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DISCUSSIONS ON THE OCCURRENCE PROBABILITIES OF OBSERVED FREAK WAVES

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Key words: freak waves, observed data, occurrence probability, unified definition.

ABSTRACT

Field observational is the most direct and reliable research approach to investigate the freak waves, particularly for the occurrence probability. In order to present the latest research state, the results related to the observed freak waves from six sea areas are summarized and analyzed with comparisons. Three key conclusions are addressed. Firstly, both the occurrence probability and the strength of freak waves vary much for different sea areas. It is shown that there is still no answer to the big question of whether freak waves are rare events. Secondly, there is no single accepted, unified definition of freak waves. It means the scientists still do not exactly know what a freak wave is. Lastly, it is suggested better to study the combination of potential disaster risk and freak wave occurrence together instead of focusing only on the characteristics of freak waves. Because the results induced by even a same freak wave will change a lot for different structures and victims.

I. INTRODUCTION

The concept of the freak wave was put forward by Draper (1966) to delegate an unexpected surface gravity wave with tremendous wave height and an extraordinarily steep crest or trough that poses a severe hazardous effect because of its giant energy. With the continuing organized international thematic conferences over the past two decades, more people have begun to pay attention to freak waves; the related research has gradually undergone three stages from theory to practice. The focus of the first research stage is to investigate the mechanism and kinetic characteristics (Tao et al., 2007 and 2012a), the second stage to carry out the experimental study of freak waves (Ma et al., 2012), and the structure based on the cognition of the kinetic and motion characteristics of freak waves, and the third stage to explore the occurrence probability in a specific sea area and the early warning or forecasting techniques. Akhmediev et al. (2011) raised the problem of freak wave warning signals for the first time; this marked the beginning of the third stage, which is most closely linked to the reality. There are still many open questions related to freak waves. One question includes clarifying the scientific definition of a freak wave and whether this type of wave is a rare event. Focusing on these types of basic questions, field observations are the most reliable research approach because they are a direct way to examine real freak waves. Hence, it is meaningful to collect the existing research results on freak waves and further analyze the data. Addressing this purpose, the results of observed freak waves in five sea areas are the focus of this work. Based on comparative analysis of the results, some key points related to the two basic questions are answered.

This article is expanded into the following four parts: the first part introduces the generally observed data situation of freak waves, the second part focuses on the research methods and results of freak wave probability, the third part compares and analyzes the current research ideas and results, and finally, suggestions and opinions are given for future related studies.

II. OVERVIEW OF THE OBSERVED DATA

The occurrence of freak waves is full of randomness and chance, so it is very difficult to develop actual measurement work specifically for freak waves. The wave height might increase rapidly and last for a short time when a freak wave occurs, and freak wave may occur while the conventional wave measurements are not continuously monitored (they are usually monitored for 20 minutes each hour). The wave height of a freak wave may exceed the measurement range of the traditional measuring instruments, which could lead to failure of the facilities. Therefore, it is very difficult to carry out research in this field.

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The most famous freak wave observation is the wave surface record obtained in the Draupner platform (Haver, 2003). Because the wave basically meets all of the parametric indicators of freak waves, many scholars regard the New Year's Wave as objective evidence to show the existence of freak wave. The evidence also supports a pattern for freak wave study and simulation.

After the recording of New Year's Wave, more researchers began to pay attention to freak waves captured in the historical wave data, and related results were started to emerge. Most of the research results are focused on six "areas": 1) Atlantic Ocean, 2) Indian Ocean, 3) North Sea, 4) sea area around Japan, 5) sea area around Taiwan island, and 6) coastal sea area close to Jiangsu. The data features of the sea areas are overviewed below. Because of the particularity of freak waves, researchers continue to investigate whether the measuring facilities can reveal the essence of freak waves as well as the authenticity of that measured data. Janssen et al. (2006) analyzed the reality of imaging data of Synthetic Aperture Radar (SAR) through two satellites, ERS and Envisat. He noted that the SAR could not acquire convincing data that could reflect the true sea surface. Consequently, it is still doubted whether the SAR data are worth analyzing. Thus, in this article, the satellite data are not listed. The statistics obtained by traditional methods are summarized instead.

1. The Atlantic Ocean

In 1995, the British ship Queen Elizabeth II encountered 30-meter-high rogue waves during a storm in the North Atlantic Ocean (ESA, 2004). In 2000, in the middle of the North Atlantic Ocean, two large Norwegian bulk ships, M/S Norse Variant and M/S Anita, disappeared together (Kieldsen, 2000; Dipena, 2003) According to the prevailing meteorological data from the shipwreck research, Kjeldsen (2000) concluded that Anita was likely hit by freak waves. Further, in the South Atlantic Ocean without currents, two ships, the Bremen and the Caledonian Star, went through 30-meter-high waves within one week, from February to March in 2001.

The wave data in the South Atlantic Ocean were separately collected from a traditional heave-pitch-roll buoy moored at two adjacent deep-water spots in the Campos Basin, situated on the northeast coast of Brazil's Rio de Janeiro State. From March 1991 to March 1993, the buoy was set at point A (22°31'S, 39°58'W, 1,250 m depth) and was then fastened at the nearby point B (22°38'S, 40°12'W, 1,050 m depth) from January 1994 to June 1995. The waves were recorded intermittently for 17.067 minutes (1,024 s) every 3 hours and sampled at 1 Hz. For this buoy, 7,457 time series records were examined and analyzed (Pinho et al. 2004).

2. The Indian Ocean

The narrow, swift and strong Agulhas Current flows through the southwestern Indian Ocean off South Africa. Moreover, there are strong winds that come from the northeast into the region from October until April of the following year. In 1968, the Liberian oil tanker World Glory suffered unexpected giant wave impact when passing through the South African coastal waters (Smith, 1976; Lavrenov, 1998). In 1980, the oil tanker Esso Languedoc experienced 30-meter-high or higher sudden waves near the Durban area (Lawton, 2001). According to oceanographic statistics, 10-meter-high waves are not rare events here. The waves high than 6 meters occur 110 days per year, and the wave height of the remaining days is still higher than 2 meters. Lavrenov (1998) collected the freak wave records used here and conducted a preliminary analysis of the causes of the freak waves.

A set of wave measurement data was obtained from a gas-drilling FA Platform (22.17°E, 37.97°S, and 100 m depth) located in the Southern Indian Ocean. The position of the platform was offshore inside the Mossel Bay in southern Africa. Waves are measured hourly by a Marex Radar Wave Monitor at the sampling frequency of 2 Hz. Liu et al. (2004) analyzed the wave data and studied the occurrence probability of freak waves in this area.

3. The North Sea

Although there are no obvious currents flowing through the North Sea, this sea area is also considered as an area where freak waves appear frequently. Sand et al. (1990) observed less than 10 freak waves in this location from 1969 to 1985, and he found that the maximum ratio of maximum wave height to significant freak wave height is 3. The 25.6-meter-high New Year's Wave was recorded at the Draupner oil platform in the North Sea at 15:20, January 1, 1995. The 1,200 s wave observation records indicate that the significant wave height was 11.92 m and that the peak height was up to 18.4 m.

There were approximately 354,000 individual waves gathered from 795 h of wave records measured during periods of severe storms in the North Sea. The raw data were collected from three Thorn EMI infra-red laser altimeters placed on three of the corners of the North Alwyn fixed steel-jacket oil and gas platform, sampling at 5 Hz. The records were saved as 2,381 times of 20-minute records of wave surface elevation measurements. Stansell et al. (2005) studied these data and analyzed the distributions of the extreme waves, the crests and the trough heights.

4. The Sea Area around Japan

The Western Pacific Ocean and the Sea of Japan in eastern Japan are traditional, natural fishing grounds with complex seabed topography and swarms of submerged reefs. In 1980, the English ore-bulk-oil combination carrier M/V Derbyshire (295-meter-long) went missing off of the coast of Japan (Vigor, 2000; Handsen, 2001). There is considerable evidence that the ship was likely destroyed by freak waves.

Yasuda and Mori (1997) utilized the wave data obtained by the Japan Meteorological Agency (JMA) in the sea area around Japan to study the occurrence probability of freak waves in this sea area. The wave data analyzed in this study were obtained from nine locations in the maritime area around

Japan. Temporal sea surface elevations were observed with ultrasonic-type wave gauges (UWG) installed on the sea bottom at approximately 50 meters mean water depth and 1-2 km away from the coast.

The other group of wave data in this area was obtained from a location 3 km away from Yura fishing harbor, facing the Sea of Japan. The observations were completed during the period of September 1986 to July 1990 by the Ship Research Institute, Ministry of Transport of Japan (Mori et al., 2002). Temporal sea surface elevations were measured with ultrasonic-type wave gauges installed at three locations with water depth of 43 m. Yasuda and Mori (1997) studied the data and found several freak waves.

5. The Sea Area around Taiwan Island

Freak wave are recorded in the sea area around Taiwan nearly every year. In the winter, freak waves occur mostly along the northeast coast, while in summer, they appear more frequently along the southwest coast. Local people call these sudden and dangerous waves rabid dog waves. Hsu et al. (1993) and Chen (1999) collected 140 abnormal wave events reported from 1954 to 1998. At least 35 vessels were destroyed by abnormal waves, and the death toll was more than 343. In 1996, Coastal Ocean Monitoring Center of the National Cheng Kung University started to install the marine monitoring system around the island. Until 2009, 14 buoys were employed supported by the Taiwan Central Weather Bureau. The three axis acceleration senor was deployed in each buoy, so that the wave surface elevation could be derived.

Chien et al. (2002) discovered approximately 175 coastal freak waves from 4,565 waves recorded by the buoys. Tseng (2011a) analyzed both the coastal freak waves from Longdong station and freak waves of deep sea from Taitung station.

6. The Coastal Sea Area Close to Jiangsu

Based on the news or reports, shipwreck accidents caused by abnormal waves were not rare in mainland China. Tao et al. (2007) discovered through official news channels and found 6 cases caused serious damage during 2005 to 2006. The first investigation on the observed data from mainland China for freak waves was provided by Wang et al. (2014). The research results were based on one whole year's wave data of 2011. The wave data were measured by the SBF3-1 wave buoy from Xiangshui station in the Jiangsu coastal waters. This station was established by the Laboratory Center of College of Harbor, Coastal and Offshore Engineering of Hohai University. The latitude and longitude of the buoy position was 34°26.2'N and 120°06.0'E. The waves were recorded intermittently for 17.067 min (1024 s) per hour and sampled at 4 Hz.

III. THE CHARACTERISTICS AND OCCURRENCE PROBABILITY OF FREAK WAVES

The analytical tools used by the researchers to investigate the wave data collected from different areas are not the same. Because the definition of the freak wave is not uniform, there is not yet any completely determined analysis criterion. In this part, all the definitions for freak waves will be present firstly and then the occurrence probabilities and related problems will be shown.

Table 1. The definitions of freak waves in different sea areas.

Sea Area	Criterion
The Atlantic Ocean	$H/H_s \geq 2$
The Indian Ocean	$H_x/H_s > 2$
The North Sea	$H/H_s > 2$
The Sea Area around Japan	$H/H_s > 2$, $H > 10$ m
	$H/H_s > 2$, $H > 10$ m
The Sea around Taiwan Island	$H/H_s > 2$①, $H_s > 1$ m②
The sea along Jiangsu coast	$H/H_s \geq 2$

1. The Definitions of Freak Waves

Klinting and Sand (1987) used three criteria to determine a freak wave: [I] the wave height H is more than twice the significant wave height H_s; [II], the wave height is more than twice the adjacent wave heights; and [III] the peak height, which is defined as the distance between wave peak and average sea level, is more than 0.65 times the wave height. The first definition is the most popularly accepted (e.g., Kjeldsen, 1990; Kharif and Pelinovsky, 2003). The criteria used by researchers are shown in Table 1.

In regard to the definition of wave height and wave period from a statistical point of view, most researchers adopted the zero up-crossing or zero down-crossing method. Some of the researchers, such as Tseng et al. (2011b), used both methods to compare the errors and concluded that the results are similar.

2. The Occurrence Probabilities of Freak Waves

According to classical wave theory, under the Gaussian assumption of wave surface elevation, the weight height distribution satisfies the Rayleigh distribution. Under the circumstances of the Rayleigh distribution, the cases with $H \geq 2$ H_s appear once in 3,000 waves (0.0333%).

Based on 7,457 data sets recorded in Campos Basin, it was found that 108 waves met the criterion of $H/H_s \geq 2$ via zero down-crossing method, whereas 197 waves were selected via zero up-crossing method. Among the selected 305 total waves, 28 waves shared the same maximum wave height. Thus the actual number of freak waves was 277. Then the freak wave occurrence probability was 3.7%, and it was much higher than the corresponding value predicted by Rayleigh distribution.

According to the criterion of $H/H_s > 2$, 1,563 freak waves were captured in a total recorded 50,359 waves over 6 years in the Indian Ocean. Straightforwardly, the corresponding occurrence probability was 3.1%. This value was is close to

3.7%, which was calculated by Liu and Pinho (2004) based on the data from the South Atlantic Ocean. More importantly, Liu and Pinho (2004) found that the freak waves' heights varied from 23.2 and 71.4 m, and the values of H/Hs fluctuated between 4.5 and 21.3. Considering the broad fluctuation range and different characteristics of the freak waves, they divided the freak waves into different groups based on the values of H/H_s. If the values of H/H_s were small than 4 and large than 2, the corresponding freak waves were regarded as 'typical freak waves'. And the freak waves with H/H_s larger than 4 were called 'uncommon freak waves'. They noted that different kinds of freak waves were due to different mechanisms. This conception was analyzed in a further step by Tao et al. (2012b) via a numerical approach.

Among the 354,000 waves recorded from the North Sea, 104 freak waves were captured. From Stansell et al. (2005) concluded that the Rayleigh distribution considerably underpredicts the occurrence probability of extreme crest heights. A new statistical model, named generalized Pareto distribution (GPD), was introduced and verified better than Rayleigh distribution, particular for the wave crest heights distribution. The wave records obtained at nine observation points in the sea area around Japan showed that the occurrence probability of giant freak waves on the Pacific Ocean side satisfy the Rayleigh distribution quite well. While that on the Sea of Japan side is fairly lower.

Through an analysis of the second set of observational data from the Sea of Japan, at least 14 freak wave events with wave heights over 10 m were obtained. The maximum ratio of freak wave height to significant wave height is 2.67. The data also indicated that the distribution of the peak amplitude is different from the Rayleigh distribution, whereas the wave height distribution is in line with the Rayleigh distribution. It is similar to the results given by Stansell et al. (2005) based on the data from the North Sea.

If only condition ① (as shown in Table 1) was used as the criterion for freak waves, 603 freak waves were selected among 1,933,998 waves recorded by Longdong station during 10 years. And 67 were selected among 381,378 waves recorded by Taitung Deep Sea station. If the additional criterion ② was also applied, the corresponding numbers of freak waves from that two stations were 262 and 51 respectively. The related occurrence probabilities of freak waves are 0.6×10^{-4} and 1.09×10^{-4}, which are lower than that from Rayleigh distribution (Tseng et al., 2011a, 2011b).

Based on one whole year's buoy data from Xiangshui Station, which is close to Jiangsu coast, 2,630,487 waves were recorded and 503 freak waves were identified. The occurrence probability of freak waves fluctuated between 0.0150% and 0.0261%, when the probabilities were counted by each month respectively. While all the values lower than that from Rayleigh distribution.

IV. DISCUSSIONS VIA COMPARISON ANALYSIS

Table 2. The occurrence probabilities of freak waves and the comparison with the value predicted by Rayleigh distribution.

<table>
<tr><th>Sea Area</th><th>Occurrence Probability of Freak Waves</th><th>Comparison with the Rayleigh Distribution</th></tr>
<tr><td>The Atlantic Ocean</td><td>3.7%</td><td>Higher than</td></tr>
<tr><td>The Indian Ocean</td><td>3.1%</td><td>Higher than</td></tr>
<tr><td>The North Sea</td><td>0.029%</td><td>Higher than (crest)/
Lower than (trough)</td></tr>
<tr><td rowspan="2">The Sea Area around Japan</td><td colspan="2">In accord with (the Pacific Ocean)/
Lower than (the Sea of Japan)</td></tr>
<tr><td colspan="2">Different with (crest, amplitude)/
In accord with (wave height)</td></tr>
<tr><td>The Sea area round Taiwan Island</td><td>Longdong 0.006%/
Taitung 0.0109%</td><td>Lower than</td></tr>
<tr><td>The sea area along the Jiangsu Coast</td><td>0.0150%~0.0261%</td><td>Lower than</td></tr>
</table>

Obviously, the occurrence probability of freak waves from different sea area varies so much. In the Atlantic Ocean and the Indian Ocean, the results show that the occurrence probability is much higher than the predicted value by the Rayleigh distribution. However, for the other four sea areas, the occurrence probability of freak waves is relatively small, even lower than that from Rayleigh distribution. The statistical values are shown in Table 2 in details. The potential causes of the various results are analyzed as follows.

Firstly, the water depth, climate state and topography of those six sea areas, where the wave data were collected, are different distinctly. For example, the water depth for Longdong station, which is close to the Taiwan coast, is relatively shallow (30 m), while that for Taitung station is very deep (5,000 m). The results show that there are more large waves from Taitung than Longdong. Thus, the frequency of freak waves might be related to the water depth. Parts of the observed data were collected mainly during the storm periods ,such as the data from North Sea, whereas the others were gathered both in storm and normal states.

Secondly, the measurement approaches differs greatly, including the choice of the instruments, the location of the facilities, and the different options. Although, most of the data present here are from wave buoys, the other approaches are also used, such as the Marex Radar Wave Monitor in Indian Ocean and Thorn EMI infra-red laser altimeters in North Sea. The physical principles for those three approaches are totally different so that the wave information changes, particularly for the extreme values. Actually, even for the data all from wave buoys, the information can also be different due to different analyzing methods. Because the wave surface elevations can only be deduced from acceleration information. Therefore, the reliability for the freak waves is different.

Furthermore, the different statistical approaches also contribute to the differences. Before analyzing the wave data, the wave sequence should be divided into many individual waves and then to calculate the maximum and significant wave heights. One key problem is how to determine the length of each sequence. For Atlantic Ocean, the length is 17.067 minutes, while for North Sea, it changes to 20 minutes. Which one is better? If the wave information is recorded continuously, what is the suitable length? If the occurrence probabilities of freak waves are calculated from wave sequences with different lengths, can we make the comparison simply?

Additionally, as listed in Table 1, the definitions of freak waves used by the researchers are different because there is no unified standards until now. And, of course, it is also questionable to make comparison among the values of freak waves with different definitions.

V. CONCLUSIONS AND SUGGESTIONS

Different research approaches were used for the investigation of freak waves. Among them, field observation is most reliable, particularly for the occurrence probability of freak waves. In order to present the latest research state, the results related to the observed freak waves are summarized and analyzed again. Most of the data are from six sea areas, including the Atlantic Ocean, the Indian Ocean, the North Sea, the Sea area around Japan, the sea area around Taiwan Island and the coastal sea area close to Jiangsu coast.

Based on detailed comparisons, some new conclusions are addressed as follows. Firstly, both the occurrence probability and the strength of freak waves vary in a large range for different sea areas. The wave heights vary from less than one meter to more than thirty meters. The occurrence probabilities vary from less than the value predicted by the Rayleigh distribution to one hundred times that value. The potential reasons are related to the difference of freak wave definitions, the measurement approaches and physical parameters of different sea areas. Here the physical parameters include water depth, climate state and topography. Then there is still no answer to whether freak waves are rare events or not, since the answer depends much on background information. Secondly, including the popular simple definition of freak wave, other criteria were also used without scientific reason. For example, the surplus standard of more than 1 m or 10 m was used in some sea area. Therefore, a key point here is that researchers still do not know what is the exact freak waves, although this information is necessary. Thirdly, it is evident that the occurrence probabilities of freak waves in deep water are larger than those in shallow water. However, no evidences show which type of freak wave is more dangerous, because the result also depends on the victims. For example, more people may be exposed in shallow water, then the occurrence of freak waves may amplify the disasters than those happen in the deep water. This is a hint to show that the further steps for freak waves research should consider the local characteristics of the potential disaster risk induced by the freak waves.

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