Freak waves and capsizing accidents

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ABSTRACT

Marine accidents, possibly caused by encounters with the "freak waves", are investigated. The result of the studies at the laboratory tank of the University of Tokyo revealed that the probability of freak waves increases when the directional spectrum narrows. Sea states during five marine accidents near Japan were analyzed using the third-generation wave model and suggested the narrowing of the directional spectrum. Based on the estimated information of the directional wave spectrum and other parameters during the marine accident, the possible causes of the accident will be discussed in the context of slamming, broaching and other possibilities.

KEYWORDS

Freak wave; Marine Accident; Directional Spectrum; Benjamin-Feir Instability; Tank Experiment

INTRODUCTION

Records of freak wave or rogue wave in the ocean are documented by seafarers as well as by scientists using advanced instrumentations (Kharif et al. 2009). Records reveal that the freak waves appear like a wall of water unexpectedly to the seafarers navigating in otherwise tractable sea states. The generation mechanism of the freak waves has become apparent in the last 10 years or so. One of the well studied mechanisms is the manifestation of the modulational instability of weakly nonlinear wave train in a random directional sea (Janssen 2003, Onorato et al. 2004,). Instability of random sea was suggested theoretically by Albers (1973) and has been elaborated by Yuen and Lake (1982) but it is only in the last decade that people associated this mechanism to the freak wave generation. However, this mechanism is not effective in realistic directional seas (Soquet-Juglard et al. 2005). Systematic studies in laboratory wave tank varying the directionality of the wave spectrum revealed that the probability of the freak wave gradually increases as the directionality narrows; i.e. as the crest length gets longer (Waseda et al. 2009ab, Onorato et al. 2009ab). Waseda et al. (2009a) suggested that such sea state is possible from hindcast wave field. The key is then to predict the meteorological condition forming a sea state with directionally narrow wave spectrum. Tamura et al. (2008) showed that the marine accident near Japan occurred when the directional spectrum narrowed due to swell and wind-sea interaction. In this paper, we analyse five other marine accident cases using the wave model outputs to estimate the freak wave indices.

FREAK WAVE OCCURRENCE AND THE DIRECTIONAL SPECTRUM

Tank Experiment

The Ocean Engineering Tank of the Institute of Industrial Science of the University of Tokyo (Kinoshita Laboratory and Rheem Laboratory, 50 m long, 10 m wide, 5 m deep) is equipped with a multi-directional wave maker with thirty-two 31 cm-wide triangular plungers that are digitally controlled to generate regular as well as random waves in ranges of wave periods (0.5 ~ 5 s). The JONSWAP-Mitsuyasu type directional wave spectrum was generated:

$$S(\omega)=\alpha g^2(\pi)\omega^{-5}\exp\left\{-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right\}\gamma^{\exp\left\{-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega^2{}_p}\right\}} \quad (1)$$

$$G(\theta)=G_n\cos^n(\theta) \quad (2)$$

The peak frequency was set to 1.2389 Hz (wavelength 1 m), the value of α was adjusted for the significant wave height in the range of 3 cm and 6 cm, and the peakedness parameter γ was set to 3.0, a typical value in growing sea. The most relevant control parameter in this experiment is the exponent n of the directional spreading function $G(\theta)$; $n=3\sim 250$. The spectral evolution was measured by an array of wave wires at 5 m interval along the tank and the directional wave array of 6 sensors (a pentagon and its centroid). The directional wave spectrum was estimated using the wavelet detection method (WDM). Each run is an hour long.

Exceedence probability and the Kurtosis

The probability of freak wave in random directional sea is quantified by the probability density function of the wave height. Onorato et al. (2004) have demonstrated experimentally that the probability of the freak wave occurrence increased as the frequency bandwidth narrowed; i.e. as the value of the peakedness parameter γ increased. They have also demonstrated that the value of the Kurtosis of the surface elevation increased due to quasi-resonance down the tank. The value of the Kurtosis depends on both frequency bandwidth of the spectrum and wave steepness and their ratio was coined the BFI by Janssen (2003).

$$BFI=\frac{ak}{\delta f/f_0} \quad (3)$$

The *BFI*, representing the relative significance of nonlinearity and dispersion, is a useful index in estimating the freak wave occurrence for a given uni-directional wave. Mori and Janssen (2006) derived an expression for the probability of the freak wave including the kurtosis as a parameter correcting linear theory. Based on these pioneering works, Waseda et al. (2009ab) and Onorato et al. (2009ab) independently conducted tank experiment to study the effect of directionality. Using the Kurtosis as an indicator, a steep reduction of the freak wave probability was found when the directional spectrum narrowed (Fig. 1).

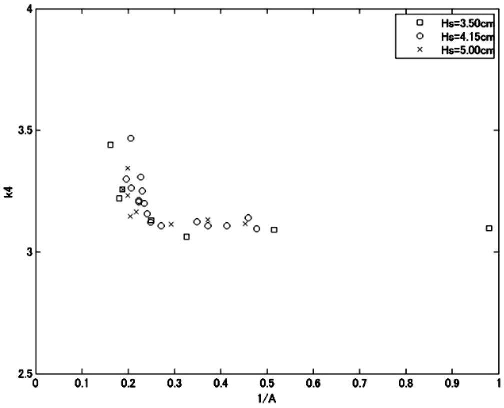

Fig. 1: Kurtosis plotted against directional spreading (1/A) where A is defined as $A\cdot K(\theta;f)\equiv G(\theta;f)$, and $G(\theta;f)$ is the directional distribution function satisfying $\max[K(\theta;f)]=1$; circle 35-40 m, square 14-15 m fetch. The figure is reproduced from Waseda et al. (2009a).

The BFI was extended in Waseda et al. (2009a) to include the effect of directionality:

$$BFI_{eff}=\frac{\varepsilon_{eff}}{\sqrt{(\delta k/k)^2-2(\delta l/k)^2}} \quad (4)$$

Effective BFI (BFI_{eff}) makes use of the effective spectral bandwidth (the denominator) introduced by Alber (1978) and also the resonant interaction coefficient that reduces as the resonance condition departs from the singularity along the resonance manifold (the numerator). The observed variation of Kurtosis was characterized as a single-valued function of the BFI_{eff} . Arbitrariness in the determination of the effective spectral bandwidth remains, and will be discussed further in the freak wave index section.

WAVE FORECASTING/HINDCASTING

Model description

The model is based on WavewatchIII™ (WW3) and covers a region near Japan at a quarter degree horizontal resolution nested within the coarse Pacific basin model (one degree). The Pacific model is forced by the U. S. Navy Operational Global Atmospheric Prediction System (NOGAPS) wind, and the Japan model is forced by the Japan Meteorological Agency Meso-Scale Model (MSM) wind. The model is configured at a default WW3 setting. Tamura et al. (2008) improved the model replacing the nonlinear source term from the default DIA method to the SRIAM method. Some of the marine accident analyses make use of this improved WW3 with SRIAM. In et al. (2009) compared the performance of the SRIAM and DIA in estimating various freak wave indices and concluded that qualitative assessment can be made using the conventional DIA. Note that, regardless of the nonlinear source terms used, the third generation wave model tends to produce broader directional spectrum than the observation (e.g. Tamura et al. 2010). The forecast model is in operation since April 2009 and the nowcast data are archived as hindcast product. The hindcast product is analyzed in this study.

FREAK WAVE INDICES

Geometry of the directional spectrum

The BFI and its extension, conveniently relates the geometry of the spectrum (frequency bandwidth and average steepness) to the probability of the freak wave. The parameters characterizing the spectral geometry are the steepness (5), the frequency bandwidth (6), and the directional spreading (7):

$$ak_s = \left(\frac{H_s}{2}\right)\left(\frac{2\pi}{\lambda_m}\right) \quad (5)$$

$$Q_p = 2m_0^{-2}\int_0^\infty \sigma\left[\int_0^{2\pi} F(\sigma,\theta)d\theta\right]^2 d\sigma$$

where (6)

$$m_0 = \int_0^{2\pi}\int_0^\infty F(\sigma,\theta)d\sigma d\theta$$

$$\sigma_\theta = \left[2\left\{1-\left(\frac{a^2+b^2}{E^2}\right)^{\frac{1}{2}}\right\}\right]^{\frac{1}{2}} \quad (7)$$

where

$$a = \int_0^{2\pi}\int_0^\infty \cos(\theta)F(\sigma,\theta)d\sigma d\theta$$

$$b = \int_0^{2\pi}\int_0^\infty \sin(\theta)F(\sigma,\theta)d\sigma d\theta$$

These parameters can be derived from the directional spectrum $F(\sigma,\theta)$. Waseda et al. (2009a) further attempted to combine Q_p and σ_θ to estimate the effective spectral bandwidth $\sqrt{(\delta k/k)^2 - 2(\delta l/k)^2}$ but had to include an arbitrary constant which needs to be calibrated.

The $Q_p - \sigma_\theta$ plot

Numerous studies suggested that the correlation between BFI (ratio of ak_s and Q_p) and the probability of freak wave was poor. On the other hand, Tamura et al. (2008) focused attention only on the directional property of the spectrum (i.e. Q_p and σ_θ) and demonstrated that the trajectory of the spectral property in the $Q_p - \sigma_\theta$ space can indicate a dangerous sea state. The $Q_p - \sigma_\theta$ diagram is reproduced in Fig.2 supplemented with annotations. In et al. (2009) further utilized the $Q_p - \sigma_\theta$ diagram suggesting possible seasonality of the freak wave occurrence near Japan. The $Q_p - \sigma_\theta$ diagram will be utilized in the investigation of the marine accident cases.

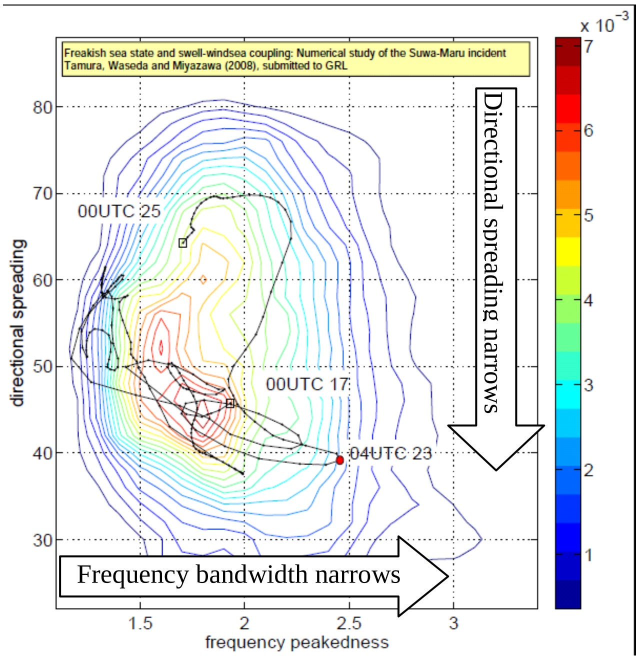

Fig. 2: The trajectory of spectral property in the $Q_p - \sigma_\theta$ diagram. The occurrence of freak wave is highest in the lower right corner and lowest in the upper left corner. The figure is reproduced from Tamura et al. (2008). Case 1 in this paper.

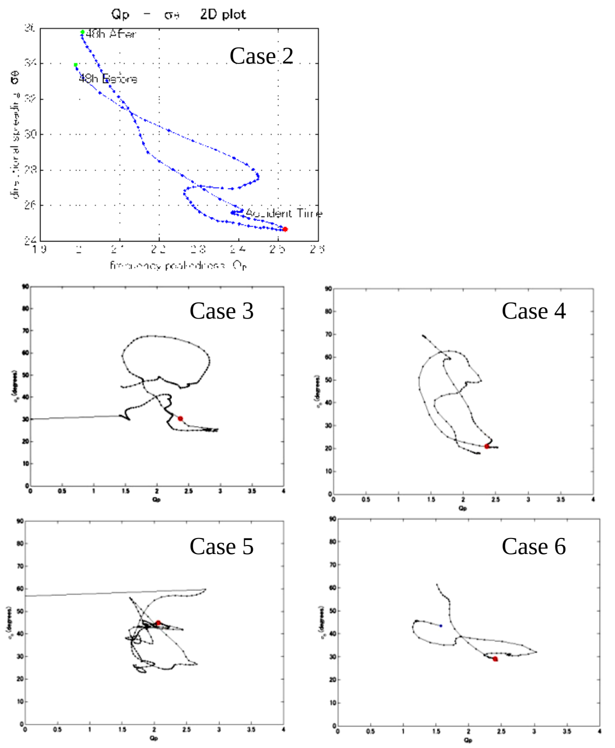

Fig. 3: The trajectory of the spectral property in the $Q_p - \sigma_\theta$ diagram for cases 2 t o 6. Except for the fifth case, the accident occur (red dot) at the lower right corner of the diagram when the directional spectrum is narrow.

MARINE ACCIDENT CASES

Summary of the cases studied

Six marine accident cases were studied. In chronological order of the incident, the gross tonnage of the vessel and the wave parameters estimated from the wave model are summarized in Table 1. Except for the fifth case, all the other cases occur when the probability of freak wave was high judged from the trajectory on the $Q_p - \sigma_\theta$ diagrams (Fig.3). The accidents occur (red dot) when the directional spectrum was narrow.

Table 1: Summary of the gross tonnage, description of the accident, and relevant wave parameters (significant wave height, mean period, mean wavelength, steepness, directional spreading, frequency bandwidth) from the wave model at the time of the marine accident cases.

GRT	accident	Hs	Tm	Lm	ak	σ_θ	Q_p
33,833	loss of bow	8.2	12.4	240	0.11	25	2.5
135	capsize	3.8	9.5	141	0.08	38	2.5
19	capsize	7.9	9.9	154	0.16	25	2.8
7,910	load shift	6.0	9.7	145	0.13	21	2.4
121	capsize	2.5	5.8	52	0.15	45	2.1
113	capsize	1.7	4.9	38	0.14	29	2.4

Case 1: Bulk carrier Onomichi (1980.12.30)

After the loss of her bow at 156.2E and 31.0N, south of the Kuroshio Extension, Onomichi had survived for two months until it finally sunk. The damaged bow has been observed and photographed, and after an intensive study of the structural strength of the hull, Yamamoto et al. (1983) concluded that the ship must have encountered a wave of height exceeding 20 m. Possible impact force due to slamming is considered to be the cause of the structural damage. The reproduced wave field suggests that the significant wave height was around 8 m or so, suggesting that the wave 20 m high is a freak wave. The possible meteorological cause of the freak wave in this case is the Eastward propagation of a strong westerly wind (In et al 2009).

A tank experiment was conducted at the Ocean Engineering Tank of the University of Tokyo, studying the bending moment on a 2m model ship encountering extreme waves generated by dispersive focusing (chirped wave group) and Benjimin-Feir wave train. The study revealed that the midpoint bending moment of the ship hull was unbounded, and increased with the encounter wave height. Both the sagging bending moment and the hogging bending moment did not saturate (Fig.4). For a 280 m long vessel, the result suggests that the bending moment did not saturate even for waves as high as 35 m. From the result of this tank experiment, we conclude that it is possible that the bottom slamming due to encounter with a wave over 20 m in height has damaged the bulk-carrier Onomichi.

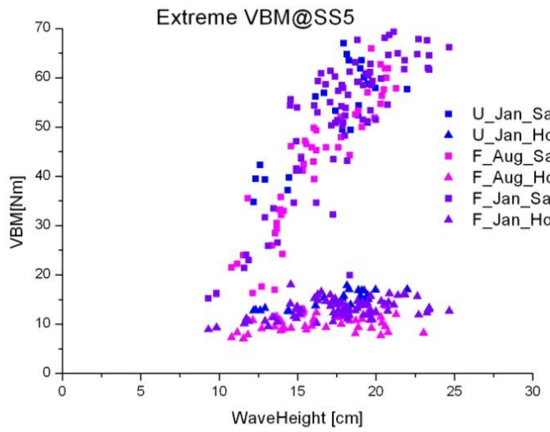

Fig. 4: The extreme vertical bending moment plotted against the encountered wave height for sagging bending moment (squares) and hogging bending moment (triangles).

Case 2: Fishing vessel (2008.6.23)

A large fishing vessel of 135 GRT capsized at 144.5E and 35.5N, North of the Kuroshio Extension, due to encounter with two consecutive extreme waves according to the survivor of the sunken ship. The meteorological conditions that lead to the formation of a freakish sea condition is the coexistence of the Baiu/Meiyu front and the depression. Peculiar spectral evolution of swell and wind-sea interaction is reported by Tamura et al. (2008). The height of the freak wave is estimated to be around 8 m based on the significant wave height of 4 m from the wave model. It is said that the sunken ship was using a para-anchor at the time of the incident. The interval between the two consecutive extreme waves (as reported) is unknown. If they were waves within a single wave group, the interval would have been around 10 seconds or so, but if they were waves from two independent groups, the interval could have been around 120 seconds or so. The combined effect of the use of para-anchor and the encounter with two consecutive extreme waves could have possibly led to the capsizing of the vessel.

Case 3: Fishing vessel (2009.10.25)

A small fishing vessel (19 GRT and LOA 19 m) capsized at 138.5E and 33.0N near the Hachijo Island during a severe sea condition of 8 m in significant wave height. The characteristic meteorological condition leading to this incidence is the stationary front south of Japan. In between the front and the Japanese archipelago, a gale condition of 10 m/s East-North-East wind and 20 m/s gust developed within 10 hours. The spectral evolution suggests a freakish sea state.

Case 4: Ferry (2009.11.12)

A large ferry boat (LOA 167 m, D 6 m) experienced a serious load shift at 136.3E and 33.6N of the coast of the Kii Peninsula, healed at large angle, drifted and eventually collided with a reef. The significant wave height was 6 m, and average wavelength was 145 m. The wave analysis suggests a freakish sea state but the estimated freak wave of 12 m height does not seem to be a threat for LOA 167 m ship. However, because the ship was sailing to the southwest followed by westward propagating wave, the possible scenario of the large heal can be the loss of transverse stability due to passage of the freak wave from the portside.

Case 5: Fishing vessel (2009.12.20)

A large fishing vessel of 121 GRT sunk during a gale condition of 15 m/s West-North-West wind at 130.0E and 35.0N near Tsushima strait. The reported significant wave height was 4 m and from the wave model was 2.5 m because of the short fetch from the coast of South Korea. The wave spectrum did not indicate a freakish sea state either. Possibility is that the spatial resolution of the numerical model was insufficient to resolve high frequency wind, for example, the gap winds from the valleys in the Korean peninsula.

Case 6: Fishing vessel (2010.1.12)

A large fishing vessel of 131 GRT sunk at 127E and 33N in the East China Sea. A possible green water loading was reported from the ship in the last radio contact. The estimated significant wave height is only 2 m. The wave spectrum suggests a freakish condition. The ship was unloaded since she was on her way to the fishing ground. Therefore, even with the possible encounter with the freak wave, it is difficult to explain the capsizing. The incident occur South-East of the Cheju Island, where the wind from the North-West can be intensified in the East side as it blows around the Island. Such wind condition is not resolved in the MSM wind product we used for the wave simulation.

CONCLUSIONS

Result from the experimental work hinted us the possibility of abnormal meteorological condition as a precursor to the development of freakish sea state when the directional spectrum narrows. Among the six incidents studied, 5 of them suggested that the sea state was freakish. In the first case, the ship experienced bottom slamming. In the second case the ship lost its stability due to combined influence of sea-anchor and green-water loading. In the third case the ship capsized because she encountered an enormous wave compared to her size. In the fourth case the ship lost its stability and healed because of the freak wave in following sea. The reason for the sink of the fifth and the sixth case is unknown because the estimated wave height is rather small. In both cases, the incidents occur close to the land where the resolution of the wind product is insufficient.

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