

# NON-EQUILIBRIUM WAVE STATISTICS IN COASTAL AREA ASSOCIATED WITH STRONG VARIATIONS OF WATER DEPTH AND AMBIENT CURRENT

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## INTRODUCTION

Freak waves, usually defined as waves with crest-to-trough heights exceeding twice the significant wave height  $H_s$  (e.g. Dysthe *et al.*, 2008), pose a significant risk to maritime and ocean engineering (Didenkulova *et al.*, 2023). These anomalous waves occur under various conditions but are particularly hazardous in coastal regions with intense human activity (Li and Chabchoub, 2023). Several possible mechanisms have been put forward for explaining the generation of freak waves (e.g. Adcock and Taylor, 2014). The modulation instability (MI) is probably the most well-known nonlinear mechanism among all (Benjamin and Feir, 1967). However, it remains debatable on the importance of MI for freak wave formation in real seas, due to the complexity of the dynamical environment (Fedele *et al.*, 2016). Moreover, the MI becomes ineffective when the relative water depth  $\mu = kh$  ( $k$  being the local wave number and  $h$  the local water depth) is below 1.363, which is common in coastal areas.

In coastal zones, the wave behavior is strongly influenced by the local seabed and ambient flow patterns, which can vary significantly. Recent research indicates that, as irregular waves interact with uneven bottoms featuring steep shoals, non-equilibrium dynamics (NED) comes into play, potentially increasing the probability of freak wave occurrence (Trulsen *et al.*, 2012; 2020; Zhang *et al.*, 2019; 2021). The NED phenomenon is characterized by a rapid redistribution of wave energy among harmonic components (Li *et al.*, 2021a, b; Mendes *et al.*, 2022; Mendes and Kasparian, 2023). While the NED could be triggered by the abrupt changes of various environmental conditions, most previous studies focused on depth changing scenarios. To the limit of our knowledge, the influence of ambient flow-related NED remains unexplored.

In this study, we present experimental evidence demonstrating that, as waves propagate over an uneven bottom with the presence of uniform following current, the mean flow velocity varies according to the changes of local water depth, and the inhomogeneity of current in the direction of wave propagation leads to NED. As a result, the freak wave probability is further enhanced by a following current, which was considered the opposite in the regime of MI (Toffoli *et al.*, 2015).

## EXPERIMENTAL SETUP

The experiments were conducted in the wave-current flume of the National Marine Environmental Monitoring Center (NMEMC) in Dalian, China. The flume is 80 m in length, 1.5 m in width and 2 m in depth. It is equipped with a piston-type wavemaker on one side, and a passive dissipation zone on the other. The current is generated with a pump, and the flow inlet is placed 2 m after the wavemaker, the outlet 1 m before the damping zone.

Throughout the campaign, the water depth close to the wavemaker is fixed  $h_1 = 1$  m. A submerged bar is installed in the flume, starting at 17.3 m away from the mean position of wavemaker. This bar consists of a 18 m long up-slope (1/30), a 10 m long flat bar crest, and a 12 m long down-slope (-1/20). The water depth over the bar is  $h_2 = 0.4$  m. The flume setup is illustrated in figure 1.

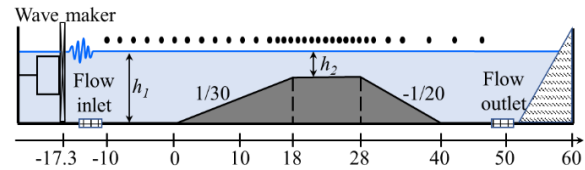


Figure 1 - Sketch of the experimental wave flume (not to scale). The black dots represent the locations of probes.

The irregular incident waves are characterized by a JONSWAP spectral shape, which involves spectral peak frequency  $f_p = 1/T_p$ , enhancement factor  $\gamma$  (set as 3.3 throughout the study) and significant wave height  $H_s$ . The current is generated by pumping water in/out at two sides of the bar with a fixed discharge of 0.15 m<sup>3</sup>/s, resulting in 0.1 m/s mean flow velocity before the bar and 0.25 m/s atop of it. We show the results of wave-bottom interaction with and without ambient flow, denoted as UWO and UWC, respectively. Flat bottom wave tests and uneven bottom with pure current tests have been performed as well but will not be detailed here. Four among eleven tested wave configurations are listed in Table 1, each was performed for 10 runs of 10 min duration each, with different sets of random phases.

Table 1 Key wave parameters before and over the bar

No.	$T_p$ [s]	Deeper region: UWO case			Bar-crest region: UWO case		
		UWC case			UWC case		
		$H_s$ [cm]	$\mu$	$\varepsilon$	$H_s$ [cm]	$\mu$	$\varepsilon$
5	2.12	9.0	1.11	0.036	8.7	0.63	0.048
		8.4	1.05	0.031	7.5	0.54	0.036
6	2.24	9.1	1.03	0.033	8.8	0.59	0.046
		8.7	0.97	0.030	7.9	0.51	0.035
7	2.35	9.2	0.97	0.031	8.8	0.56	0.043
		8.7	0.92	0.028	8.0	0.48	0.034
8	2.45	11.0	0.92	0.036	10.8	0.53	0.051
		10.8	0.87	0.033	10.1	0.46	0.041

The table shows non-dimensional wave parameters steepness  $\varepsilon \equiv \sqrt{2}k_p H_s / 4$ , and relative water depth  $\mu \equiv k_p h$ , with  $h$  taking either  $h_1$  or  $h_2$  depending on the location,  $k_p$  denotes the wavenumber corresponding to the peak frequency and the local water depth. The wavenumber is evaluated with current effect considered via Doppler-shifted dispersion

relationship:

$$\omega = 2\pi f = \omega_{int} + kU = \sqrt{gk \tanh(kh)} + kU \quad (1)$$

where  $\omega_{int}$  denotes the intrinsic wave frequency,  $U$  the mean flow velocity (in UWO cases,  $U = 0$  m/s, and in UWC cases,  $U = 0.1$  m/s or  $0.25$  m/s). The wave measurements were performed with sampling frequency  $50$  Hz.

## RESULTS AND DISCUSSION

In previous studies on the NED induced by the depth variation, the local variation of spectral and statistical properties is commonly used to characterize the relative importance of NED. Especially, the variation of skewness and kurtosis in space received more attention, as they are closely related to the probability of freak waves. Following this idea, we focus on the evolution of kurtosis  $\lambda_4$ , defined as:

$$\lambda_4 = \left\langle \left( \frac{\bar{\eta}}{\bar{\eta}} \right)^4 \right\rangle \quad (2)$$

where  $\langle \cdot \rangle$  denotes a mean operator, and  $\bar{\eta}$  denotes free surface elevation with zero mean and normalized by its standard deviation. It is known that  $\lambda_4$  is positively related to the freak wave probability.

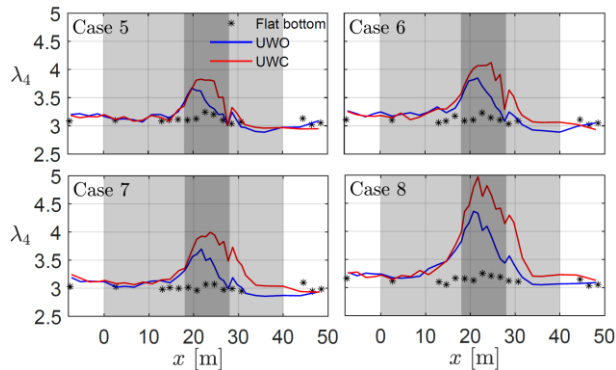


Figure 2 - Comparison of kurtosis evolution in space. Gray areas indicate the submerged bar, results of UWO and UWC cases are shown and results of flat bottom tests (with  $h_1 = 1$  m) of the same wave trains are superimposed.

Figure 2 shows that, if the irregular waves propagate over flat bottom (black asterisks) with depth  $h_1 = 1$  m, no evident modulation on the kurtosis occurs. When the wave trains encounter uneven bottom with steep up-slope, then the kurtosis, thus the probability of freak waves, is locally enhanced, and the enhancement is related to the reduced relative water depth after the slope. More importantly, as noticed in Zhang *et al.* (2023), if the wave trains pass over non-homogeneous media with steep up-slope and following current (nearly uniform in the vertical direction and accelerating in the horizontal direction), then the kurtosis gets further enhanced. The observation seems to be contradictory with the intuition that an accelerating following current reduces the wave nonlinearity, thus suppresses the MI as well as the occurrence of freak waves. In fact, they are not conflicting as MI is not the governing mechanism over the shallower region with  $\mu < 1.363$ .

In the present study, we performed additional in-depth analyses of the experimental data, including spectral analysis, and wave height distribution analysis. More

features of the NED effects induced by wave-current-bottom interaction are summarized and reported. As a general remark, an accelerating following current could enhance the probability of freak waves via NED and without the effect of MI. This should not be overlooked for coastal engineering applications.

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