EXPERIMENTAL INVESTIGATION OF EXTREME CREST HEIGHTS OVER SLOPING BEDS

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ABSTRACT

This paper explores the spatial evolution of the short-term statistical distributions of zero-crossing crest heights of waves propagating over various sloping bathymetries. The analysis is based on laboratory data obtained from long random wave simulations in realistic sea-state conditions. The experiments were specifically designed to isolate the contributions of key metocean parameters, such as sea-state wave steepness, effective water depth and seabed slope. The crest height distributions are assessed against some of the most widely-applied statistical models in engineering practice. Their range of applicability is investigated, and key deviations are observed. Taken together, the results presented herein offer important insights for improving extreme crest height prediction, and thus provide significant practical implications for and the design of coastal structures.

INTRODUCTION

The accurate prediction of the statistical distributions of crest heights in extreme sea-states across a broad range of effective water depths and incident wave conditions has traditionally been a particularly difficult challenge. This has resulted in large uncertainty in the estimation of design conditions for many offshore and coastal installations. One of the most widely-applied statistical models for crest heights is the Forristall (2000) distribution. This has been extensively validated and is the present recommended design practice (DNV 2010). However, recent findings by Karmpadakis et al. (2019) suggest that noteworthy discrepancies between the model predictions and real crest height distributions can arise for flat beds in intermediate water depths. Building upon these results, the present study aims to provide physical insights into the evolution of the crest height distributions of waves as they propagate shoreward.

EXPERIMENTAL SETUP & METHODOLOGY

The experimental setup is illustrated in Figure 1. Unidirectional random waves propagating over uniform bed slopes were recorded using a densely-packed array of wave gauges. The fine spatio-temporal resolution of the measurements provides in-depth insights into the competing physical processes of nonlinear amplification and wave breaking, as well as their dependence on the investigated parameters. The experimental cases are presented in Table 1. These correspond to 6 sea-states of increasing offshore steepness propagating over 4 different seabed configurations. The water depth ranges from intermediate to shallow, and the sea-states cover near-linear to highly nonlinear storms. The data are generated using JONSWAP spectra with a peak enhancement factor γ=2.5 to reflect realistic storm conditions in intermediate water depth. The methodology follows the phase-alignment approach described by Karmpadakis et al. (2019). Multiple realisations were performed resulting in a large number of waves recorded, which allowed us to reach very low exceedance probabilities (Q<10-4) and investigate extreme wave events under increased confidence. An exhaustive list of the cases conducted and detailed descriptions of the experimental facility are provided in Bellos et al. (2023).

Table 1 - List of experimental cases

Sea-state	T_p [s]	$1/2H_{s0}k_{p0}$ [-]	s [-]	k_pd [-]
S_p1		0.035		
S_p2		0.070	0	1.22
S_p3		0.105	1/15	⋮
S_p4	1.4	0.140	1/30	0.13
S_p5		0.170	1/50	
S_p6		0.190		

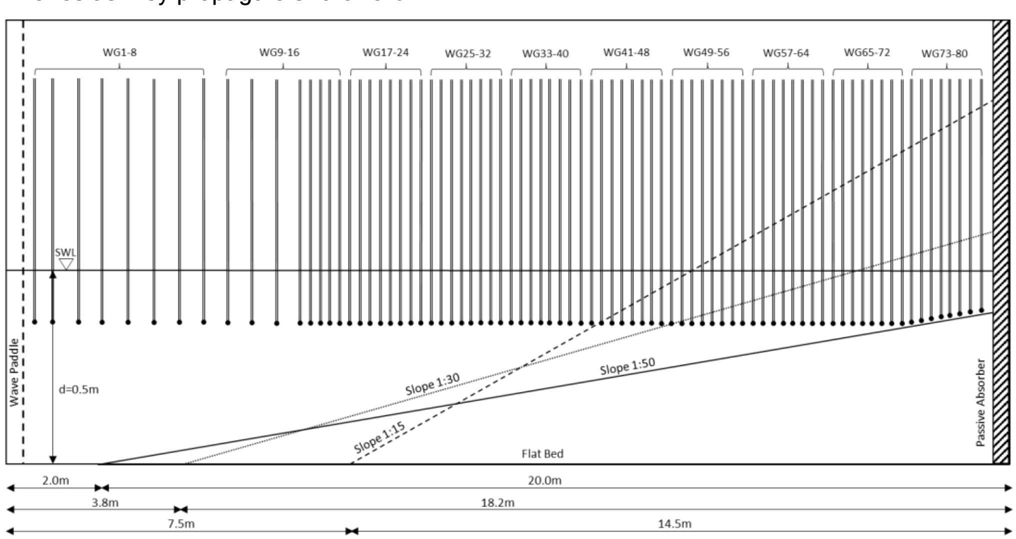

Figure 1 - Experimental Setup

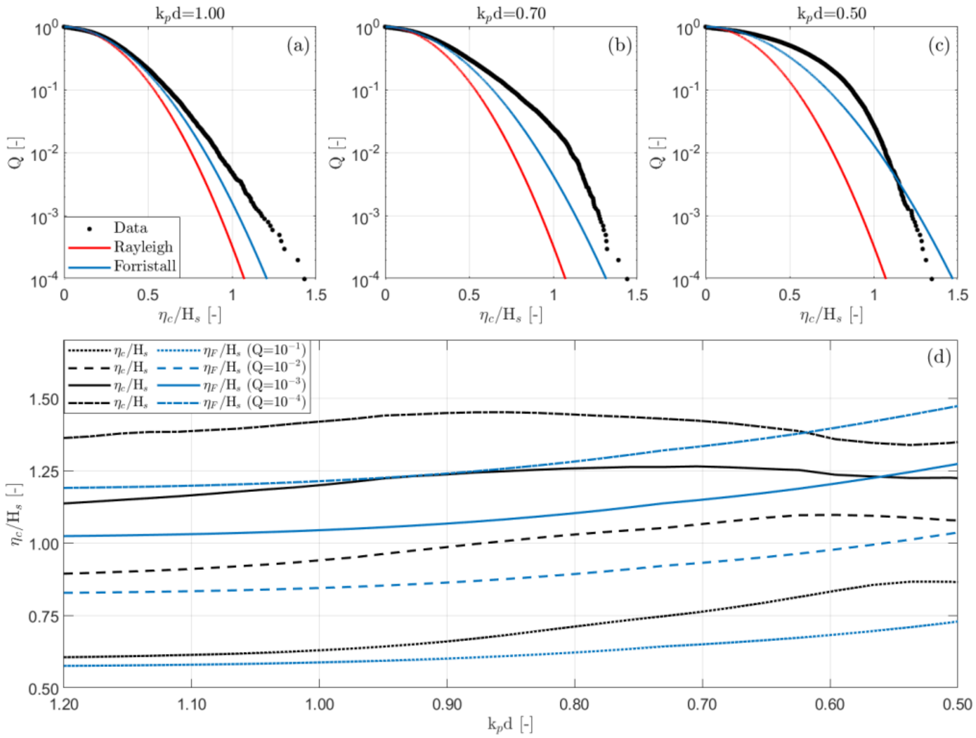

Figure 2 - (a-c) Normalised crest height distributions (n_c/H_s) and the corresponding Rayleigh and Forristall model predictions for selected effective water depths (k_pd). (d) Spatial evolution of n_c/H_s and the corresponding Forristall model predictions (n_F/H_s) for representative exceedance probabilities (Q). The data relate to a bed slope of s=1/15 and offshore wave steepness $1/2H_{s0}k_{p0}$=0.105

DISCUSSION

To isolate the individual contributions, comparisons are performed while varying the parameter of interest. Such a comparison is presented in Figure 2. For a selected bed slope and sea-state steepness, the evolution of the crest height distributions is examined. In subplots (a-c), the measured crest height distributions at selected effective water depths are compared against the corresponding predictions of the Rayleigh model (Longuet-Higgins, 1952) and the Forristall model. We observe that the linear Rayleigh model consistently underpredicts the data for all examined water depths. This is not surprising, particularly considering the enhancement of the nonlinear characteristics of waves as the effective water depth reduces. While the second-order Forristall model also underpredicts the data for the bulk of the distributions, we observe that it starts to overpredict the data in the tail of the distributions for the shallowest location. This is caused by the downward shift exhibited in the tail of the distributions, with a reduction in the largest crest heights as the water depth reduces, and is attributed to the increased relative importance of wave breaking. To further investigate this, subplot (d) shows the cross-shore evolution of crest heights at selected exceedance probability levels with comparisons to the Forristall model predictions. We observe that the second order model consistently underpredicts the crest heights at the offshore location. The relative error initially increases as the effective water depth reduces and the waves become more nonlinear. However, it starts to decrease as the effect depth further reduces. This occurs progressively earlier for lower exceedance probability levels. This is due to the onset of depth-limited wave breaking, which is not incorporated into the model. Importantly, this shows that the same model can simultaneously both over- and underpredict the crest height distributions of waves of the same offshore sea-state steepness as they propagate over a uniform sloping bed. Overall, the findings of this research allow for an in-depth understanding of the effects of nonlinearity, reduced water depth, bathymetric configuration, and the dissipative effect of wave breaking on the statistical distributions of crest heights. These can be used to identify the physical reasons behind observed deviations in the most widely-applied statistical models. In extending these results to different slopes and incident wave steepnesses, the relative importance of the slope angle, nonlinearity and wave breaking is determined, providing invaluable insights for improving extreme crest height prediction.

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