NUMERICAL MODELING OF WAVE OVERTOPPING OF COASTAL BREAKWATERS FOR BIMODAL SEA STATES WITH DEPTH-AVERAGED MODELS

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INTRODUCTION

To assess the safety of coastal infrastructures against marine hazards or to design coastal or harbor protections, wave overtopping rates for extreme sea-state conditions must be estimated. A usual practice is to use empirical formulas predicting average wave overtopping discharges for a given structure profile and sea-state conditions, with the state-of-the-art being the EurOtop manual (van der Meer *et al.*, 2018). However, the configurations for which these formulas can be applied are in limited number, simplified, and assume a uniform breakwater profile in the longshore direction.

Additionally, for complex sea states, e.g. with bimodal incident spectra resulting from a superposition of a swell and a wind-sea components, the wave characteristics used in the formulas might not be enough to estimate accurately the overtopping discharge (Villefer *et al.*, 2023). In such cases experiments in a wave flume or wave basin need usually to be performed (e.g. Orimoloye *et al.*, 2021). Numerical modeling on the other hand is a more flexible way of computing average overtopping discharges, among other parameters, for more complex structures and flow configurations. Refined Computational Fluid Dynamics (CFD) codes solving the primitive Navier-Stokes equations, for either the water phase alone, or the water and air phases, can be applied (e.g. Altomare et al., 2021; Chen *et al.*, 2021), but the required computational burden remains high and limits the number of cases that can be simulated in realistic situations. The purpose of this work is to investigate the performance of simpler numerical models for the simulation of wave overtopping over coastal structures of simple profile, namely depth-averaged weakly-dispersive wave models.

EXPERIMENTS OF WAVE OVERTOPPING OF SMOOTH AND RUBBLE-MOUND BREAKWATERS

Experiments of irregular wave overtopping characterized by bimodal long-crested spectra, conducted in the Institut Pythéas wave tank in Marseille (France), were considered as a set of reference data (Villefer *et al.*, 2023). The wave tank is 40 m long and 2.6 m wide, and the still water depth in the experiments varied between 72 and 74 cm.

A low-crested breakwater with a slope 2:3 (V:H) and relative crest freeboard R_c/H_{m0} varying between 0.4 and 2 was investigated (R_c being the freeboard above the still water level and H_{m0} the incident significant wave height), with both smooth and rock-armored slopes. Figure 1 shows a picture of the breakwater with the smooth slope. During the experiments, R_c was varied by adding successively 1 to 4 wooden planks of thickness 1.5 cm each on the breakwater crest. The overtopping water volume was collected in a dedicated tank located at the rear of the breakwater, and the total volume for each test (of 30 min duration) was measured.

Figure 1 - Picture of the breakwater with a smooth slope.

8 different unidirectional sea states were considered, either unimodal or bimodal obtained as superpositions of two JONSWAP-type spectra of varying significant wave height: one swell spectrum of peak period $T_p = 1.67$ s, and one wind-wave spectrum with varying peak period $T_p \in [0.57, 1]$ s. The significant wave height H_{m0} varied between 4.34 and 7.39 cm. The wave energy spectra of 4 out of these 8 sea states are plotted in Figure 2. They are colored by the representative wave steepness:

$$s_{m-1,0} = \frac{H_{m0}}{L_{m-1,0}} \tag{1}$$

with $L_{m-1,0} = gT_{m-1,0}^2/(2\pi)$ the deep-water wavelength, based on the energy period $T_{m-1,0} = m_{-1}/m_0$ defined from the moments of the variance density spectrum. Cases A and B correspond to pure swell and wind-waves respectively, and cases C to H are bimodal sea states.

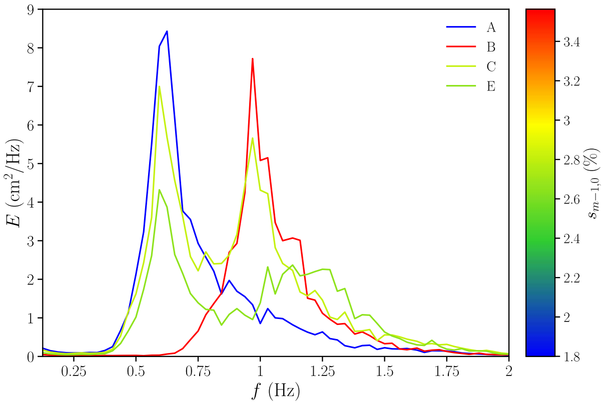

Figure 2 - Typical variance density spectrum as a function of frequency for 4 of the 8 cases considered in the wave flume experiments.

NUMERICAL MODELING OF WAVE OVERTOPPING

Numerical models based on depth-averaged weakly-dispersive and nonlinear equations (Boussinesq-type equations) allow to simulate accurately wave propagation in coastal areas, in shallow and intermediate waters, with an affordable computational cost compared to solving the Euler or Navier-Stokes equations. Examples of such equations can be found in Nwogu (1993), Kennedy *et al.* (2001) or Bonneton *et al.* (2011), among others. They can also be used to simulate wave run-up and overtopping with a similar accuracy as more computationally demanding models (Lashley *et al.*, 2020).

In this work, various Boussinesq- or Serre-Green-Naghdi (SGN)-type wave models, existing and under development, are used to simulate wave propagation and overtopping of breakwaters with smooth slopes first. Some results obtained when simulating the smooth slope cases from the experimental campaign of Villefer *et al.* (2023), with 73 different trials in total, with the fully nonlinear weakly dispersive Boussinesq model FUNWAVE-TVD (Shi *et al.*, 2012), are presented as an example in Figure 3.

The relative overtopping discharge $q^* = q/\sqrt{gH_{m0}^3}$, with q the discharge over the breakwater crest averaged over the 30 min duration of the test, is plotted against the relative crest freeboard. The corresponding EurOtop formula predicting the overtopping discharge in this case is:

$$q^* = 0.09e^{-1.5\left(\frac{R_c}{H_{m0}}\right)^{1.3}} \tag{2}$$

The formula (black solid line) and the bounds of its 90% confidence interval (dashed black lines) are also represented. The experimental results are marked with grey symbols. The numerical data points are again colored by representative wave steepness. As for the experiments, the significant wave heights used to scale the numerical results are obtained from the incident spectra computed from free surface elevation time series at 5 numerical wave gauges.

The experimental results agree well with the empirical EurOtop formula. The numerical model results slightly underestimate experimental overtopping as a whole, but similar trends observed in the experimental points are recovered and the results are overall satisfying.

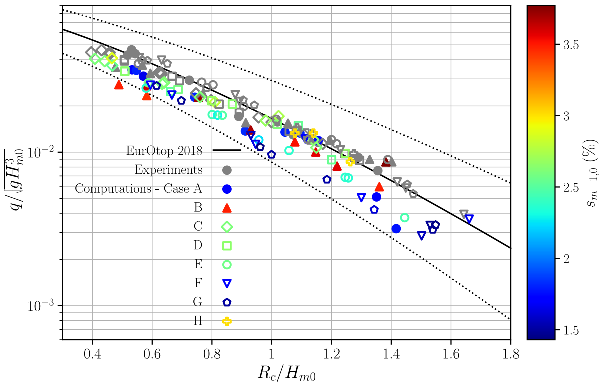

Figure 3 - Relative wave overtopping discharge computed with FUNWAVE-TVD as a function of the relative crest freeboard for the smooth slope breakwater.

CONCLUSION AND OUTLOOK

The results obtained up to now (illustrated by those from FUNWAVE-TVD in Figure 3) are very promising for the smooth slope breakwater. A more in-depth comparison of different wave models will be presented at the conference. Work is planned to model numerically rock-armored breakwaters as porous regions, as was done with depth-averaged wave models in Wurjanto & Kobayashi (1993) or van Gent (1994) among others.

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