FULLY NONLINEAR SIMULATION OF FLOW KINEMATICS BENEATH REGULAR AND IRREGULAR WAVES PROPAGATING OVER SUBMERGED SILLS

Michel Benoit, EDF R&D, Laboratoire National d'Hydraulique et Environnement (LNHE), France, michel.benoit@edf.fr
Jie Zhang, Dalian University of Technology & Harbin Engineering University, China, Jie.zhang@dlut.edu.cn

INTRODUCTION

In the coastal zone, irregular wave trains undergo strong changes due to variable water depth inducing shoaling, refraction and nonlinear wave-wave and wave-bottom interactions. Knowing the evolution of the wave spectrum and statistical distributions of free surface elevation (FSE), wave crest height and wave height is of utmost interest for many applications in coastal engineering. This includes the design of coastal and harbor structures, the prediction of morphodynamical changes and beach erosion, just to mention few of them.

In the recent years, the capabilities and accuracy of deterministic (or phase resolving) wave numerical models have experienced significant progress, in particular with the development of fully nonlinear potential flow (FNPF) models. This family of models introduces no restrictive assumptions regarding the level of dispersion and nonlinearity of the wave field, so that these models can be used whatever the relative water depth and the wave steepness. The numerical model whispers3D solves the FNPF problem in a variable seabed configuration by approximating the velocity potential using a spectral approach in the vertical, with the basis of Chebyshev polynomials of the first kind (Yates & Benoit, 2015; Benoit *et al.*, 2017). It has been extensively validated against various experimental campaigns considering both regular and irregular non-breaking wave conditions (Raoult *et al.*, 2016; Zhang *et al.*, 2019; Zhang & Benoit, 2021). Recently, the model was extended to include the dissipation of energy due to depth-induced breaking, with various breaking criteria and dissipation formulations implemented and validated (Simon *et al.*, 2019).

In this study, the whispers3D model is used to simulate the wave induced kinematics beneath regular and irregular wave trains propagating over a submerged bar. This seabed configuration provokes strong changes in the wave fields and the wave kinematics underneath resulting from the combined effects of dispersion and nonlinearity. Two wave flume experiments offering refined measurements of FSE and horizontal velocity are used to assess and quantify the accuracy of the model.

EXPERIMENTS USED FOR MODEL'S VALIDATION

The two sets of experiments have been performed in a wave flume at the University of Oslo (Norway) and are described in Lawrence *et al.* (2021) for the regular wave case, and in Trulsen *et al.* (2020) for the irregular wave case. The lay-out of the wave flume and seabed profile is the same for both sets of experiments, and is shown in Figure 1. It consists of a submerged trapezoidal bar laid over an otherwise flat bottom. The still water depth away from the bar is 0.53 m, while the depth atop the bar is reduced to 0.11 m. The inclined faces of the bar have a slope of 1:3.81, each covering a distance of 1.6 m. The length of the bar crest is 1.6 m. Numerous wave probes and current-meters are available to measure the spatial evolution of FSE and wave induced orbital velocities, at an elevation $z_0 \approx 0.05$ m below the Still Water Level (SWL).

Two cases are selected and simulated in this study: (I) the regular wave case with wave period T = 1.43 s, and wave height H = 0.027 m from Lawrence *et al.* (2021), and (II) the irregular wave case called run 3 in Trulsen *et al.* (2020) with peak period T_p = 1.1 s, significant wave height H_s = 0.025 m (using a JONSWAP type spectrum with peak enhancement factor γ = 3.3).

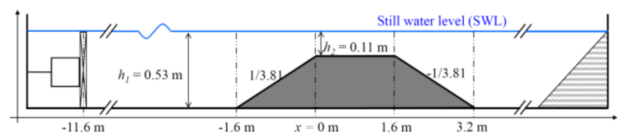

Figure 1 - Sketch of the experimental wave flume of the two experimental campaigns (not to scale).

RESULTS AND DISCUSSION

1. Methods of analysis and comparison

In each case considered, several analyses and comparisons were performed to evaluate the accuracy of the model regarding both the FSE η and the horizontal velocity $u(z_0)$, including the comparisons of:

- the time series of the signals at numerous locations;
- the spatial evolution of the amplitudes of up to the 6th harmonics for case (I), and of the power spectrum for the irregular wave case (II);
- the third- and fourth-order statistical moments, namely skewness (λ_3) and kurtosis (λ_4), respectively:

$$\lambda_3(\bar{X}) = \langle \bar{X}^3 \rangle \qquad \lambda_4(\bar{X}) = \langle \bar{X}^4 \rangle \tag{1}$$

  where $\langle\cdot\rangle$ denotes a mean operator, and $\overline{X}$ denotes the variable X (= η or $u(z_0)$) with zero mean and normalized by its standard deviation;
- the so-called asymmetry parameter defined as:

$$\lambda_3[\mathcal{H}(\bar{X})] = \left\langle \mathcal{H}(\bar{X})^3 \right\rangle \tag{2}$$

  with $\mathcal{H}$ denoting the Hilbert transform operator;
- the Probability Density Function (PDF) of η and $u(z_0)$, with comparison to existing statistical distributions, and in particular to the Gaussian PDF.

Excerpts of these results are presented below. The full set of comparisons and analyses will be shown and discussed during the conference.

2. Regular wave case (I)

The comparison of temporal profiles of horizontal velocity $u(z_0)$ at 6 abscissas along the wave flume for case (I) (Figure 2) shows a very good agreement at all locations. This is confirmed by the spatial evolution of harmonics amplitudes of $u(z_0)$ obtained by a Fourier analysis at each node of the domain (Figure 3), with an accurate reproduction of up to the 6th harmonics.

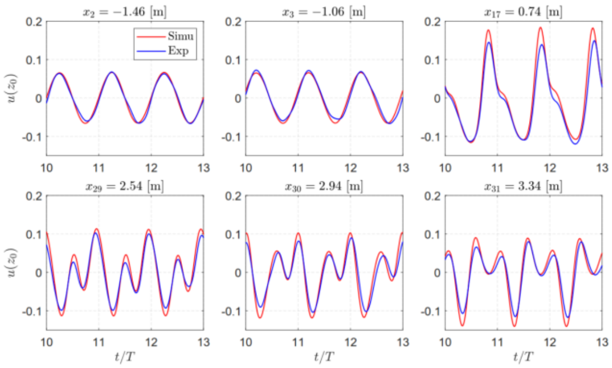

Figure 2 - Comparison of measured and computed horizontal velocity $u(z_0)$ temporal profiles at 6 locations for the regular wave experiment (I).

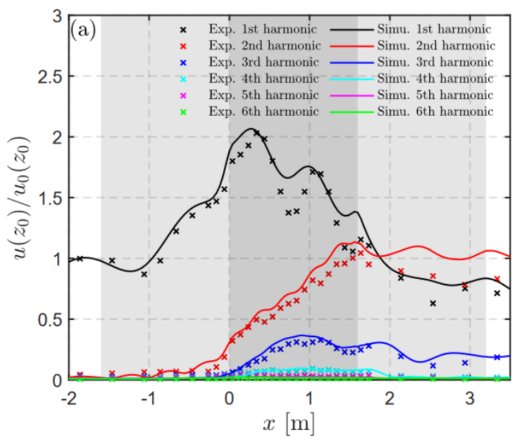

Figure 3 - Spatial evolution of measured and computed amplitudes of the first 6 harmonics of the horizontal velocity $u(z_0)$ for the regular wave experiment (I).

3. Irregular wave case (II)

For the irregular wave case (II), we present the comparison of the power spectrum of $u(z_0)$ in Figure 4, and the evolution of skewness of $u(z_0)$ in Figure 5. As for regular waves, both figures confirm the excellent behavior of the model in simulating all the nonlinear features of the transformation over the submerged bar.

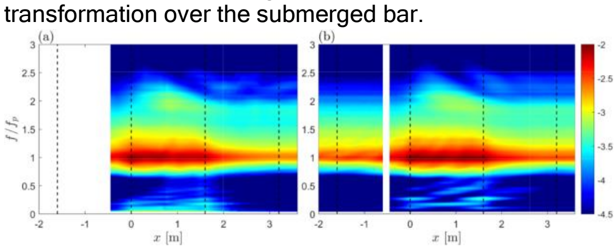

Figure 4 - Spatial evolution of the spectrum of horizontal velocity $u(z_0)$ in the experiment (a) and in the simulation (b) for the irregular wave experiment (II). The vertical dashed lines indicate the shape of the bar. The simulated spectral evolution before and over the upslope without the corresponding measurements is separated by a blank strip.

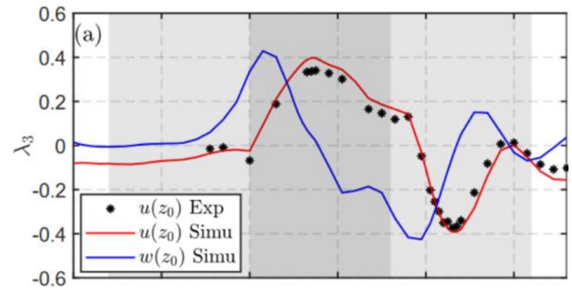

Figure 5 - Spatial evolution of measured and simulated skewness of horizontal velocity $u(z_0)$ for irregular wave experiment (II).

CONCLUSION

All the comparisons performed in this study demonstrate the extremely high accuracy of the FNPF model whispers3D to simulate not only the FSE of either regular or irregular nonlinear waves over variable bottom, but also the orbital velocities and accelerations beneath waves (the latter are not presented in this abstract due to space limitation). Of particular interest regarding coastal applications (e.g. calculation of wave loads on structures, improvement of wave kinematics for sediment transport), the nonlinear wave-wave and wave-bottom interactions are remarkably well captured, typically up to 5 to 6 times the fundamental wave frequency.

REFERENCES

Benoit, Raoult, Yates (2017): Analysis of the linear version of a highly dispersive potential water wave model using a spectral approach in the vertical, Wave Motion, vol. 74, pp. 159-181.

Lawrence, Gramstad, Trulsen (2021): Variational Boussinesq model for kinematics calculation of surface gravity waves over bathymetry, Wave Motion, vol. 100, 102665.

Raoult, Benoit, Yates (2016): Validation of a fully nonlinear and dispersive wave model with laboratory non-breaking experiments, Coastal Engineering, vol. 114, pp. 194-207.

Simon, Papoutsellis, Benoit, Yates (2019) Comparing methods of modeling depth-induced breaking of irregular waves with a fully nonlinear potential flow approach, Journal of Ocean Engineering and Marine Energy, vol. 5, pp. 365-383.

Trulsen, Raustøl, Jorde, Rye (2020): Extreme wave statistics of long-crested irregular waves over a shoal, Journal of Fluid Mechanics, vol. 882, R2.

Yates, Benoit (2015) Accuracy and efficiency of two numerical methods of solving the potential flow problem for highly nonlinear and dispersive water waves, International Journal for Numerical Methods in Fluids, vol. 77, pp. 616-640.

Zhang, Benoit (2021): Wave-bottom interaction and extreme wave statistics due to shoaling and de-shoaling of irregular long-crested wave trains over steep seabed changes, Journal of Fluid Mechanics, vol. 912, A28.

Zhang, Benoit, Kimmoun, Chabchoub, Hsu (2019): Statistics of extreme waves in coastal waters: large scale experiments and advanced numerical simulations, Fluids vol. 4, 99.