SIMULATION OF STEEPNESS-LIMITED BREAKING WAVES IN A FULLY NONLINEAR POTENTIAL FLOW MODEL

Sunil Mohanlal, LHSV, Ecole des Ponts, EDF R&D, Chatou, France, sunil.mohanlal@enpc.fr
Lili Kimmoun, Centrale Marseille, IRPHE, France, lili.kimmoun@centrale-marseille.fr
Stephan Grilli, Department of Ocean Engineering, University of Rhode Island, Narragansett, RI, USA, grilli@uri.edu
Jeffrey Harris, LHSV, Ecole des Ponts, EDF R&D, Chatou, France, jeffrey.harris@enpc.fr

INTRODUCTION

Steepness-limited wave breaking is simulated in a fully nonlinear potential flow model and validated with laboratory data. Breaking onset is based on the ratio of horizontal particle velocity at the crest, relative to the crest velocity reaching a threshold value. A breaking dissipation model, where the non-dimensional breaking strength parameter is predicted based on the linear wave steepness is used. A new time-dependent dissipation is tested, and the breaking termination criterion is studied.

NUMERICAL MODEL

Fully non-linear potential flow model (FNPF) assumes the fluid flow to be irrotational and inviscid, therefore the Laplacian of the velocity potential equal to zero. These models are computationally more efficient than the Navier-stokes models, but dissipation processes have to be explicitly modelled - for example, in situations when breaking waves are present. The FNPF model used here solves this Laplacian equation based on a boundary integral equation derived from Green's second identity, and time-integration of the free surface kinematic and dynamic boundary condition with a 2^{nd} order Taylor series expansion (Grilli et al., 1989).

EXPERIMENTAL SETUP

The test facility is a wave flume at a constant depth of $h = 0.667\ m$, where a flap wavemaker hinged $0.4\ m$ below the actual bottom is located at $x = 0$, and a wall at $x = 12.535\ m$ (Fig. 1). Focused waves are generated by the wavemaker based on a Ricker spectrum given by,

$$s(\omega) = H\sqrt{T}e^{-\omega^m T}[1 - a(\omega^m T - 1)] \qquad (1)$$

with $a = 1/(\omega_p^m T - 2)$, where ω_p is the peak angular frequency, H is a design wave height, m and T are spectral design parameters. The corresponding first-order transfer function is used to obtain the wavemaker kinematics (angular displacement, velocity and acceleration) in time. These kinematics are used as boundary conditions in the NWT (Grilli et al., 1997).

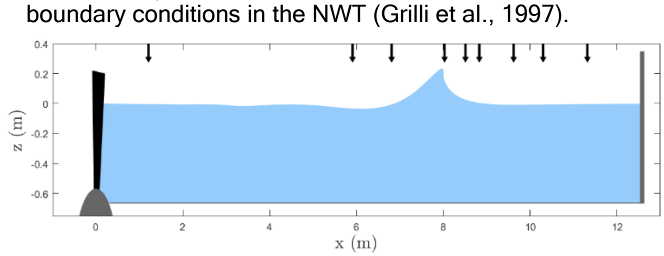

Figure 1: Experimental setup showing the flap wavemaker on the left and a wall on the right and a typical free surface elevation at the breaking onset. The arrows on the top indicates the location of gauges (Note: axis not equal).

BREAKING DISSIPATION

Implementing wave breaking in a fully nonlinear potential flow model is carried out in three steps. First, an onset, the instant at which wave breaking starts, is identified. We use the recently proposed universal criterion, i.e., an evolving crest whose ratio of horizontal particle velocity at the crest u, relative to the crest velocity c, $B = u/c$ exceeds 0.85, has not yet, but will break (Barthelemy et al., 2018). Derakhti et al. (2020) showed that this criterion applies well to arbitrary wavetrains in all ranges of water depth, including shallow water. Second, the magnitude of the energy dissipated is determined. This is done in two steps, the non-dimensional breaking strength parameter b (defined such that wave energy dissipation rate per unit length of the breaking crest, $\varepsilon = b\rho g^{-1}c^5$) is determined, which is used to obtain an instantaneous power to be dissipated. This power is then modelled by applying a damping pressure across the breaking wave free surface (Grilli et al., 2020; Papoutsellis et al. 2019). Lastly, a breaking termination criterion is specified to cease this dissipation.

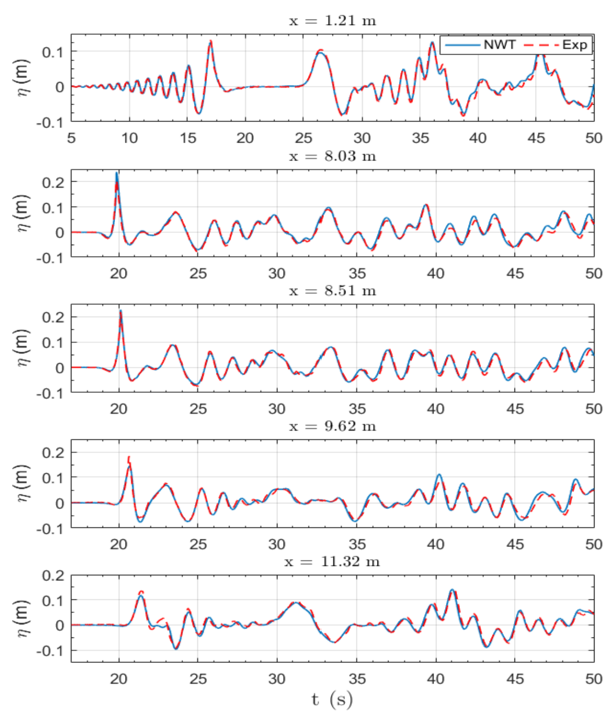

Figure 2: Free surface time series measurements at 5 gauges (dashed: experiment and solid: NWT) for a test case with $T_p = 2.4\ s$, $H = 0.2593\ m$, $T = 0.2285$ and $m = 1.42$. Onset is identified at $x = 8.05\ m$ and $t = 19.83\ s$.

B_{off}	$\bar{\bar{\eta}}(cm^2)$
Measured	110.1
0.1	83.3
0.2	97.7
0.3	106.1
0.4	109.7
0.5	112.9

Table 1: Sensitivity of B_{off} to the breaking dissipation. $\bar{\bar{\eta}} = \int_t^{t+T_p} \eta^2 dt$ where η is the elevation at $x = 9.62\ m$. T_p is the peak period and t is the instant the breaking wave crest reaches this gauge.

RESULTS

In the test cases under study, focused waves are generated that break in the domain and are reflected back from the wall. Free surface time series are measured at 9 gauges for a series of test cases with different wave steepness and focusing distances (x_f). Several videos and snapshots of the breaking waves are captured. Fig. 2 shows free surface measurements at 5 gauges of a test case with $x_f = 7.8\ m$. This test case corresponds to a linear wave steepness, $S = \sum_i a_i k_i = 0.45$, where a^i is the wave amplitude and k^i, the wave number of the i^{th} component, with $T_p = 2.4\ s$, $H = 0.2593\ m$, $T = 0.2285$ and $m = 1.42$. At the breaking onset has $d/L_b = 0.1618$ and $H_b/L_b = 0.0656$, thus characterising the breaker as an intermediate one, where d is the water depth, L_b is the wavelength measured as twice the distance between two zero-crossing points and H_b is the crest to trough height.

Testing different values of the dissipation strength, we see that the empirical prediction of Romero et al. (2012) for breaking strength based on linear wave steepness is reasonable, with $b \approx 0.033$, and is used to model the resulting breaking wave dissipation. The instantaneous power is then dissipated as in Mohanlal et al. (in revisions).

The breaking termination criterion, $B_{off} = 0.4$ is used, after testing a variety of values (see Table 1). Results show a very close agreement achieved between numerical simulations (NWT) and measurements, including close to the onset (Fig. 3) (at $x = 8.03\ m$) and beyond breaking (at $x = 11.32\ m$).

CONCLUSION

From the results, we see that the NWT is able to simulate non-linear waves accurately until the onset. Then, with the onset criterion $B = 0.85$, that determines a wave that is about to break, is seen to be an instant when the free surface is close to being vertical. The dissipation strength for steepness-limited breaking waves, predicted by their linear wave steepness (Romero et al. 2012), then models the resulting breaking wave to reasonable accuracy. This prediction however is determined by a narrow spread of data. Therefore, a quantitative study will be shown at the conference, showing the sensitivity in simulation results on b. A similar study will be done on the sensitivity of the breaking termination criterion.

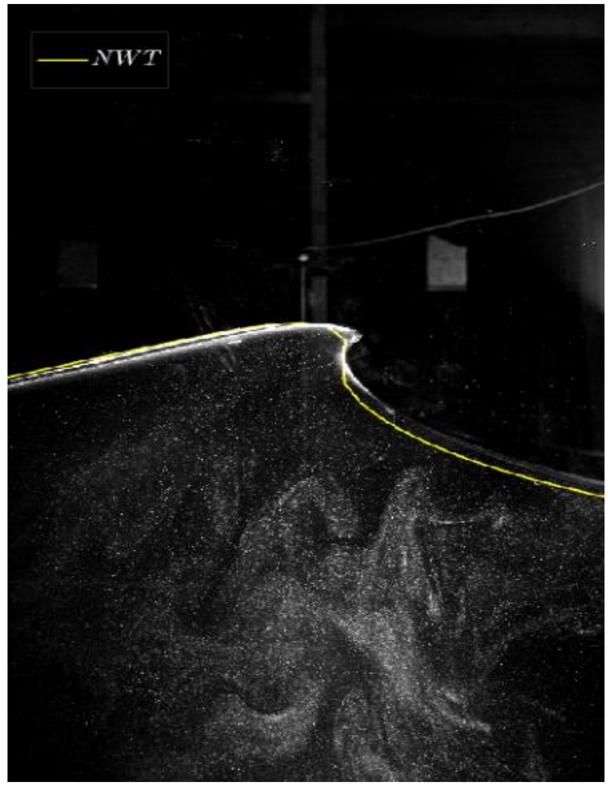

Figure 3: Free surface elevation at the onset, of NWT results for the case of Fig. 2 (yellow) compared with the experimental figure at an overturning instant.

REFERENCES

Barthelemy, X., Banner, M.L., Peirson, W.L., Fedele, F., Allis, M., Dias, F., 2018. On a unified breaking onset threshold for gravity waves in deep and intermediate depth water. Journal of Fluid Mechanics 841, 463-488.

Derakhti M. , J.T. Kirby, M.L. Banner, S.T. Grilli and J. Thomson 2020. A unified breaking onset criterion for surface gravity water waves in arbitrary depth. J. Geophys. Res., 125(7), e2019JC015886.

Grilli, S.T., Horrillo, J., 1997. Numerical generation and absorption of fully nonlinear periodic waves. Journal of engineering mechanics 123, 1060–1069

Grilli, S.T., Horrillo, J., Guignard, S., 2020. Fully nonlinear potential flow simulations of wave shoaling over slopes: Spilling breaker model and integral wave properties. Water Waves 2, 263-297.

Grilli, S.T., Skourup, J., Svendsen, I., 1989. An efficient boundary element method for nonlinear water waves. Engineering Analysis with Boundary Elements 6, 97-107.

Mohanlal, S., Harris, J., Yates, M., Grilli, S., In Revisions. Unified depth-limited wave breaking detection and dissipation in fully nonlinear potential flow models. Coastal Engineering.

Papoutsellis, C.E., Yates, M.L., Simon, B., Benoit, M., 2019. Modelling of depth-induced wave breaking in a fully nonlinear free surface potential flow model. Coastal Engineering 154, 103579.

Romero, L., Melville, W.K., Kleiss, J.M., 2012. Spectral energy dissipation due to surface wave breaking. Journal of Physical Oceanography 42, 1421-1444.