Numerical study of the suction effect during the freak wave slamming with an FDM model with enhanced momentum conservation treatment

Xin Wang[a], Dominic E Reeve[a], Min Luo[b], Harshinie Karunarathna[a]

[a] Faculty of Science and Engineering, Swansea University, Swansea, United Kingdom
[b] Ocean College, Zhejiang University, Zhoushan, China

Email: Xin.Wang2@swansea.ac.uk

Abstract
The impact of extreme breaking waves is a severe threat to offshore structures, but the numerical simulation of this problem is difficult, because of the strong non-linearity and multi-phase properties. For the accurate simulation of breaking wave impact, we establish a numerical flume, with enhanced momentum conservation treatment (FDM-EMC) and perform the numerical simulation of a lab-scale freak wave impact on a box-shaped structure. Through the validation against experimental and published numerical data, the efficiency and accuracy of the established numerical flume is proved. The suction effect on the bottom wall of the structure is successfully reproduced and analysed.

Highlights
- FDM-based numerical flume is established, capable of simulating highly-deformed breaking waves.
- Suction effect on the offshore structure during wave impact is reproduced and analysed.
- Detailed simulation of the kinematics and dynamics during freak wave impact.

1 Introduction
Offshore structures are exposed to the threat of extreme waves, especially the breaking freak waves with large wave height. Breaking wave impact on widely-used box-shaped structures is a complicated problem, with strong non-linearity and multi-phase properties. The flow properties across the water-air interface may change rapidly, and in computational treatments, the large gradient across the water-air interface can lead to unphysical momentum transfer to the water or air phase, resulting in numerical error and instability. As a result, accurate simulation of this problem is still challenging.
To address this knowledge gap, we have proposed an interfacial treatment to deal with the interfacial instability, and established a numerical flume based on an open-source FDM code. A freak wave case is simulated with the numerical flume. Validation is performed to check the accuracy of the established numerical flume. The kinematics and dynamics during the impact on a box-shaped structure are analysed based on our numerical results. With the reproduction of the suction effect during the wave impingement, we designed two types of modifications for the shape of the corner, to explore the mitigation of this suction effect.

2 Numerical algorithm
An open-source and FDM-based model (REEF3D) is adopted in the study (Bihs et al., 2016), which is based on incompressible NS equation as shown in Eqs. (1) and (2), and the water-air interface is defined by Level Set method (Osher and Sethian, 1988).

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\left[\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i \quad (2)$$

For a better momentum conservation, we choose the advection of momentum and mass instead of the advection of velocity (Eqs. (3) and (4)), and the advected velocity field is re-constructed by Eq. (5):

$$\frac{\partial M_i}{\partial t} + u_j \frac{\partial M_i}{\partial x_j} = 0 \quad (3)$$

$$\frac{\partial \rho}{\partial t} + u_j \frac{\partial \rho}{\partial x_j} = 0 \quad (4)$$

$$u_i^* = \frac{M_i^*}{\rho^*} \quad (5)$$

in which M, u and ρ stand for the momentum, velocity and density respectively. The calculation sequence of solving NS equation and surface capturing is also modified to provide a strong coupling between them, to achieve a good synchronization of the variables. The proposed algorithm is named after FDM-EMC, and for a detailed introduction, the reader is referred to (Wang et al., 2023).

3 CASE SETTINGS

The numerical flume is set to replicate the settings of the experiment of Case 3 in Sun et al. (2019). The experimental set-up is briefly reproduced here. As shown in Figure 1, the two sides of the platform are equipped with a numerical paddle and wave absorber, respectively. Three wave gauges and two velocity probes are set in the flume, with the locations specified in Figure 1. A box with 0.12 m height and 0.5 m length is set to be 12.557 m away from the paddle and 0.049 m above the still water level (0.7 m). 2 pressure sensors are located on the front face of the box with 0.035 m and 0.08 m from the deck bottom, and 2 more pressure sensors are located on the bottom face with 0.035 m and 0.205 m away from the front border. For more detailed information, the reader is referred to Sun et al. (2019).

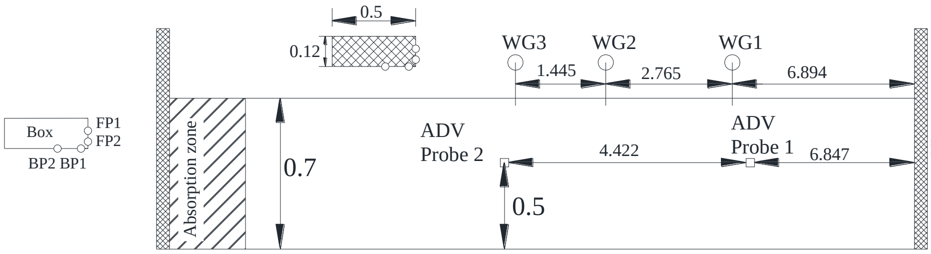

Figure 1: Case settings for the freak wave impingement on a box-shaped structure

In the study of Sun et al. (2019), the experiment case is also simulated by an advanced SPH model (δ^+ SPH) which shows high accuracy. As a result, their numerical results and the experimental data are used for the validation of the FDM simulation in this study. In our FDM simulation of this case, the grid resolution is 0.005 m * 0.005 m and the simulated pressure is normalized by ρc^2, in which ρ is the density of water and c is the equivalent celerity of the freak wave (3.312 m/s).

4 Numerical results and validation

The simulation results of the histories of the wave elevations and velocities are validated in Figure 2. Figure 3 presents the validation of the pressure histories at the four pressure sensors. The simulated impingement process with the pressure contour is shown in Figure 4, with the snapshots of the wave face at the corresponding time. It is evident that the histories of wave elevation, velocity and pressure are well reproduced and the simulated wave profiles show great similarity with the experimental snapshot. The wave hits the front wall by the wave face and the wave tongue is developed before the impact, which falls freely to the top wall of the box and becomes green water. High pressure develops on the front and bottom walls upon the slamming.

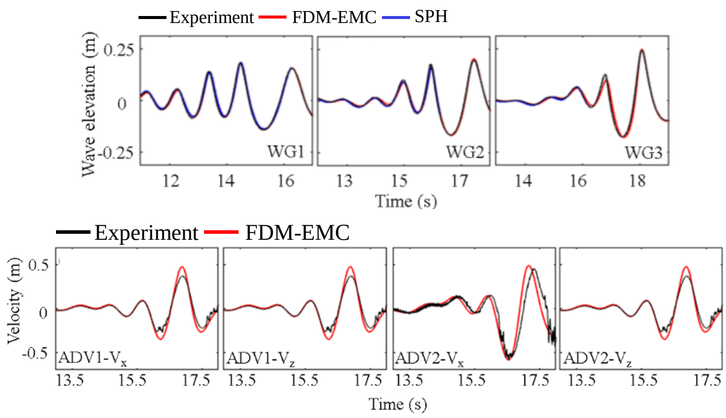

Figure 2: Validation of the wave elevation histories at the three wave gauges and the velocity histories at the two ADV probes (Data of SPH-simulated velocity is not available)

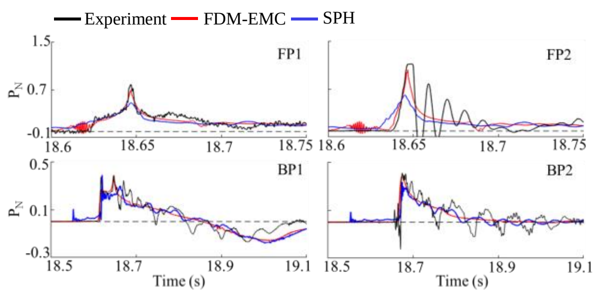

Figure 3: Validation of the pressure histories at the four pressure sensors

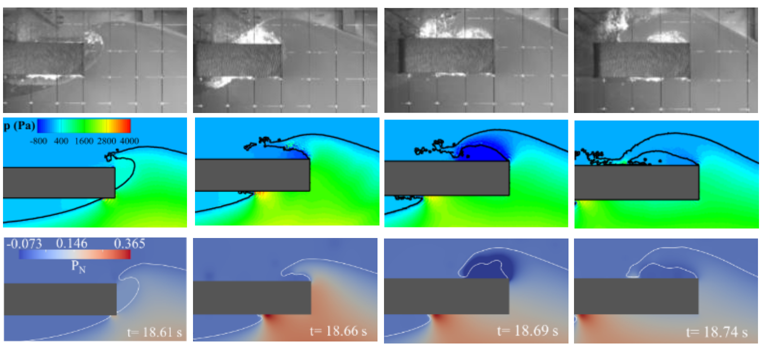

Figure 4: Comparison of the water-air interface shapes and pressure distributions at typical time instants (first row: experiment snapshots; second row: SPH results; third row: FDM-EMC)

Figure 5 presents the simulated spatio-temporal pressure distribution on the front and bottom walls of the structure. On the front wall, the pressures rise sharply near the deck top and moderately near the bottom, the highest pressure is located at the top part, as high as $1.5\rho c^2$. On the bottom wall, a high-pressure area moves downstream with the magnitude of ~ $0.4\rho c^2$.

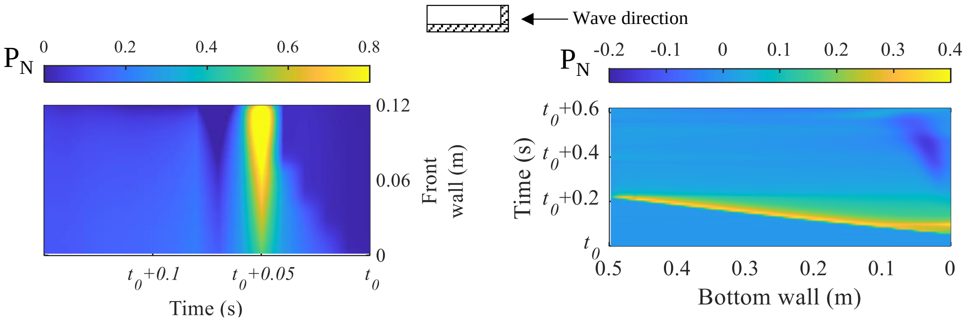

Figure 5: Spatio-temporal pressure distribution on the front and bottom walls of the structure

Figure 6 shows the simulated pressure, velocity vector map and zero-pressure border at the front corner in the exit stage. It is seen that a negative pressure area begins to form from 18.85 s, which is associated with a vortex. The vortex expands and moves downwards, leads to the increase of the area and intensity of the negative pressure.

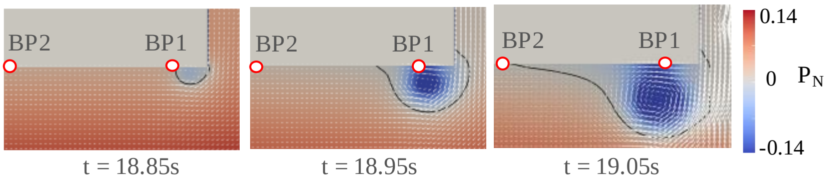

Figure 6: Flow field at the front-bottom corner of the structure

5 Conclusion

In this study, we develop an algorithm with enhanced momentum conservation which is capable of the simulation of highly deformed freak wave. The key phenomena during the impact are well reproduced, and the results show high accuracy. The wave impact leads to an impulsive effect on the front wall and a longer effect time on the bottom wall, which is the main threat to the structure stability. Negative pressure forms during the wave exit stage, due to the vortex develops at the bottom corner of the wave-facing side.

References

Bihs, H., Kamath, A., Chella, M. A., Aggarwal, A., & Arntsen, Ø. A. (2016). A new level set numerical wave tank with improved density interpolation for complex wave hydrodynamics. Computers & Fluids, 140, 191-208.

Osher, S., & Sethian, J. A. (1988). Fronts propagating with curvature-dependent speed: Algorithms based on Hamilton-Jacobi formulations. Journal of Computational Physics, 79(1), 12-49.

Sun, P. N., Luo, M., Le Touzé, D., & Zhang, A. M. (2019). The suction effect during freak wave slamming on a fixed platform deck: Smoothed particle hydrodynamics simulation and experimental study. Physics of Fluids, 31(11), 117108.

Wang, X., Luo, M., Karunarathna, H., & Reeve, D. E. (2023). An enhanced momentum conservation treatment for FDM simulation of two-phase flows with large density ratio. Journal of Computational Physics, 111949.