank, demonstrating the effect of grid resolution on wave propagation accuracy.

**Figure 3**: The experimental setup and numerical model of the submerged bar, including the dimensions and wave gauge locations.

In this section, the wave propagation over a submerged bar is studied using both experimental and numerical methods. The results show good agreement between the experimental and modelled wave profiles, with minor discrepancies observed in the higher frequency components.

The grid convergence study indicates that a grid of 53 cells per wavelength provides adequate resolution for accurately capturing the wave propagation, with finer grids requiring more computational resources.

The experimental setup includes a submerged bar with a single wavelength energy peak at the toe of the submerged bar, with the energy reduction following a slope of 1:20 until it reaches the top platform.

The numerical beach of two wavelengths is studied to understand the transformation of wave energy as it interacts with the submerged bar. The energy reduction is seen to be more gradual compared to the previous study with a constant bottom depth.

The reader is referred to the article for further details on the methodology and results.
In this section, the wave propagation over a submerged bar is examined. The wave profiles at the various gauges are compared to the experimental data to assess the accuracy of the numerical model. The figures illustrate the wave heights (\(\eta[m]\)) at different times (\(t[s]\]) for gauges 1 to 9 at positions 1 to 9.

Two models are compared: FNPF and CFD. The FNPF model shows a good agreement with the experimental data, while the CFD model exhibits minor discrepancies, particularly at higher wave frequencies.

The figures also highlight the transformation of the wave profile as it propagates over the submerged bar. The wave energy is dissipated as the wave shoals, and the wave height decreases.

In conclusion, the numerical models are capable of simulating wave propagation over a submerged bar with a high degree of accuracy, as evidenced by the close agreement with the experimental data at all wave gauges.

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**References**


Typical Norwegian Coast

Andenes, Versterålen Archipelago
Bichromatic Waves (full tank 250m)

- Experiments: C. Pakozdi, 2014

- Experimental Wave Flume:
  - SINTEF Ocean (Marintek)
  - L = 250 m
  - d = 10.0 m

- Bichromatic waves
  - T1 = 2.1s
  - T2 = 1.6s

- 2D grid: 250m x 10m
  - 2500 x 25 = 62,500 cells
Bichromatic waves (portion of NWT)
Bichromatic Waves

- $x = 10 \text{ m}$
- $x = 40 \text{ m}$
- $x = 70 \text{ m}$
- $x = 160 \text{ m}$
Coastal Modeling: Mehamn

**Input wave**
- $H = 3.5 \text{ m}$
- $T = 14 \text{ s}$
- Regular wave

**FNPF includes**
- wetting/drying
- breaking
Conclusions

- **REEF3D Open-Source Hydrodynamics:**
  - Phase-resolved Waves on all Scales

- Coastal / Marine / Hydraulic Engineering

- **Ongoing FNPF:**
  - structures
  - wave communication protocol (WCP) for consistent coupling

- **Outlook FNPF:**
  - floating
  - mooring