# Hydrodynamics of random waves and extreme storms over planar beaches

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## Introduction

Storm waves in the coastal zone undergo strong nonlinear transformations and wave breaking. The complexity of these processes poses significant challenges on the accurate prediction of wave statistics. Nevertheless, the design of coastal structures, sediment transport calculations and coastal flooding predictions critically depend upon the correct representation of wave characteristics. More specifically, it is the hydrodynamics of the largest waves arising within significant storms that concern engineering design. As such, the present study examines the statistics of long-crested, zero-crossing waves contained in sea-states with steepnesses varying from linear to extreme. Planar beaches of varying slopes are used as proxies for realistic bathymetric configuration of coastal areas. The findings presented herein are based on the combined analysis of an extensive set of experiments, generated at the Hydrodynamics Laboratory at Imperial College London, and the digital equivalent of these experiments simulated using the well-established numerical model SWASH (Zijlema et al., 2011). Results arising from both these methods are compared to each other, as well as the corresponding predictions of state-of-the-art statistical models.

## Methods

Experiments were conducted in the Coastal Flume, at Imperial College London (Fig. 1). A false bed was installed downstream of the wavemaker, extended beyond the shoreline and was varied to provide slopes of $\boldsymbol{s = 1{:}15, 1{:}30}$ and $\boldsymbol{1{:}50}$. The offshore water depth was held constant at $\boldsymbol{d = 50\ \mathrm{m}}$ (at field scale). An array of 80 densely spaced wave gauges was installed over the full length of the sloping bed.

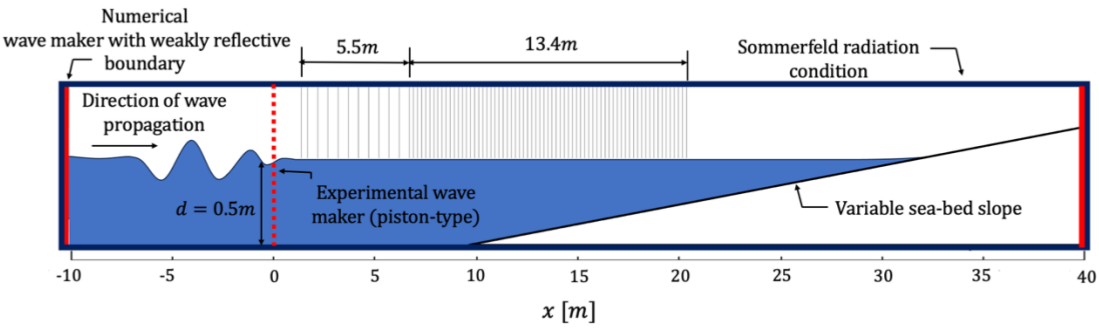


Fig. 1. Experimental and numerical setup.

The numerical wave flume in SWASH mirrored the experimental setup with the addition of an initial relaxation zone to ensure the correct generation and absorption of waves. Full details about the numerical setup and simulation parameters can be found in (Al Khalili et al., 2024). The sea-states considered in this study correspond to JONSWAP spectra defined by their significant wave height, $\boldsymbol{H_s}$, and peak period, $\boldsymbol{T_p}$ (Table 1). Each one consists of 20, 3-hour long, simulations with random initial phases sampled from a uniform distribution, $\boldsymbol{\Phi \sim U[0, 2\pi]}$).

Table 1. Sea-states expressed in field scale adopting Froude similarity scaling with $\boldsymbol{L_s = 1{:}100}$.

| Case | $\boldsymbol{H_s}$ (m) | $\boldsymbol{T_p}$ (s) | $\boldsymbol{\frac{1}{2}H_s k_p}$ (-) | $\boldsymbol{s}$ (-) |
|---|---|---|---|---|
| B1 | 2.9 | 14 | 0.04 | 1:15<br>1:30<br>1:50 |
| B2 | 5.7 | | 0.07 | |
| B3 | 8.6 | | 0.11 | |
| B4 | 11.5 | | 0.14 | |
| B5 | 13.9 | | 0.17 | |
| B6 | 15.6 | | 0.19 | |

## Results

The time-series of water surface elevations were analysed to produce statistical distributions of zero-crossing wave heights and crest heights for all test cases and wave gauge locations. The amalgamated datasets of approximately 15,000 waves per sea-state were compared to commonly adopted statistical models as shown in the examples of Figure 2. Overall, numerical simulations show relatively good agreement with experimental results for weakly nonlinear conditions, $\frac{H_s}{d} < 0.3$. However, steeper and shallower sea-states are less well modelled and notable discrepancies arise for extreme waves. Existing statistical models cannot capture nonlinearities arising above second order of wave steepness or breaking. This results in a divergence between measured and predicted distributions, particularly for low exceedance probabilities.

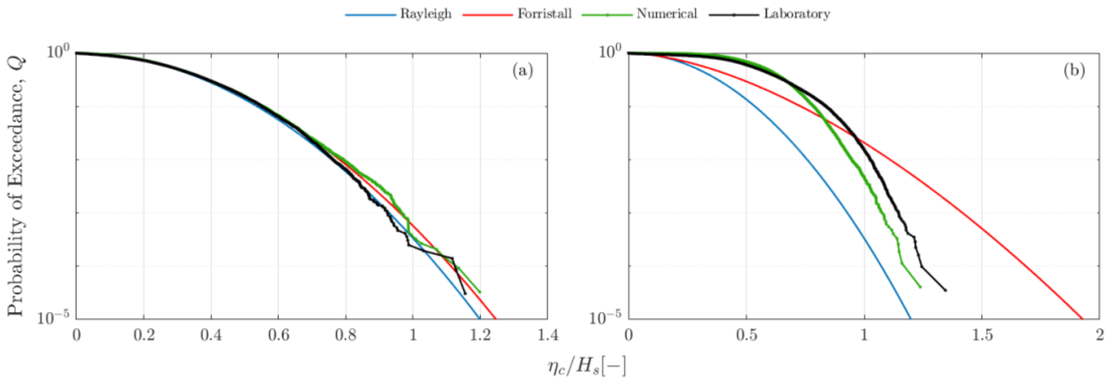


Fig. 2. Exceedance distributions of normalised crest heights, $\frac{\eta_c}{H_s}$, corresponding to $s = 1{:}50$, (a) Case B1 at gauge 5 ($k_p d = 1.16$) and (b) Case B5 at gauge 75 ($k_p d = 0.57$).

## Conclusions

An extensive laboratory dataset consisting of long random wave simulations over uniform bathymetries with varying slope has been generated. This has been reproduced numerically using the SWASH model. Experimentally derived wave statistics diverge from numerical and theoretical predictions for steeper and shallower storms. This indicates the need for an improved parametrization of higher-order nonlinear interactions in shallow water and wave breaking.

## References

Al Khalili, U., Karmpadakis, I., Christou, M., & Bellos, V. (2024). Performance of SWASH in modelling regular and irregular waves on mild bathymetries. *Coastal Engineering (under review)*.

Zijlema, M., Stelling, G., & Smit, P. (2011). SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. *Coastal Engineering*, *58*(10), 992–1012. https://doi.org/10.1016/j.coastaleng.2011.05.015