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# Note on the appearance of Freak Waves from in-situ ocean wave data

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**Abstract.** Freak waves in the ocean are recently drawing much attention as a natural disaster to ocean structures and navigating ships as well. Several observation data, among them the Draupner New Year Wave, show the very impressive feature of Freak waves whose wave height is up to three times as high as the significant wave height of surrounding waves. In addition, Freak wave appears as an isolated very high crest in somewhat stationary random waves of same order in their wavelengths. Bearing such characteristics in mind, one notices its extraordinary steepness. This strongly suggests that Freak wave is not long lived but transient nature on the whole. A great number of studies to explain these natures were published from both theoretical and numerical point of view. However it is not sure if they are applicable to actual ocean environment. In this paper, we deal with the results concerning abnormal and/or Freak waves from in-situ ocean wave data and point out several remarks to the problems lain behind the contributions in this context. A physical experiment is described to reinforce the subject discussed from the observation data.

## Introduction

On October 2004, an enormous typhoon No.23 hit Japan and the observation site off Muroto recorded 15m in significant wave height with 26m in maximum wave height. The study of extreme wave becomes more important to prevent people from marine disaster. The wave, which is one of the quite curious wave phenomena is known as Freak Wave. It was recognized in an earlier paper by Klinting (Klinting and Sand, [1]) from the wave record taken at an observation site off Denmark in the North Sea 1981. After that many events like that features were found in several sea area worldwide including the North Pacific Ocean and the Sea of Japan. Those results were reported in the Rogue Wave 2000, 2003 Symposium [2, 3]. The second round of this symposium was held at the same spot in 2004. Many sort of numerical techniques to investigate such phenomena were presented and the practical problems such as the prediction of Freak wave were proposed in this symposium. However any general consensus has not been made up to present.

For the study of Freak waves as a geophysical phenomenon, observation results from in-situ data are indispensable. However, they are thought not to be ample enough because Freak waves do not appear frequently and observation in offshore sea area cost so many times and much money.

In this paper we first deal with the actual ocean wave statistics of maximum wave height up to Freak waves in several observation sites and summarize the overall feature of the abnormal waves from in-situ data. A great many set of data from recent measurements in the Northern North Sea are analyzed and the preliminary results are described for comparison. Secondly, a directional random wave generation experiment is performed to examine the 2D characteristics of wave field with emphasis on its non-Gaussian statistics. Some remarks to the modeling of Freak waves are presented in concluding section.

## Ocean wave statistics from the sites offshore of Japan

Since actual wave data are time-limited (17-20 minutes), maximum wave height distribution is defined from Rayleigh distribution (narrow band spectra ) as follows:

$$\xi = Ne^{-(1.416x_{\max})^2}, \quad p^*(x_{\max}) = 4.01\xi x_{\max} e^{-\xi}, \tag{1}$$

where $x_{\max}$ represents the maximum wave height of the time series normalized by significant wave height (we denote it AI hereafter)and N is the number of waves in it. Exceedence probability is given simply

$$P^*(x_{\max}) = 1 - e^{-\xi}. \tag{2}$$

In contrast for broad band spectra, maximum wave height distribution defined from Forristall distribution [4] is

$$\xi = Ne^{-\left(\frac{x_{\max}}{0.7218}\right)^{2.126}}, \quad p^*(x_{\max}) = 2.9454\xi\left(\frac{x_{\max}}{0.7218}\right)^{1.126} e^{-\xi} \tag{3}$$

Note that above formula depend on N, it is preferable to analyze observed data with N=constant.

***Yura site***

Yura site is located in the north-west part of Japan and faced to the Sea of Japan. Offshore waves were measured by Ship Research Institute during 1983-84. The wave data was analyzed in detail by Yasuda et al. [5], Tomita et al. [6,7] and Mori et al. [8]. Herein, we present some results from the different point of views.

Fig.1 shows the correlation of maximum wave heights with corresponding significant wave heights with N=100. Overall feature of linearity between Hs and Hmax is confirmed, that is, AI is not dependent on Hs and their ratio (AI) is about 1.5-1.6.

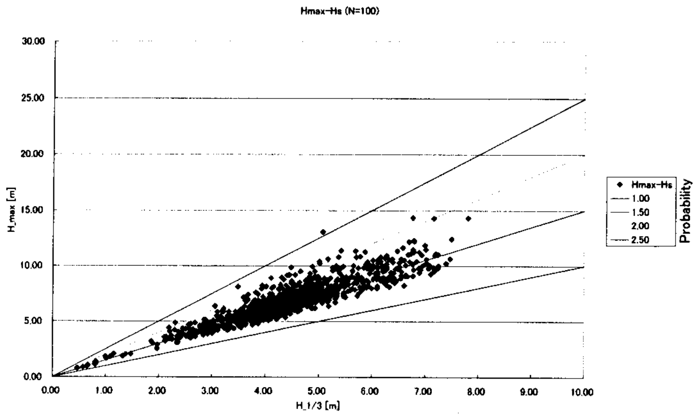


Fig1. Plot of Maximum v. s. Significant wave heights in records [Yura(N=100)]

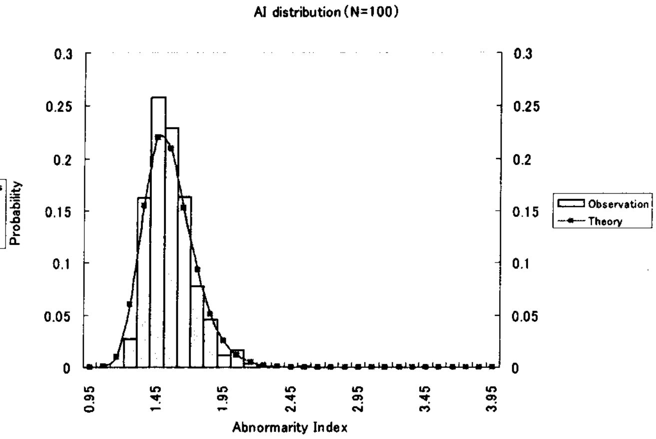


Fig2. Distribution of AI index in records [Yura(N=100)]

Fig.2 shows the comparison of the formula (1) with actual ocean data with N=100. As the number of data sets are insufficient, agreement is not so excellent.

***Hiratsuka site***

Hiratsuka site is located in the central part of Japan and faced to the Sagami Bay. It is relatively near-shore from the coast so that the wave climate is not very rough. However this site is constructed for the academic purpose in particular for study of wind wave generation for long time.Therefore it provides very precise data and we can use them during 1992-2004 continuously.

In Fig.3, we present the same comparison as in Fig.2. In here, the number of data is very vast and one can confirm the excellent agreement of the in-situ data with theory.

***Comparison of observations***

We made comparison of several in-situ data analysis including ourselves. Table 1 gives the results of several independent observations concerning the occurrence of Freak Event and Freak Waves.

In Fig.4, we present an evidence of the nonlinearity of Freak Waves. In this figure, abscissa means the steepness of a maximum wave which is usually around 0.05. The ordinate means the horizontal asymmetry defined by Myrhaug [9], which must be 0.5 for sinusoidal wave.

Three groups of maximum wave are plotted. Blue points represent normal maximum (AI<1.5), while red points represent abnormal maximum (AI>2). In addition, yellow points represent so called "historical" event measured at GormField and Draupner. As is seen, abnormal (Freak) ones are clearly discriminated from normal ones and historical events. The latter cases show nonlinear nature from this point of view.

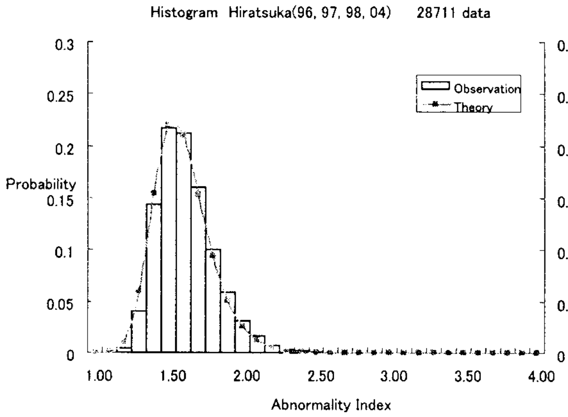


Fig3. Distribution of AI index in records [Hiratsuka(N=100)]

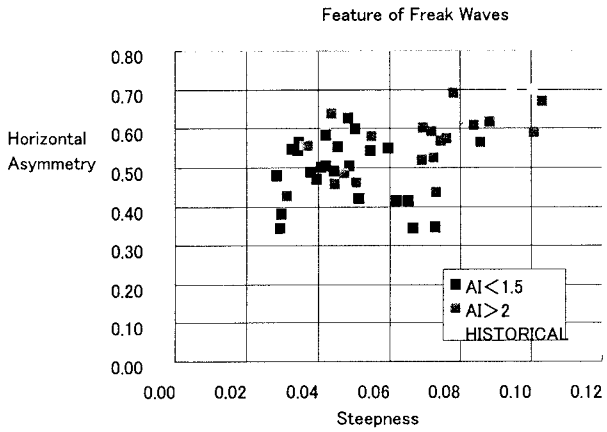


Fig4. Nonlinearity of Freak Waves (Yura)

Table1. Occurrence probability of Freak Waves: Theory and Observation

Occurrence Probability (AI≧2)

| | | Freak wave event | Freak wave | Remark |
|---|---|---|---|---|
| Theory | Rayleigh dist. | – | 0.032% | |
| | Max wave dist. (N=50) | 1.63% | 0.033% | |
| | 〃 (N=70) | 2.27% | 0.032% | 8.5min. mes. |
| | 〃 (N=150) | 4.81% | 0.032% | 20min. mes. |
| | 〃 (N=250) | 7.89% | 0.032% | |
| | 〃 (N=300) | 9.39% | 0.031% | |
| Obsevation | Shirepa (Yasuda et al. 1992) | 9.0% | 0.041% | offshore |
| | Aogashima (Tomita 2005) | 3.2% | 0.051% | open sea (780m) |
| | Yura | 4.5% | 0.032% | ZUC+ZDC |
| | Yura | 3.4% | 0.020% | ZUC (42m) |
| | Yura (N=100) | 2.3% | 0.023% | ZUC |
| | the North Sea (Stansell 2004) | – | 0.029% | (130m) |
| | Hiratsuka | 14.6% | 0.037% | offshore(20m) |
| | Hiratsuka (N=100) | 3.9% | 0.039% | |
| | Gormfield (AI=2.6) (N=150) | 0.0195% | 0.0013% | *0.002% (Klinting 1987) |
| | NNS (Tomita 2006) | 2.09% | 0.015% | |

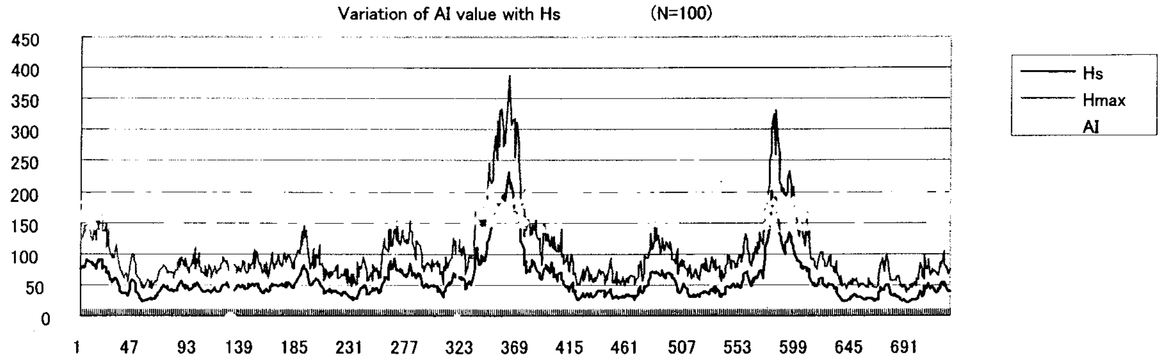


Fig5. Time series of wave heights with AI [Hiratsuka(N=100)]

Fig.5 shows the one month temporal variations of maximum wave height, significant wave height with AI index taken from N=100 waves in each observation. AI>2.5 events appear at relatively calm weather.

**Wave analysis from the Northern North Sea**

Wave records from the Northern North Sea (provided by S. Harver of Statoil) will be analyzed. The surface elevation time series was obtained by Saab radar from the Kvitebjorn platform (0E, 60N and 190 m depth) and covers the period from December 2003 until May 2005. The total volume of data is over 2800 twenty-minute wave records sampled at around 0.13 s period. Two sets of data are analyzed: first, dataset from December 2003 and January 2004 that provided longest uninterrupted data sequence (~40 hours) together with wind information; second, dataset that covers the entire period of 2003 to 2005 but sporadic. The former is useful in assessing temporal evolution of wave parameters during a passage of storm by the platform. The latter dataset includes various weather conditions but since the local wind record is not available, only wave parameters are studied.

***Averaged wave parameters:***

During December 14 to 16, 41-hour continuous record was obtained during a passage of a storm whose maximum wind speed was close to 30 m/s at the platform. The significant wave height ranged between 5 m to 11 m. The maximum wave height, kurtosis, AI, BFI (Benjamin-Feir index) were estimated from each 20 minutes record. BFI is derived following Janssen and Bidlot [10] as:

$$BFI = k_0 m_0^{1/2} Q_p \sqrt{2\pi} \tag{4}$$

The peakedness factor $Q_p = 2/m_0^2 \int d\omega\, \omega E^2(\omega)$ was estimated from the wave spectrum of around 20 degrees of freedom following the definition by Goda. All the analyses were made for zero-up-crossing wave. The temporal evolutions of each parameter are summarized in Figure 6. As the storm passes by (see evolution of W), both Hs and Hmax increased with time but with some delay (correlation without lag is around 0.5, Table 2). The wind was North-North-Westerly for this storm and so the windsea has a relatively long fetch stretching from the Southern coast of the Green Land. Thus the dataset includes both duration and fetch limited windsea conditions. The AI, the ratio of Hmax and Hs, exceeded 2 twice during the 41 hour period but for the rest of the time, it remained small. The time series of the wave record from these two cases showed clearly an isolated wave crest that resembles a typical freak wave (Figure 7 shows one example). The kurtosis was estimated as well. The AI and the kurtosis has the highest correlation among the parameters but this is perhaps not surprising since, as often said, the kurtosis and AI both indicate weather the freak wave appears within the wave record or not. As Stansell [11] states, the magnitude of kurtosis reduces by removal of the freak waves themselves from the record. Finally, the estimated BFI ranged between 0.4 and 1 which is a reasonable value but had very little correlation with most of the averaged parameters. Janssen [12] suggests a strong constraint that the kurtosis is proportional to the square of the BFI. Such strong correlation was not found from the current dataset (in fact the correlation was almost zero).

Table 2: Correlation among various averaged wave parameters

| | Hs | Hmax | Kurtosis | BFI | W(m/s) | AI |
|---|---|---|---|---|---|---|
| Hs | | | | | | |
| Hmax | 0.8351 | | | | | |
| Kurtosis | -0.0370 | 0.2791 | | | | |
| BFI | 0.1331 | 0.1543 | -0.0089 | | | |
| W(m/s) | 0.4999 | 0.4715 | 0.0791 | 0.3612 | | |
| AI | -0.0584 | 0.4942 | 0.5727 | 0.0664 | 0.0851 | |

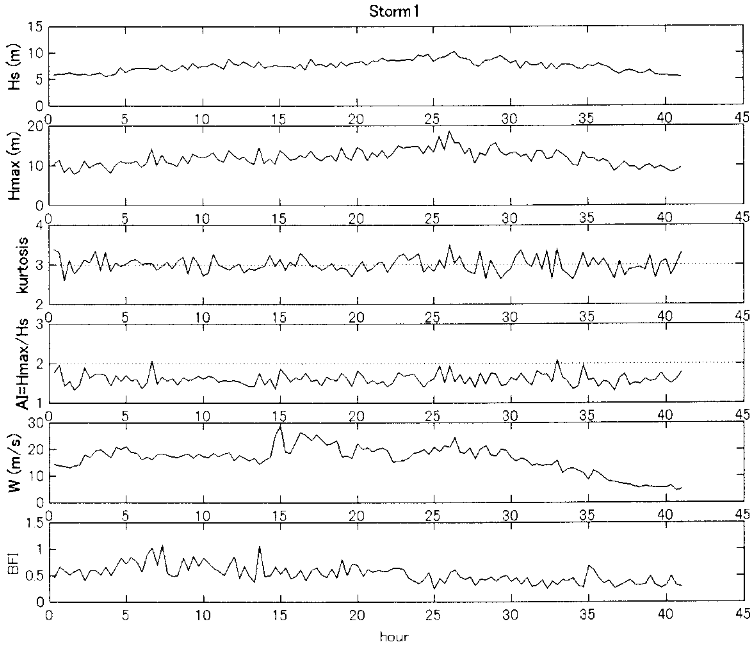


Figure 6: Time series of averaged wave parameters from each 20 minutes record.

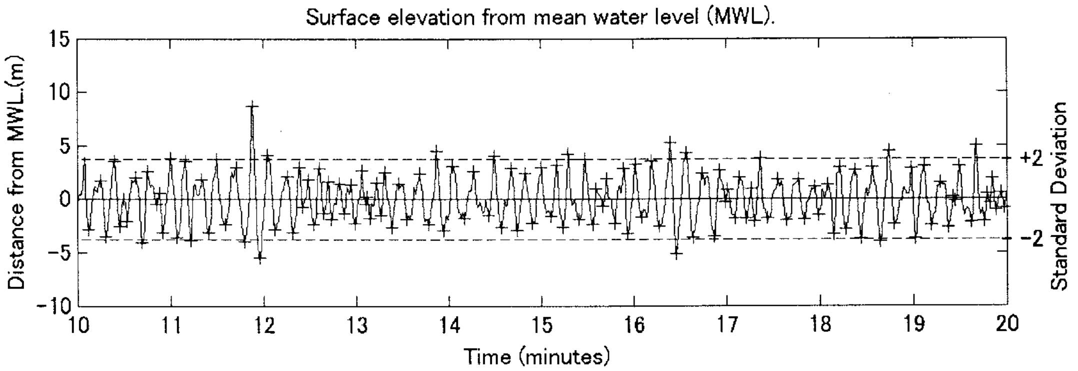


Figure 7 Freak event during the storm in December 2003 at the Kvitebjorn platform

***Wave height probability distribution*:** Figure 7 is a typical wave record that evidences the existence of a freak wave. However, a single wave record alone cannot prove that such event is indeed "freak" and not just one realization in a linear random wave system (one out of 3000 waves). To study that, we estimated the exceedence probability of the wave height from the collection of 2723 twenty-minute records. Since the wind speed was not made available to us, we have classified all the records into groups of significant wave height at 1 m intervals. In this way, undesirable introduction of non-stationarity of the time record is circumvented. For each significant wave class (e.g. 5<Hs<6), exceedence probability was compared with the following distribution functions:

$$\begin{cases} P(x) = \exp(-2\,x^2) & \text{Ralyleigh distribution} \\ P(x) = \exp(-\,(x/a)^c\,) & \text{Forristall distribution; } a = 0.7218, c = 2.126 \end{cases} \qquad (5a,b)$$

The distribution resembled each other for all the significant wave height classes. In Figure 8 the most statistically reliable distribution (6>Hs>5 m, with over 200,000 waves) are shown for both semilog plot and linear-linear plot. The analysis suggests that the dataset fits well to the Forristall distribution for waves exceeding H/Hs=1 (see left figure) but the Rayleigh distribution gives a better fit to waves at lower wave height (see right figure). Since Forristall distribution is just an empirical fit of the Weibull distribution to the NNS record prior to year 2003, the result suggests that the NNS windsea climate was more or less consistent among the years and that the actual exceedence probability does not follow the Rayleigh distribution. This result is rather shocking because the freak wave occurrence is even less than what is expected for a linear narrow banded Gaussian process (AI was over 2 for only 57 records out of 2723 records). We consider that this is likely because of the broad bandedness of the spectrum not only in frequency domain but in directional distribution. The latter will be discussed more in the physical experiment section.

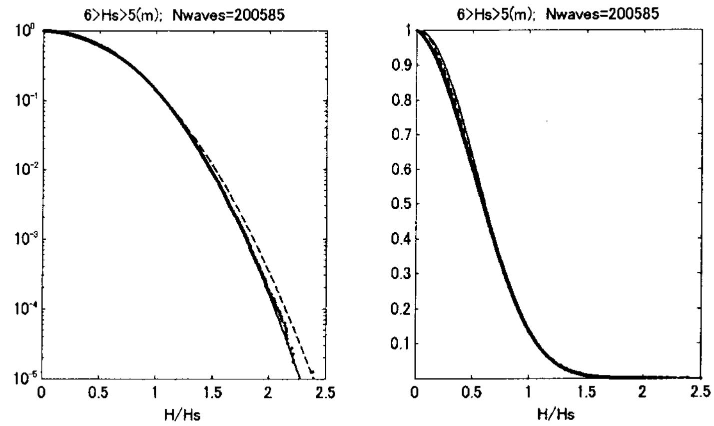


Figure 8 Exceedence probability; left: semilog plot, right: linear-linear plot. Dots are data from the NNS data; solid line: Forristall distribution; dashed line: Rayleigh distribution

***Wave shape of the freak wave***: Since the wave record sampling rate was high enough to provide high resolution wave shape, we have investigated the nonlinearity of the freak wave as indicated by the asymmetry of the wave shape. The asymmetry of the wave shape is defined as the ratio of the crest height and the wave height of the maximum wave in each twenty-minute record and that is compared with the steepness of the maximum wave. The scatter of the data is quite significant (Figure 9 left) and so the averaged quantities were obtained for each AI value classes (Figure 9 right). The tendency is that the nonlinearity of the wave shape gently increases as the AI increases and for the freak wave (AI>2.0, right most point in Figure 9 right) the nonlinearity is largest. This result is consistent with the earlier analysis by Tomita (Fig 5) of the Yura record.

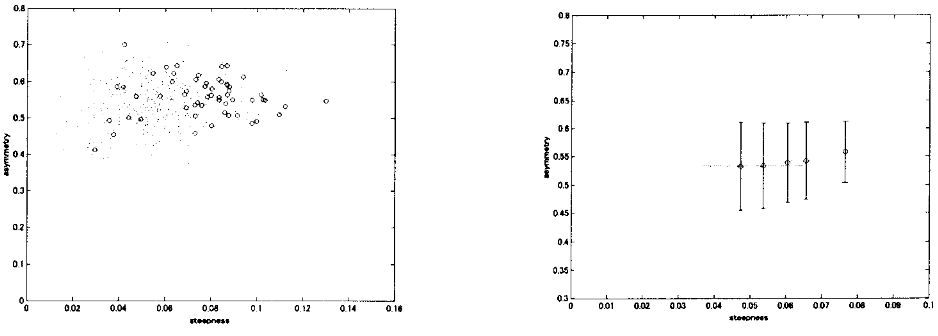

Figure 9 Asymmetry vs. steepness of the maximum wave. Left: Scatter plot from 2723 records, circle denote those for AI>2.0 (57 cases). Right: Averaged values for each AI classes, from left to

right, 1.2<AI<1.4, 1.4<AI<1.6, 1.6<AI<1.8, 1.8<AI<2.0 and 2.0<AI. The vertical error bar and the horizontal line segment indicate a range of data spread of one standard deviation.

**Physical Experiment**

The analysis of the wave records from NNS suggests the following two facts:

1) Wave height distribution does not follow Rayleigh distribution but is better represented by Forristall distribution whose large wave probability is smaller than Rayleigh
2) BFI is uncorrelated with either kurtosis or AI and is not a good indicator for the freak event for ocean waves

These results are somewhat consistent with other observational studies (e.g. Stansell [11]) but disagree with suggestions and evidences from wave tank that BFI is a good indicator for freak wave occurrence (Janssen [12], Onorato et al. [13]). The evidences of the BFI parameterization of the kurtosis and the derived freak wave probability (e.g. Mori and Janssen [14]) are provided only for unidirectional wave system and have been contemplated not to be valid for directional windsea (Socquet-Juglard et al. [15], Onorato et al. [16]). A short introduction to the recent tank experiment conducted at the University of Tokyo, Institute for Industrial Science will be made here since the finding seems to support the two facts from the NNS analyses. A more thorough report is given elsewhere ($9^{th}$ Wave WS, extended abstract Waseda [17]).

Experiment was conducted at a 50m long, 10 m wide, and 5 m deep wave tank equipped with directional wave maker (32 plungers). The directional wave was generated using single summation method which assigns single direction for each frequency component (1024 frequencies were used). This method assures ergodicity (i.e. statistics does not depend on the location) and so suitable when the number of sensor is limited (10 wave wires used). The directional spectrum is of JONSWAP-Mitsuyasu type:

$$S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left\{-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right\} \gamma^{\exp\left\{-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right\}} \quad , \quad G(\theta-\theta_0) = G_n \cos^n(\theta-\theta_0) \qquad (6)$$

and the control parameters were α, γ and n. Significant wave height is closely related to α, the frequency bandwidth to γ and n will alter the directional spread. Among the numerous experiments conducted, we introduce a case with fixed BFI but with variable directionality. For a fixed BFI, the experimental result shows that the value of kurtosis drops significantly with small directional spread (less than 10 degrees). The value of the kurtosis ranges between 3.1 and 3.2 for directional waves (Figure 10). The exceedence probability for cases with small kurtosis (i.e. wider directional spread) showed distribution at high waves less than the Rayleigh distribution. Thus the tendency found in the wave tank experiment agrees quite well with the NNS analyses. This is quite natural since open ocean windseas inevitably have directional spread. Furthermore, it is likely that the directionality changes in time in response to rapidly changing wind field and therefore annuls the small dependency of kurtosis or AI on the BFI. Then the BFI will be totally uncorrelated with those indices. Since we do not have access to directional information of the NNS data, we cannot quantify this point yet.

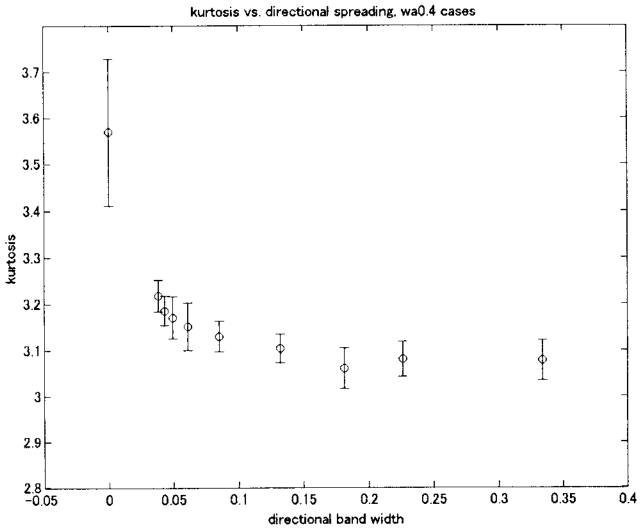


Fig 10 kurtosis vs. directional bandwidth

## Conclusion

We investigated into the actual ocean wave statistics on Yura, Hiratsuka and Kvitebjorn platforms. Long/medium term characteristics of the wave parameters were showed with reference to Freak Waves. Analyses were based upon the sample distribution of maximum wave height in each piece of 20 minutes record by taking N=100 waves in it. Many results were found in particular from the vast amounts of datasets from the Northern North Sea observations. Among them we must mention that:

1. AI is almost uncorrelated with Hs.
2. Rayleigh distribution gives overestimation of wave heights in their extreme region. This result comes from the broad band spectra which are common in the actual ocean.
3. AI is somehow correlated with Kurtosis however this correlation seems superficial.
4. AI is almost uncorrelated with BFI.
5. Mutual correlation between Kurtosis and BFI is very weak. We surmise this is because of 2D crossing of actual ocean waves in a confused storm seaway.

These results 3-5 come from the angular spreading of wave system which is usual in open sea. This is partly confirmed by an experiment of directional wave generation in 2D wave tank.

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