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Experimental study of freak waves due to three-dimensional island terrain in random wave

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Abstract

An experimental study is carried out for waves passing an isolated reef terrain in a wave tank. A three-dimensional model of a representative and isolated reef terrain in the West Pacific is built. Random wave trains with various periods and wave heights are generated by a wave maker using the improved JONSWAP spectrum. It is observed that there are different kinds of generation processes and waveforms of freak waves. The freak wave factor H_m/H_s (where H_m is the maximum wave height of wave series, and H_s is significant wave height) is analyzed in detail, in terms of the skewness, kurtosis and water depth, as well as the relationship between freak wave height H_{fr} and skewness. The freak wave factor H_m/H_s is found to be in positive correlation with the kurtosis, while larger H_{fr} tends to be related with bigger skewness. The rapid variation of water depth, such as slope and seamount, contributes to the occurrence probability of freak waves.

Key words: freak waves, random wave, skewness and kurtosis, three-dimensional island terrain

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1 Introduction

Freak waves are steep waves with large amplitude, which are a huge threat for marine and offshore structures. It is also called rogue wave or giant wave. Dean (1990) defined freak waves as the waves with amplitude being more than twice of the significant wave height. Other definitions of freak waves can be found in the related references (Soares et al., 2003; Kharif et al., 2009). It was reported that 22 accidents of large vessels were caused by freak waves from 1969 to 1994 (Lawton, 2001). The Draupner wave or "New Year" wave was the first freak wave detected by a measuring instrument, occurring at the Draupner platform in the North Sea off the coast of Norway on 1 January 1995 (Haver, 2004). A set of available measurements of freak waves are gathered from several periods of continuous wave recordings made in the Sea of Japan during 1986–1990 (Mori et al., 2002). Other *in-site* observed data of freak waves in the open sea are recorded and analyzed (Soares et al., 2003; Veltcheva and Soares, 2012; Didenkulova, 2011; Cherneva and Soares, 2014). Those records of freak wave events in the ocean are valuable for studying the features of freak waves.

Some physical mechanisms of freak waves are researched, for example, geometrical focusing, focusing due to dispersion of the wave group velocity and the modulational (Benjamin–Feir) instability, essentially nonlinear wave interaction and wave-current interaction (Slunyaev et al., 2011). The influence of the seabed terrain is another important factor causing freak waves. The probability of freak waves increases within the transition zone (Sergeeva et al., 2011). Trulsen et al. (2012) had shown that, for a long unidirectional wave, the probability of large wave envelope has a local maximum near the shallower side of a slope. The probability of freak waves is also studied numerically both at the shallow end of a slope and for some distance after the slope (Gramstad et al., 2013). Some effects of nonuniform bathymetry on wave statistics are investigated for variable depth based on nonlinear Schrodinger equation (Zeng and Trulsen, 2012).

The relationships between various parameters of wave trains and freak waves have been investigated, such as the kurtosis of wave surfaces (Toffoli et al., 2008; Zeng and Trulsen, 2012; Li et al., 2013, 2015; Toffoli et al., 2015), skewness of wave surfaces (Toffoli et al., 2008; Shemer and Sergeeva, 2009; Zeng and Trulsen, 2012; Li et al., 2013, 2015), and distribution of wave height (Tayfun and Fedele, 2007; Onorato et al., 2006; Li et al., 2013). The probability of freak waves and the value of kurtosis are positively related. It is a good indicator of freak waves.

Studies have been conducted on physical mechanisms for the generation of freak waves, using field measurements in the ocean and water tank, experiments, computations and analytic method. Experiment is an important method to study the mechanisms of

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freak waves, since the *in-site* measured data are scarce and these data are always measured at fixed points without the information of surrounding area, which could reveal the generation and evolution process of freak waves. Onorato et al. (2006) discussed the statistical properties of surface elevation for long crested waves characterized by the JONSWAP spectra with random phase. Freak waves in random waves are observed in lab experiments (Waseda et al., 2009; Li et al., 2013, 2015; Toffoli et al., 2015). Other studies of freak waves in water tanks include Pei et al. (2007), Cui et al. (2013), and Deng et al. (2016). Toffoli et al. (2011) studied extreme waves propagating over an oblique current. There are also some numerical studies of freak waves (Zhang et al., 2007; Liu et al., 2011; Lu et al., 2016; Qin et al., 2017).

Although, Tank experiments are of vital importance for the engineering community, their controlled circumstances might not pay proper tribute to the uncontrollable nature of freak waves in the open sea (Dysthe et al., 2008). In the exiting knowledge, the ideal model is chosen or freak waves are generated with manual interventions. However, freak waves are occur from random waves in a three-dimensional terrain in the open sea. The research about freak waves based on three-dimensional natural terrain in random wave is insufficient. So it is significant and necessary to complete the research in this area and carry out in the current research. We study a random wave over a three-dimensional terrrain. A representative isolated reef terrain in the West Pacific is built in a wave tank. Random wave trains with various significant periods and wave heights are generated from a wave maker using the improved JONSWAP spectrum (Goda, 1999).

In this work, freak waves generated by random wave over a three-dimensional island terrain are observed and analyzed. The experimental setup is briefly introduced in Section 2. In Section 3, several characters and influence for freak waves are discussed, such as the significant period and wave height, wave direction, wave profile, skewness, kurtosis and depth of water. It is the first time to observe freak waves in the diffraction region. Different types of freak waves are observed with large crests and/or deep troughs. The experiment evidenced that freak waves can emerge from different types of waves groups. It is demonstrated that a freak wave is always with larger kurtosis. The variation of water depth increases the probability of freak waves.

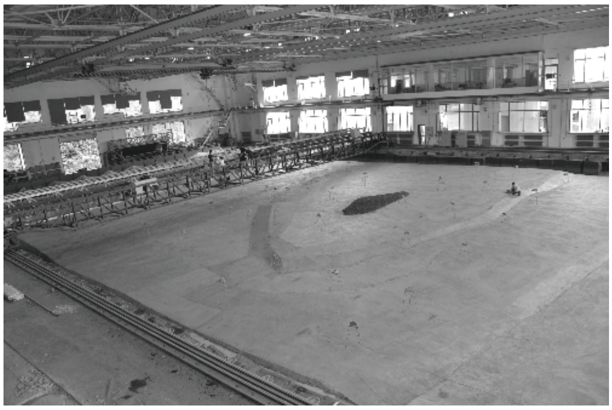

Fig. 1. Multi-function integrated basin and model of the island.

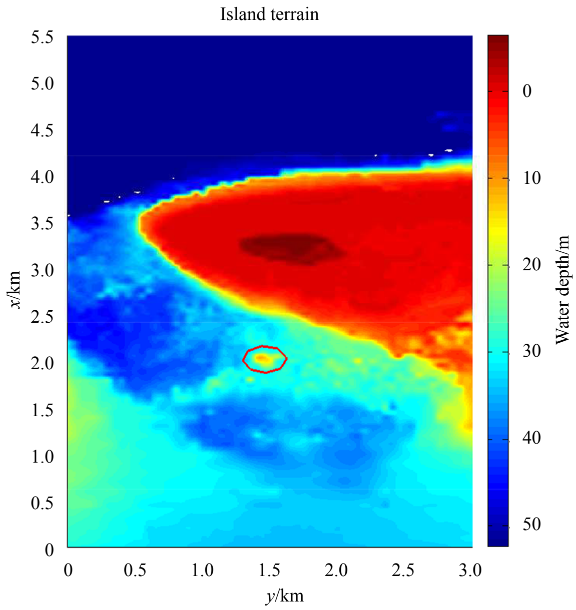

Fig. 2. The natural island located in the West Pacific.

2 Experimental setup

2.1 *Test model*

This experiment is carried out in the multifunction integrated water tank of the State Key Laboratory of Coastal and Offshore Engineering in Dalian University of Technology. The effective dimensions of the basin are 55 m×34 m×0.7 m. The water tank is provided with a hydraulic servo wave making machine. The wave damping facility is provided at the end of wave tank to reduce the wave reflection. On both sides of wave tank, a wave-dissipation plate is provided to remove effect of the wall. The terrain in experiment is constructed with the ratio of 1:100 between test model and real conditions, including the island body, surrounding steep slope and partial lagoon terrain, as shown in Fig. 1.

The random wave passing an inshore island reef terrain is studied in a water tank. A representative isolated reef terrain in the West Pacific chosen for the study is 700 m long, 300 m wide and height of 6.4 m (perennial average sea level as a benchmark). The depth of water increases sharply on one side of the island. But on the side of lagoon terrain, the water is shallower and water depth changes gently, as shown in Fig. 2. There is a seamount in the red ellipse area.

The level contour of the inshore island reef terrain and arrangement of 50 wave probes are shown in Fig. 3. The water depth of test is set based on the perennial average sea level of the target area around the corresponding island in the real sea. A total of 39 irregular wave conditions are considered, in terms of various wave height, wave direction θ and period, as shown in Table 1. The wave direction is shown in Fig. 3. The north is defined as zero degree and clockwise is positive. The wave direction of Cases A1 to A4 is 22.5° north by east, Cases A10 to A13 is 22.5° north by west and the remained cases is north (0°). Each working condition is repeated three times to reduce random error.

2.2 *Experimental wave parameters*

A wave probe is set up at the center of the wave tank before installing the model. For obtaining the desired wave spectrum, the control parameters of the wave maker are determined in an iterative manner. The JONSWAP spectrum is chosen in the irregular wave simulation. The improved JONSWAP spectrum (Goda, 1999) can be described as

$$S(f) = \beta_J H_s^2 T_p^{-4} f^{-5} \exp\left[-1.25(T_P f)^{-4}\right] \times \gamma^{\exp\left[-(f/f_P-1)^2/2\sigma^2\right]}, \tag{1}$$

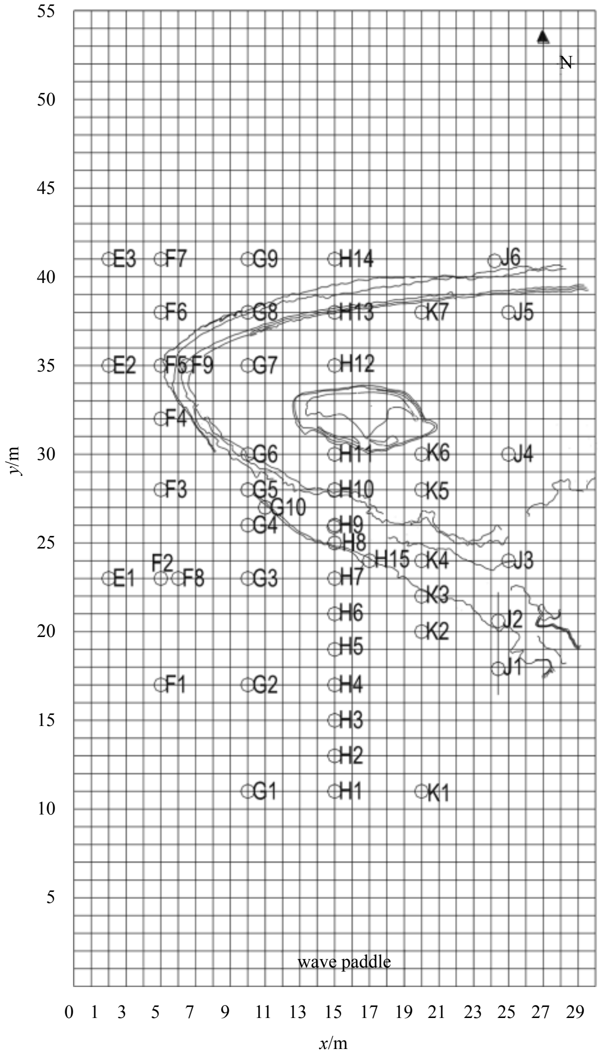

Fig. 3. Test terrain and arrangement of wave height gauges.

$$\beta_{\rm J} \approx \frac{0.062\,38}{0.230 + 0.033\,6\gamma - 0.185(1.9+\gamma)^{-1}} \times (1.094 - 0.019\,15 \ln \gamma), \tag{2}$$

$$T_{\rm p} \approx \frac{T_{\rm s}}{1.0 - 0.132(\gamma + 0.2)^{-0.559}}, \tag{3}$$

$$\sigma = \begin{cases} 0.07 & f \leqslant f_{\rm P}, \\ 0.09 & f > f_{\rm P}, \end{cases} \tag{4}$$

where $f_{\rm P}$ is the spectrum peak frequency, $T_{\rm P}$ is the spectrum peak period, $T_{\rm s}$ is significant period, and γ is the spectrum peak elevation parameter. It is recommended as 3.3 in open sea. Here, we set $\gamma = 2.0$, since our research is concentrated near the island reef.

3 Results and discussion

3.1 *Freak waves observed in random wave*

The significant period versus the significant height of freak waves is shown in Fig. 4. It shows that freak waves are correlated to a wide range of significant wave heights but a relatively centralized wave period. The significant periods of freak waves roughly focus within the range between 0.67–0.87 s. The instability (Benjamin–Feir) is an important mechanism of freak wave generation and freak waves occur more frequently with large *BFI* (Benjamin–Feir index) (Toffoli et al., 2008; Li et al., 2013). *BFI* is defined as $BFI = \sqrt{2}\varepsilon/(2\Delta f/f_{\rm p})$, here ε is the wave steepness, Δf is the spectral bandwidth, and $f_{\rm p}$ is the peak frequency. The wave steepness ε is influenced by wave height and period. Larger wave height and lower period correspond to higher wave steepness ε, so that the value of BFI is larger. So freak waves occur more frequently for lower periods (0.67–0.87 s).

However, when the significant period and wave height value are equal to 1.2 s, 1.61 cm and 1.14 s, 6.35 cm respectively, freak waves are also observed. For case $T_{\rm s} = 1.2$ s, $H_{\rm s} = 1.61$ cm and $\theta = 0^\circ$, freak wave is observed at Probe G5, where the depth of water has a sharp decrease, from deep domain to shallow one. For case $T_{\rm s} = 1.14$ s, $H_{\rm s} = 6.35$ cm and $\theta = 0^\circ$, freak wave is observed at Probe G6 with a shallow depth of water (1.8 cm). This indicates that large variation of water depth has a significant influence, which will cause the occurrence of freak waves. For larger significant wave heights ($H_{\rm s} \geqslant 8.05$ cm), wave breaking is observed, which reduces the probability of freak waves occurrence. Only one freak wave event is observed at Probe G9 in the diffraction region. It is the new finding and there has been no report of

Table 1. Working conditions of irregular wave tests for 39 cases in terms of significant wave height $H_{\rm s}$ and significant period $T_{\rm s}$

Case	Wave directions (θ)	$H_{\rm s}$/cm	$T_{\rm s}$/s
A1	22.5°	1.61	0.73
A2		3.59	0.73
A3		6.35	0.87
A4		8.05	0.87
A5	0°	1.61	0.67, 0.73, 0.8, 0.87, 0.93, 1, 1.07, 1.2
A6		3.59	0.67, 0.73, 0.8, 0.87, 0.93, 1, 1.07, 1.14
A7		4.82	0.73
A8		6.35	0.8, 0.87, 0.93, 1, 1.07, 1.14, 1.21
A9		8.05	0.8, 0.87, 0.93, 1, 1.07, 1.14, 1.21
A10	−22.5°	8.37	1.05
A11		1.71	0.65
A12		3.59	0.80
A13		7.08	0.91

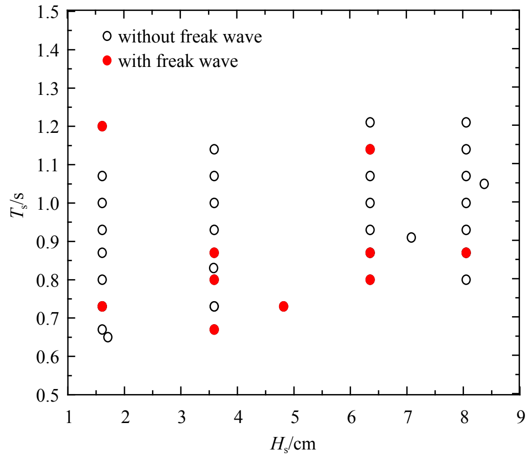

Fig. 4. The distribution of freak waves about period and wave height.

freak waves in diffraction region.

The mechanisms of freak waves have been investigated intensively, and consequently several freak wave generation mechanisms (Dysthe et al., 2008; Slunyaev et al., 2011) have been proposed. But there is no widely accepted conclusion so far. In this work, different typical generation processes of freak waves are found when random waves pass the three-dimensional island terrain. Figure 5 shows two representative cases of waveform evolution of freak waves. In Fig. 5a, freak wave is found on Probe K3 at about 47 s with $H_{fr}/H_s = 2.28$, $H_{cr}/H_s = 1.45$ (where H_{fr} is the maximum wave height of freak waves, and H_{cr} is the crest height of freak waves). Two larger waves with deep trough are discovered at Probe K1. Before freak wave generated, three larger waves appear at Probe K2. The water depth at Probe K5 is significantly smaller (0.61 cm) than others, which results a smaller wave height. Another type of freak wave generation process is also observed as follows.

Freak wave is found at Probe F3 at about 17.5 s with $H_{fr}/H_s = 2.0$, $H_{cr}/H_s = 1.36$ as shown in Fig. 5b. It is generated from several smaller height waves without any indication. After freak wave, it reduced back to normal distribution without any signs of it.

Figure 6 shows the representative freak waves that we have observed in our experiment. In Fig. 6a, freak wave is nearly symmetric. The crest of freak waves is steep and very high, which is more than sixty percent of the wave height. However, there is also a freak wave with deep trough shown in Fig. 6b. Moreover, freak wave with large crest and trough is observed, as shown in Fig. 6c. The shape of trough is gentler than that of crest. In the natural open sea, these types of freak waveforms are also obtained (Glejin et al., 2014).

3.2 *Skewness, kurtosis of freak waves*

The skewness B_1 and the kurtosis B_2, which are defined as follows:

$$B_1 = \frac{1}{\eta_{rms}^3} \frac{1}{N} \sum_{n=1}^{N} (\eta_n - \overline{\eta})^3, \tag{5}$$

$$B_2 = \frac{1}{\eta_{rms}^4} \frac{1}{N} \sum_{n=1}^{N} (\eta_n - \overline{\eta})^4, \tag{6}$$

where N is number of measuring points of wave height. η_n is the n times wave height measurement, η_{rms} is root-mean-square

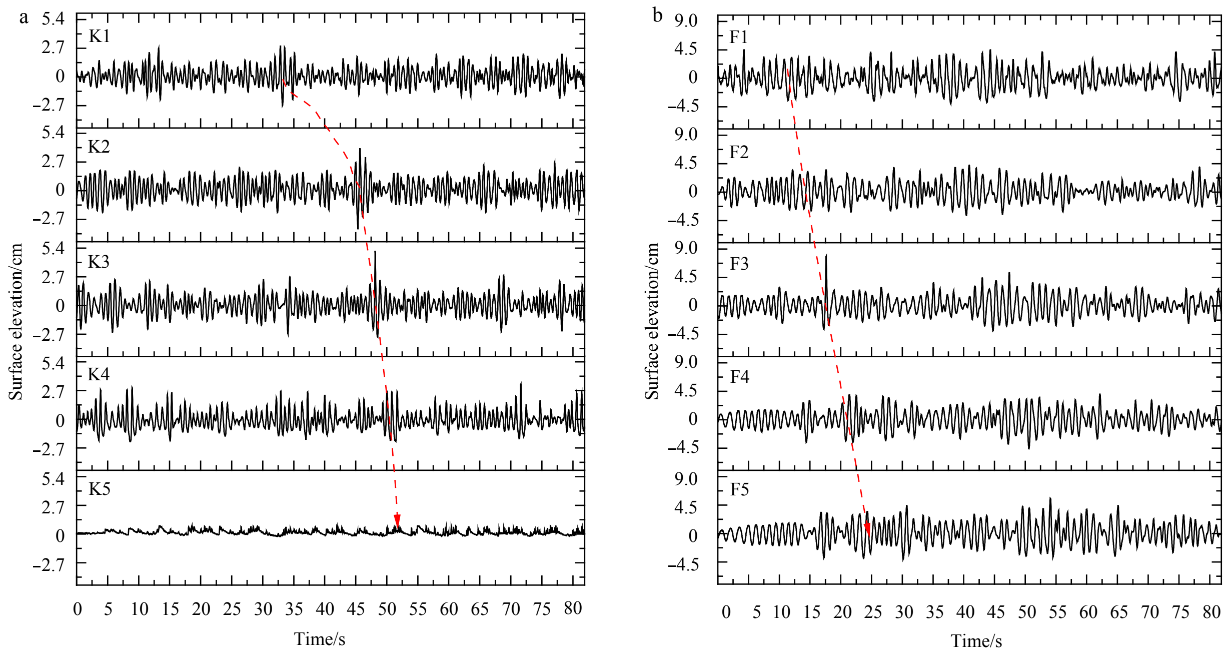

Fig. 5. The wave surface elevation of freak waves. a. $H_s = 3.59$ cm, $T_s = 0.80$ s, $\theta = 0°$; and b. $H_s = 6.35$ cm, $T_s = 1.14$ s, $\theta = 0°$.

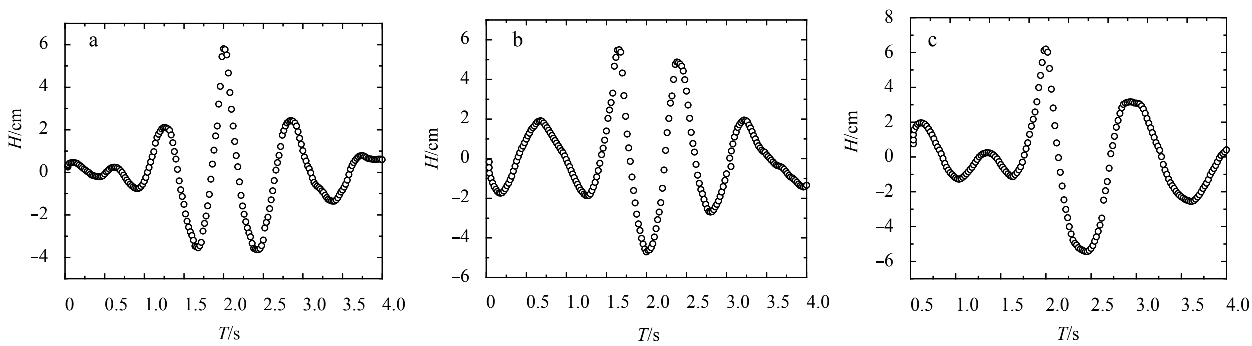

Fig. 6. The various surface of different type freak waves in our experiment.

value and $\overline{\eta}$ is average value of wave surface elevation. For Gaussian distribution, $B_1 = 0$ and $B_2 = 3.0$. Ocean waves often have positive skewness, which means flat shallow troughs and high/sharp peaks. The skewness and kurtosis of our experimental results are plotted as functions of H_m/H_s and H_{fr}, which are shown in Figs 7 and 8.

The skewness of wave surface vs. H_m/H_s and H_{fr} are shown in Fig. 7. The skewness increases withH_s. It is distributed around the zero line for $H_s = 3.59$ cm. The value of B_1 is distributed in the range of -0.05 to 0.25 when freak waves generate shown in Fig. 7a. In Fig. 7b, the variation of skewness along the H_{fr} is shown. Larger wave height of freak waves corresponds to larger skewness. The equation of linear regression with skewness and H_{fr} is given in Eq. (7) with the value of Pearson's $r = 0.74$. Except only one case with freak wave with smallest H_{fr}, the skewness of freak waves with large crest distribute within 95% significance levels of the regression. The linear regression analysis of the skewness vs. H_{fr} of freak waves end up with the following equation:

$$B_1 = -0.164 + 0.036\,5H_{fr}. \tag{7}$$

Figure 8a presents the scatter plot between the kurtosis and H_m/H_s calculating with measured data except those from shallow water and diffraction regions. It can be seen that freak waves have larger kurtosis, which is similar with results obtained later (Soares et al., 2003). The resulting linear regression of kurtosis vs. H_m/H_s is given in Eq. (8) with the value of Pearson's $r = 0.598$. A total of 95% significance levels of regression are shown in Fig. 8a. It is found that, except one case with freak wave at Probe G6 in shallow water, all of freak wave data are within 95% significance levels.

Figure 8b presents the scatter plot between the kurtosis and skewness. It is shown that bigger kurtosis usually corresponds to bigger skewness when it is greater than -0.2. A nonlinear equation between kurtosis and skewness has been derived as given in Eq. (9). A total of 95% significance levels of regression are shown in Fig. 8b. It is observed that 56% of freak wave cases are outside 95% significance levels on the scatter plot between the kurtosis and skewness. Except two cases with freak waves, all of other data are also above the cubic fit (Eq. (9)).

$$B_2 = 0.794 + 1.377\,H_m/H_s, \tag{8}$$

$$B_2 = 2.824 + 1.273\,B_1 + 0.554\,{B_1}^2 - 2.114\,{B_1}^3. \tag{9}$$

3.3 *The influence of terrain on wave propagation*

Trulsen et al. (2012) had shown that the probability of large wave envelope has a local maximum near the shallower side of the slope. The influence of two-dimensional terrain for freak waves has drawn the attention of many researchers (Cui et al., 2012; Gramstad et al., 2013). However, there are few reports of freak waves at three-dimensional terrain. In our experiment, in

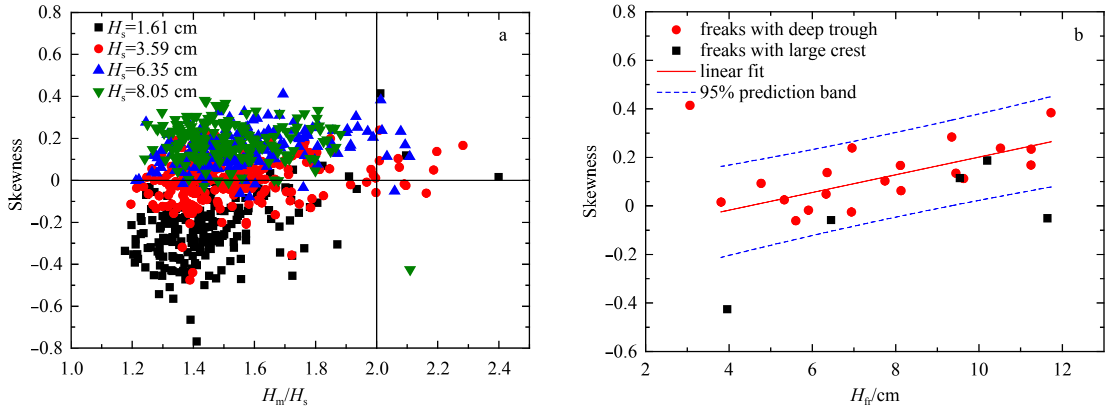

Fig. 7. The relationships between freak factor H_m/H_s and skewness (a), and H_{fr} and skewness (b).

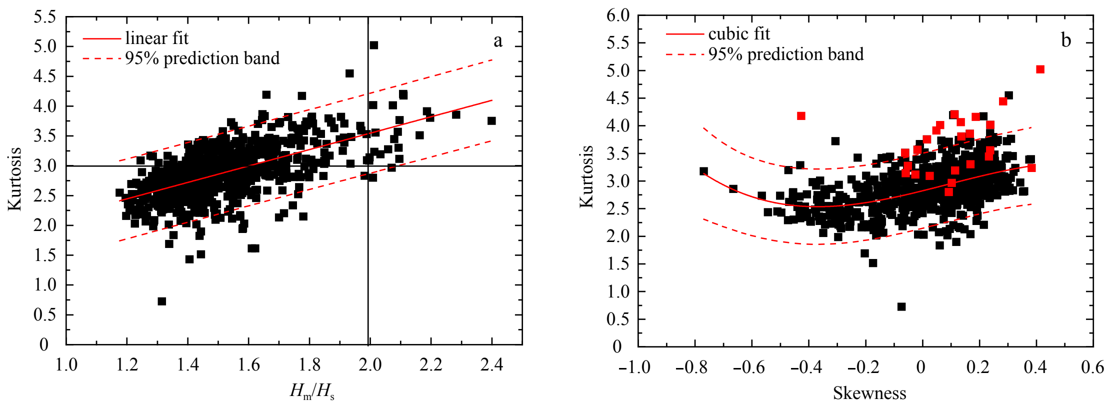

Fig. 8. The relationship between freak factor H_m/H_s, skewness and kurtosis. a. Freak factor H_m/H_s and kurtosis, and b. skewness and kurtosis. The red solid (■) represents cases with freak waves, the black solid (■) cases without freak waves.

order to study the influence of three-dimensional terrain in random wave around a representative island, six columns wave probes are set up. Since the influence of water depth on skewness is not obvious, in the following context, the focus of analysis is distribution of freak waves and kurtosis variation along the terrain.

Figures 9 and 10 show the nephogram of significant wave height and kurtosis along the terrain, where solid curve is contour of test model. For cases with different wave directions, the variation of significant wave height and kurtosis is different along the terrain. Waves are greatly affected when passing the seamount marked in Fig. 2. In Figs 9b and c, for cases $\theta=0^\circ$, the significant wave height will increase on both sides of the seamount. Even after seven meters from the rear of the seamount, it also has the same effect. For other cases with different wave directions shown in Figs 9a and d, $\theta=22.5^\circ$ and $\theta=-22.5^\circ$, this effect is not as significant as the previous one. Figures 10b and c show that the variation of kurtosis is similar as the situation of significant wave height for cases $\theta=0^\circ$ and the rear of seamount also has similar phenomenon. In Fig. 10a, the value of kurtosis is larger in front of the seamount. However, in Fig. 10d, the effect of seamount for kurtosis is not obvious. The different effects on the wave height and kurtosis indicate that the terrain has a big influence on the propagation process of waves.

Some recent research suggested that kurtosis is a good indicator of freak waves (Gramstad et al., 2013; Li et al., 2015). Figure 11 shows the variation of H_m/H_s (solid line), kurtosis (dot line) along the terrain with wave evolution. Figure 11a shows freak waves occurred twice at Probe G5 as indicated by $H_m/H_s>2.0$. The value of kurtosis is even larger than that at Probe G6. The reason is that it is shallow at G6, where waves will break and consequently cause large wave steep. For Probe H, freak waves can be discovered at Probes H2, H6 and H8, as shown in Fig. 11b. It can be observed that the emergence of freak waves is often accompanied by large kurtosis. Kurtosis will increase as waves propagating over a slope, which is in agreement with the results obtained later (Trulsen et al., 2012). However, kurtosis is smaller than expected at Point H10. Because of waves breaking, propagating over gentle slope, the energy dissipates significantly and consequently. It shows the difference of kurtosis between gentle slope and steep slope at shallow area. Moreover, it illustrates that the value of kurtosis of shallower side at steep slope is larger than that at gentle slope.

In addition, experimental evidence demonstrates that there do exist the second time freak wave even with larger H_m/H_s, which generates from other one, as shown in Fig. 11b. The value of H_m/H_s is 2.09 and 2.20 respectively when waves at Point H6 propagate towards Point H8. This means that a freak wave event could cause another larger one, which will be more dangerous for ships and offshore structures.

Figure 12 shows the times of freak wave occurrence. Curved line is the contour of our test model. It shows the number of times of freak wave events. Gramstad et al. (2013) had shown that long-crested waves propagating over a slope, from a deeper to a shallower domain, can experience significantly increased probability (nearly 4×10^{-3}) of freak waves both at shallow end of slope and for some distance after the slope. Figure 12 shows that the frequency of freak waves is indeed increased when waves

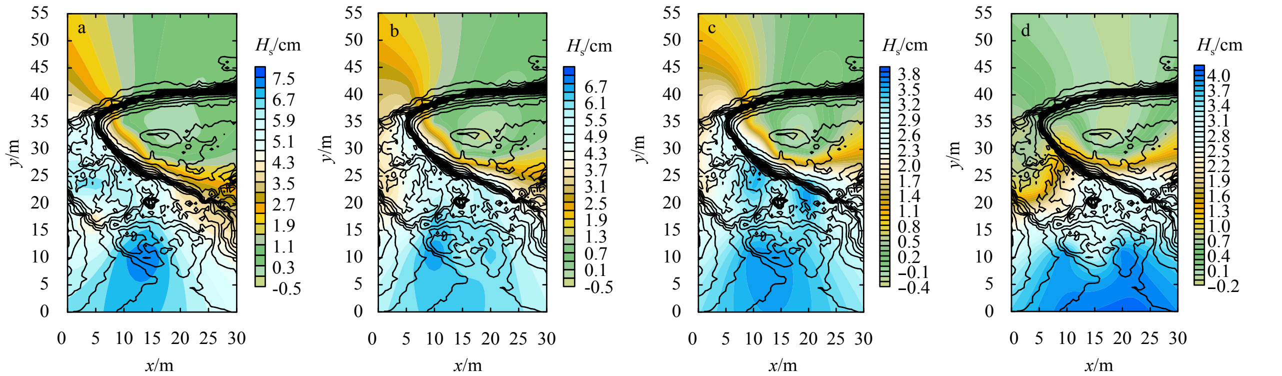

Fig. 9. The variation of significant wave height along the terrain (solid curve). a. $H_s=6.35$ cm, $T_s=0.87$ s, $\theta=22.5^\circ$; b. $H_s=6.35$ cm, $T_s=0.87$ s, $\theta=0^\circ$; c. $H_s=3.59$ cm, $T_s=0.8$ s, $\theta=0^\circ$; and d. $H_s=3.59$ cm, $T_s=0.8$ s, $\theta=-22.5^\circ$.

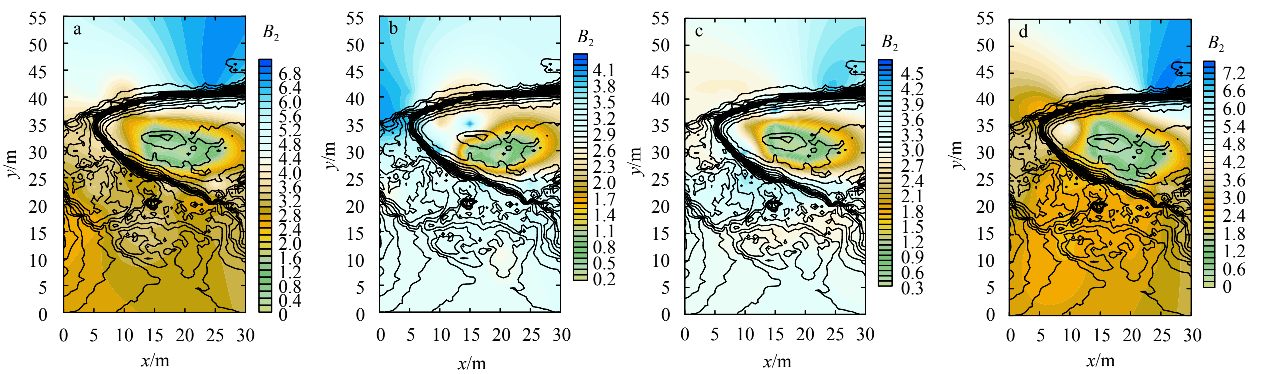

Fig. 10. The variation of kurtosis along the terrain (solid curve). a. $H_s=6.35$ cm, $T_s=0.87$ s, $\theta=22.5^\circ$; b. $H_s=6.35$ cm, $T_s=0.87$ s, $\theta=0^\circ$; c. $H_s=3.59$ cm, $T_s=0.8$ s, $\theta=0^\circ$; and d. $H_s=3.59$ cm, $T_s=0.8$ s, $\theta=-22.5^\circ$.

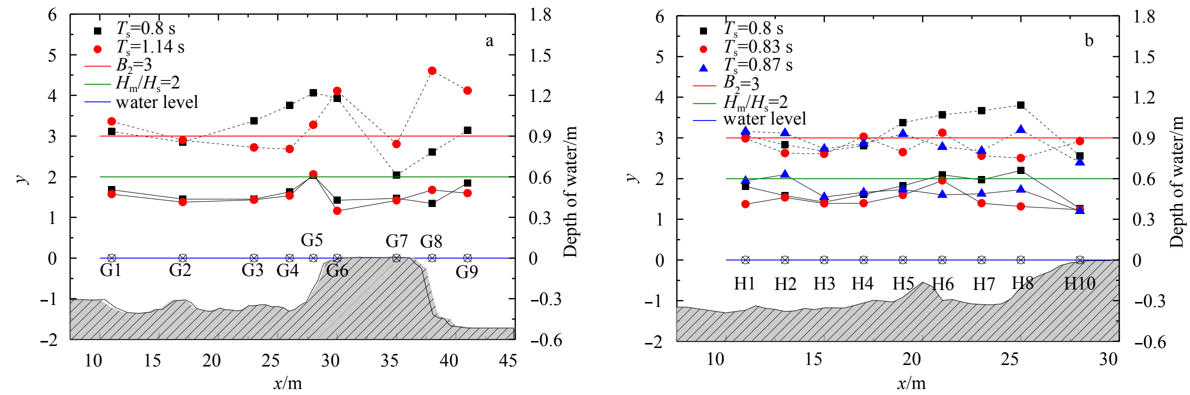

Fig. 11. The variation of freak factor H_m/H_s (solid line), kurtosis (dot line) along the wave evolution. a. $H_s = 6.35$ cm at Probe G, $\theta = 0°$; and b. $H_s = 3.59$ cm at Probe H, $\theta = 0°$.

propagating over a slope, from deeper domain to shallower domain. It can be found that higher probability of freak waves corresponds to higher changing rate of the water depth, which is indicated by intensive contour of sea bed as shown in Fig. 12. Meanwhile, in this experiment, a corresponding behavior for waves propagating from shallow domain to deep one is found as follow. When waves pass the seamounts, freak waves are prone to occur behind the seamounts (shallower domain to deeper one), such as Points H2 and H6 rather than Point H5, the front slope of seamount, where no freak wave event is observed. Their difference is variation of water depth, deeper domain to shallower one or opposite tendency, at where freak waves occur. Moreover, it illustrates that there are freak waves in the diffraction region at Probe G9. These experiment results imply that those areas in the real sea should be paid more attention.

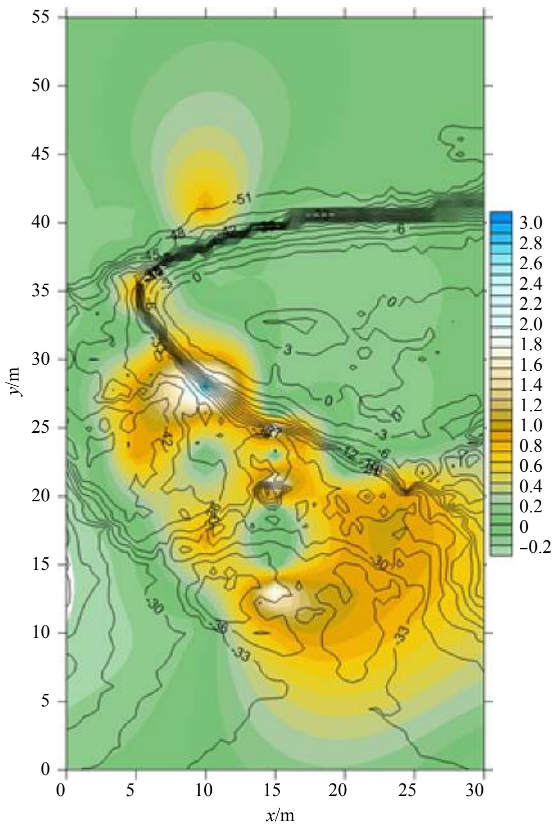

Fig. 12. The times variation of freak wave occurrence along the terrain (solid curve).

4 Conclusions

In this study, an experiment is carried out for random waves propagating over a three-dimensional isolated reef terrain with a scaled down model. The following features of freak waves are noticed.

(1) The possibility of freak waves is higher when the significant period is less than 0.87 s corresponding to the natural sea state of 8.7 s. It is the first time to observe freak waves in the diffraction region. Several kinds of freak waves with various waveforms are observed with large crests and/or deep troughs. The experiment evidenced that freak waves can emerge from different types of waves group. Although it occurs without warning, sometime it comes with a couple of large waves.

(2) The features of a freak wave are analyzed in terms of its skewness/kurtosis. It is noticed that larger skewness corresponds to larger H_s, and it is roughly linearly dependent on H_{fr}. The skewness of freak waves with deep troughs is lower than the value predicted by the linear theory. The relationship between kurtosis and H_m/H_s can be approximated by the linear theory. Larger kurtosis is accompanied with freak waves, which may be an indicator of freak waves.

(3) It can be found that the seabed terrain has a significant influence on the occurrence probability of freak waves. It is higher at the slope with intensive contour. Freak waves are more likely to occur at slope and behind the seamounts.

Multiple types of freak waves and different generation processes are found in this experiment, which shows the effectiveness of using three-dimensional model test of a real terrain compared with the commonly used simplified geometry. In the future, more detailed parameter tests are suggested, such as various depth of water, increasing the number of probes or sampling time.

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