Probability of Ocean Freak Wave Occurrence

-- Leng-Hsuan Tseng *, Fuh Shiang, Chang **, Dong-Jiing Doong ***, Aifeng Tao ****

* Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, 70101, Taiwan, N86004254@mail.ncku.edu.tw
** Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung, 20224, Taiwan, dukenzo81@gmail.com
*** Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung, 20224, Taiwan, doong@mail.ntou.edu.tw
**** Key Laboratory of Coastal Disasters and Defence of Ministry of Education, Hohai University, China, 210098, aftao@hhu.edu.cn

ABSTRACT

The purpose of this study is to understand the occurrence probability of the freak waves in the ocean. This study mines the freak waves from in-situ measurement at Taiwanese waters. Extreme statistics theory was applied. The definition of dangerous freak wave used in this study is the wave whose wave height is twice bigger than the significant wave height and the significant wave height should larger than 1m. According to this criterion, 262 freak waves were found from Longdong buoy and 51 were found from Taitung deep sea buoy. The probabilities of occurrence of freak waves both are very close; it is around 1.4x10^{-4}. However, the probability of occurrence of dangerous freak wave (significant wave height larger than 1m) in deep sea is much higher than in shallower sea area. Results also show that the occurrences of freak waves have high correlation with kurtosis and grouping factor. Kurtosis of more than 75% freak wave cases are higher than 3.5.

KEYWORDS

Freak wave; Field measurement; Occurrence probability

1. INTRODUCTION

Recently people have started to notice the existence of freak waves. Freak or rogue waves are the abnormal waves with a height exceeding twice or more the significant wave height; they appear on the sea surface only for a short time. Freak waves have high impacts on ships in the ocean as well as offshore and coastal structures. They are also a hazard to the people at the coast. At January 1th, 1995, a huge freak wave was measured at the Draupner platform in the North Sea, which is called the New Year Wave (Figure 1). According to the statistics from Dysthe et al. (2008), there are more than 22 super carriers was lost due to suddenly bed sea states during 1969-1994, and most of these events have been associated with freak waves (Figure 2). So far, scientists have done many researches about freak waves. Most of these studies are focus on the occurrence mechanism. For instance, Kharif and Pelinovsky (2003) pointed out that the occurrence of freak waves may be caused by the energy convergence of one or more factors. Those factors include wave superimposition, wave-current interaction, topography influence, wind, wave instability and so on. Other studies also indicated some factors that affect the occurrence of freak wave. Mori and Yasuda (2002) pointed out that high-order nonlinearity is one of the factors that affect deep sea freak wave.
occurrence. The other studies presented that Benjamin-Feir instability (the modulational instability or sideband instability of waves, which is first brought out by Benjamin and Feir (1967)) may be the reason why freak waves appear. Wave grouping is also thought as one of the conditions for freak wave searching (Tsai et al., 2004). Chien et al. (2002) mentioned that the occurrence probability of freak wave is highly dependent on the wave grouping factor. Liu et al. (2009) also believed that freak wave must appear in continuous group waves.

Since we have to understanding the origin of freak wave before its prediction, many researches of freak waves are focus on the occurrence mechanism in recent years. Most of scientists used numerical modeling or wave-tank experiment for study freak wave, but seldom use in-situ measurement. It is because of the lack of freak wave cases. However, there is an ocean monitoring network established in the sea around Taiwan in decade (Figure 3). Enough data for freak wave statistic researches can be used for this study. The definition of dangerous freak wave which is used in this study is the wave whose wave height is twice higher than the significant wave height (Sand et al., 1990) and the significant wave height must bigger than 1m.

Fig. 1 An freak wave called the New Year wave was measured at the Draupner platform in the North Sea on Jan. 1,1995.

![Graph showing time vs. surface height for a freak wave](image1.png)

Fig. 2 Locations of 22 shipwrecks which might were caused by freak waves. (Dysthe et al. 2008)
2. FREAK WAVE MINING IN THE FIELD

There are lots of wave buoys being deployed in the sea around Taiwan in recent 10 years. In this study, data from two buoys were used. One is Longdong buoy, the other is Taitung Deep Sea buoy. The water depth of Longdong buoy is thirty meters. It is shallower than the water depth of Taitung Deep Sea, which is about 5000m. Since the water depth of Longdong is shallower, Longdong sea area was called “shallow water” in this study while Taitung Deep Sea area is called “deep Sea”. They are all operated by the Central Weather Bureau of Taiwan. Other informations of these two buoys are listed on table 1.

The buoys measure the acceleration of water particles. To transform acceleration record into elevation information, the wavelet transformation was used. (Wu et al., 2009) Based on the theory of 1-dimentional continuous wavelet transform, the acceleration record can be broken into various wavelets which are scaled and shifted versions of a pre-chosen mother wavelet function. In this study, the Morlet wavelet function is chosen as the mother wavelet function. The inverse wavelet transform is also used for calculate the elevation time series from energy. (Doong and Wu, 2010)

Elevation data has to be divided into individual waves before being analysis. Since using zero-up crossing method to divide elevation data has different results than using zero-down crossing method, this study used both methods for Longdong buoy data analysis to find whether zero-up/down crossing method will affect the occurrence probability of freak wave or not. In this study, two criteria were used. First, the general definition of freak wave, which is used in this research, is the wave whose wave height is twice bigger than the significant wave height (Eq. 1). Second, the significant wave height must larger than 1.0m (Eq. 2). The freak waves which were found with the two criteria are called “dangerous freak waves” for separation.

\[
\text{Condition I : } \frac{H_{\text{freak}}}{H_{1/3}} > 2 \\
\text{Condition II : } H_{1/3} > 1 \text{m}
\]
The main purpose of this study is to find freak wave cases and the characteristics of these cases. If only condition 1 were used as the criterion of freak wave, there are 603 freak waves were found in Longdong buoy data and 67 were found in Taitung Deep Sea buoy data; nevertheless, 262 dangerous freak waves were found in 1933998 waves (24650 records) in ten-year-long Longdong buoy data and 51 were found in 381378 waves (5047 records) in Taitung Deep Sea buoy data. These results are listed in Table 2. Figure 4(a)(b)(c) were some cases of those freak waves that were found at Longdong. Fig 4.(a) is a freak wave whose significant wave height of the record is less than 1.0m. Fig 4(b) is a freak wave that the significant wave height is larger than 1.0m but less than 2.0m. Fig 4(c) is a freak wave case with the significant wave height higher than 2.0m.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Water Depth(m)</th>
<th>Data duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longdong Buoy</td>
<td>1 km offshore from Longdong yacht harbor at</td>
<td>30</td>
<td>2000-2009</td>
</tr>
<tr>
<td></td>
<td>northeastern Taiwan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taitung Deep</td>
<td>210 km east from Orchid Island</td>
<td>5000</td>
<td>2006/6-12 2009/8-10</td>
</tr>
<tr>
<td>Sea Buoy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 Freak wave cases with different regions of significant wave heights ($H_{1/3}$)
(a) $H_{1/3}<1.0m$ (b) $1.0m<H_{1/3}<2.0m$ (c) $H_{1/3}>2.0m$
3. OCCURRENCE PROBABILITY

Table 2 is the results of freak wave mining. N_R means the record number, N_W means the number of waves. FWN_W - I and FWN_W - I & II are the number of freak waves which satisfy only condition 1 and both condition 1 & 2, respectively. P(FWN_W - I) means the probability of freak wave that satisfy with condition 1 as well as P(FWN_W - I & II) means the probability of freak wave that satisfy with condition 1 & 2.

The occurrence probabilities of freak waves at Longdong (shallow water) area and at Taitung Deep Sea (deep sea) area are about $1.4 \times 10^{-4}$ (zero-down crossing method). It means that one freak wave might appear every 7142 waves. But the occurrence probability of dangerous freak waves is higher at Taitung Deep Sea area than at Longdong area. The front one is $1.09 \times 10^{-4}$ and is almost 1.8 times the latter one, which is $0.6 \times 10^{-4}$. According to this result, deep sea area is believed to have higher probability of freak wave appearance (80% higher). The reason was presumed that deep sea area has more big waves.

In addition, this study also analyzed the results of using different methods for elevation division. Figure 5 shows different results of waves of one record by using zero-down and zero-up crossing method. The consequence of freak wave probability shows that there is almost no difference between using zero-down crossing method and using zero-up crossing method for data analysis.

<table>
<thead>
<tr>
<th></th>
<th>Longdong Buoy</th>
<th>Taitung Deep Sea Buoy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>zero-down</td>
<td>zero-up</td>
</tr>
<tr>
<td>N_R</td>
<td>50880</td>
<td>50880</td>
</tr>
<tr>
<td>N_W</td>
<td>4347676</td>
<td>4347866</td>
</tr>
<tr>
<td>Samples with $H_{1/3} &gt; 1$ m</td>
<td>24650</td>
<td>24621</td>
</tr>
<tr>
<td>Wave numbers with $H_{1/3} &gt; 1$ m</td>
<td>1933998</td>
<td>1932133</td>
</tr>
<tr>
<td>FWN_W - I</td>
<td>603</td>
<td>-</td>
</tr>
<tr>
<td>FWN_W - I &amp; II</td>
<td>262</td>
<td>266</td>
</tr>
<tr>
<td>P(FWN_W - I)</td>
<td>$1.39 \times 10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>P(FWN_W - I &amp; II)</td>
<td>$0.60 \times 10^{-4}$</td>
<td>$0.61 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Fig. 5 different results of the same record using zero-down crossing (left) and zero-up crossing method (right).

4. DISCUSSION

The distribution of wave heights should be the Rayleigh distribution. According to the Rayleigh distribution, the probability distribution of wave heights can be calculated. Figure 6 is the probability distribution of wave heights at Longdong area. The result shows that the Rayleigh distribution and the probability distribution of wave heights are well fit at low wave heights. Besides the occurrence probability of freak waves, the characteristics of freak wave is another thing that scientists may be interest. Janssen (2003) pointed out that the kurtosis of the elevation record has became one of the indexes of freak wave definition. Other studies presented that freak wave is related to wave grouping; therefore, grouping factor (GF) is also an index for freak wave mining. Figure 7 is the probability distribution of kurtosis, grouping factor and skewness of surface elevation records measured by Longdong buoy, respectively. The probability distribution of kurtosis shows that the kurtosis is higher when freak waves appear. But still there are some freak wave cases which have low kurtosis. The average kurtosis of records which includes freak wave cases is 3.84. 75% kurtosis of records measured when freak wave occurred are larger than 3.5. Grouping factor has similar result as kurtosis. The average of grouping factor is 1.018 when freak wave appeared. To sum up, kurtosis and grouping factor can be one of the indexes for looking for freak waves, but can’t be the only one criterion for freak wave searching. Nevertheless, skewness seems does not have this tendence.

Fig. 6 The probability distribution of wave heights at Longdong area.
Fig. 7 The probability distribution of (a) kurtosis (b) grouping factor (c) skewness of wave heights recorded by Longdong buoy during 2000-2009.

5. CONCLUDING REMARKS

Freak waves are hazards to ships and people who do actions in the ocean or coastal area. In this study, our purpose is to find out the cases of freak waves from field measurement data, count the occurrence probability of freak wave and try to understand the characteristics of freak waves for further freak wave studies. We had analyzed 10-year-long Longdong buoy data and Taitung Deep Sea buoy data whose data duration is 10 months and have got the occurrence probability of freak wave is around 1.4x10^{-4}. However, 262 dangerous freak wave cases (significant wave height larger than 1m) from 24650 records of Longdong buoy and 51 cases from 5047 records of Taitung Deep Sea buoy were found. The probabilities of dangerous freak waves are 0.6x10^{-4} and 1.09x10^{-4}, respectively. It means the occurrence probability of dangerous freak wave is 80% higher at sea area where has deeper water depth. Results also show that using zero-up crossing or zero-down crossing method doesn’t affect the probabilities.

This research had confirmed that the appearance of freak waves has relation to kurtosis and wave grouping. The average of kurtosis is 4, which is higher than the kurtosis of normal distribution (equal to 3). When freak wave appear, the kurtosis of the record may be larger. However, there are still some freak wave cases whose kurtosis isn’t very high. In other words, though kurtosis can be used as one of criterions for freak wave mining, it can’t be used along. Grouping factor which is
calculated by smoothed instantaneous wave energy history (SIWEH) has similar result, more than
80% grouping factor of cases are bigger than 0.9.

REFERENCES

1. Benjamin, T.B, and Feir, J.E. The disintegration of wave trains on deep water. *J. Fluid
2. Chien, H., Kao, C.C., Chuang, Z.H. On the Characteristics of Observed Coastal Freak Waves,
5. Doong, D.J., Wu, L.C. Searching for freak wave from in-situ buoy measurement. *Proceeding of
8. Mori, N., and Yasuda, T. Effects of high-order nonlinear interactions on unidirectional wave
10. Tsai, C.H., Su, M.Y. and Huang, S.J. Observations and conditions for occurrence of dangerous
Elevation from Acceleration Signals, *Proceedings of the 4th East Asian Workshop on Marine
Environments*, 5-7 November, Busan, Korea, 2009.