Abstract: This paper presents a search for freaque waves from wave measurement data made in the northeastern coastal water of Taiwan during Typhoon Krosa, October 2007. Not knowing what to expect, we found rather astonishingly that there were more freaque wave types during the build-up of the storm than we ever anticipated. We also developed an empirical wave grouping approach to identify freaque waves from time series wave data, as the conventional approach of defining freaque waves as $H_{max}/H_s>2$ is ineffective to discern all the conspicuous cases.

Introduction

Freaque (freak or rogue) waves were first recognized by Draper (1964) nearly four and one-half decades ago. But it has only been in recent years that the concept of and term freaque (freak or rogue) wave has become common in the media and has been mentioned frequently as a possible cause in a plethora of relevant, semi-relevant, or even irrelevant events. For the ocean wave studies, however, freaque waves remain under-explored beyond a number of theoretical as well as empirical conjectures. We still do not really know where, when, why, and how freaque waves occur in nature. As in many severe storm cases where freaque waves were implicated, we do not even know how to differentiate between a freaque wave and a storm generated wave, or if they can exist simultaneously.

In one of the most tragic shipping disasters, the loss of the bulk carrier *MV Derbyshire* during Typhoon Orchid in September 9, 1980 in Western Pacific south of Japan, all hands (42 crew and two wives) on board perished. There were two official investigations into the possible cause. Perhaps Faulkner (2000) summarized the findings of all those investigations best by his postulate that “a steep elevated abnormal wave probably collapsed the forward hatch covers during Typhoon Orchid.” As one of the appointed assessors who examined all possible loss scenarios along with available underwater survey of the wreckage and laboratory experiments, Faulkner’s finding is certainly irrefutable. The postulate of the cause of a steep abnormal wave, however, while entirely conceivable will remain to be a speculative conjecture unless actual measurement or veracious evidence can be manifested.

There are also other similar disasters in the later part of 20th Century, for instance, the sinking of the *SS Edmund Fitzgerald* during a gale storm in eastern Lake Superior on November 10, 1975 with 29 crew members onboard (NTSB, 1978); and the wreck of the semi-submersible, offshore rig *Ocean Ranger* during a storm linked to a major Atlantic
cyclone while drilling in the Grand Banks area on the North American continental shelf on February 15, 1982 with 84 crew members onboard (Royal Commission, 1984). In both cases they seemed to have happened suddenly, there were no survivors, and thus there is speculation that they were overwhelmed by the force of a freaque wave.

Are there freaque waves during a hurricane, typhoon, or severe storm? In this paper we expect to answer this question by using wave measurements made in the northeastern coastal waters of Taiwan during the Typhoon Krosa in October 2007.

The Typhoon Krosa

In the early days of October 2007, a tropical depression that originated east of the Philippines in the Western Pacific Ocean, rapidly intensified to become Typhoon Krosa. It was later upgraded to a Category 4-equivalent super typhoon as it advanced northwestward toward Taiwan. Its track momentarily hovered and made a small loop back out to sea over the northeastern coastal waters of Taiwan before making landfall on October 6, 2007 (Figure 1). There were several moored buoys deployed around Taiwan where wave conditions during Krosa were summarily recorded. In particular, the buoy located at longitude 121°55’30”E and latitude 24°50’57”N in 38 m water depth recorded a very large trough to crest maximum wave height of 32.3 m, which could be the highest known $H_{max}$ ever recorded (Liu, et al. 2008). The buoy was located near the small Gueishantao Island (Figure 5), 12 km offshore of the northeast coast town of Suao, which was located close to the center of Krosa.

![Figure 1. Typhoon Krosa approaching Taiwan.](image)
Figures 2 gives the detailed track and the corresponding central pressure record of the Typhoon Krosa as given in the web site http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/s/200715.html.en. It is shown that Krosa followed a fairly steady northwestern path toward northeast Taiwan, while the central pressure deepened as wind intensity gradually strengthened to 70 m/s (140 kt) just before making landfall on October 6, 2007.

**The wave measurement**

The Central Weather Bureau (CWB) of Taiwan has been constantly developing, deploying, and maintaining moored 2.5 meter circular discus hull foam buoys (Figure 3) in the coastal waters around Taiwan Island for meteorological and marine measurements including ocean wave measurement since 1997. The buoys were designed for reliable operations, with wave following characteristics, and are lightweight for convenient and safe land and sea transportability. Currently there are nine buoys in operation, all are equipped with heave, pitch, and roll accelerometers sampled at 2 Hz frequency for 10 minutes duration each hour. In this paper we are concentrating on the one buoy located at longitude 121°55’30”E, and latitude 24°50’57”N in 38 m water depth in the lee of the small offshore Gueishantao Island (Figure 4). The buoy is located 12 km offshore of the
northeast coast of Taiwan, which was closest to the center path of Typhoon Krosa prior to its landfall. The wave conditions during the onward movement of Krosa at this buoy location, as represented by the ocean surface fluctuations inferred from the recorded heave displacements, are used in this paper in search of possible occurrences of freaque waves during the passage of the typhoon.

Figure 3. A deployed CWB Buoy.

Figure 4. The buoy location near Gueishantao off the northeast coast of Taiwan.
The portrait of a freaque wave

What are freaque waves and how do we identify them? These seemingly, simple-minded questions are still lacking unified, clear-cut answers. Currently, information is limited to descriptions of the waves at best. It is usually described or displayed as one singular, unexpected wave profile characterized by an extraordinarily large and steep trough or crest over the others in the field. Freaque waves were not being regarded as part of the ocean wave process during most of the second half of the 20th Century, while vigorous growth in ocean wind wave research endeavors were flourishing. All the currently available wave measurements, as well as the conventional wave measurement systems, have been based on and primarily designed for ocean waves that are presumed to be from a stationary Gaussian random process that basically negates the existence of the kind of freaque waves we are considering. But that does not necessarily mean freaque waves have never been measured. The well-known North Sea freaque wave records of Gorm field (Sand et al., 1990) and Draupner platform (Haver, 2004) were both discovered from conventional wave measurements. The wave profile from the Draupner platform, as shown in the upper left panel of Figure 5, has been widely recognized and generally identified as the exemplary depiction of a freaque wave. Since it is also generally construed that freaque waves can happen any time and in any part of the world’s oceans, there must be more Gorm/Draupner-like freaque waves being recorded but that simply have not been discovered or noticed.

The time series plot of the ocean surface fluctuation shown in the upper left panel of Figure 5 is widely considered as the portrait of a freaque wave, also known as the Draupner freaque wave. We see that it clearly does not fit the conventional conceptualization that expects the ocean surface as a Gaussian random process. This is shown by the discord in the cumulative distribution between the Gaussian process and the Draupner data on the upper right panel of Figure 5, especially at the high end. In contrast, measurement at the same sensor one hour later, as shown in the two bottom panels, displays a more customary time series plot and a nearly accordant Gaussian cumulative distribution.
As the discovery and recognition of the Draupner freaque wave time series shown above was basically through visual means, other generally objective approaches of recognizing freaque waves have also been employed. One frequently used approach is to examine the ratio $H_{\text{max}} / H_s$, the maximum wave height, $H_{\text{max}}$ in the time series to the significant wave height, $H_s$, which we feel should be more appropriately called the standard deviation wave height since it is given by $4\times$standard deviation in the data. For the Gaussian random process, the zero-upcrossing or zero-downcrossing wave heights usually follow a Rayleigh distribution where statistically $H_{\text{max}}$ should be at most twice the $H_s$, thus it is frequently thought that cases with $H_{\text{max}} / H_s > 2$ are freaque waves. One of the well-known equations that correlates $H_{\text{max}} / H_s$ with the number of zero-upcrossing or zero-downcrossing waves needed in the data for it to occur is

$$H_{\text{max}} / H_s = \left[\ln(N)/2\right]^{1/2}$$

(1)

where $N$ is the number of waves encountered in the data.

Another minor approach that has only been used for reference purposes is to check into the kurtosis of the data set. The kurtosis for a perfect Gaussian process is 3. Larger kurtosis values signify a greater departure from Gaussian. As shown in Figure 6, the Draupner freaque wave has a kurtosis of 4.0648, but an hour later, without the freaque wave, the kurtosis is 3.2842.
In search of freaque waves during Krosa

We started by visually examining the wave time series data recorded at Gueishantao buoy during the build up of Typhoon Krosa prior to landfall on Taiwan, October 3 – 6, 2007. We looked at each data set during this period for Draupner-like cases and are rather astonished to have found more cases than we ever expected. The results are shown in Figure 6 where the vertical red bars denote the cases that were visually recognized cases, and two samples of the Draupner-like freaque wave time series plots and their corresponding test of Gaussian probability distributions, similar to Figure 5, are shown in the Figure 7.

Figure 6. Time history of wave heights during Typhoon Krosa. For the three digit numbers on the abscissa, the first number is the day of October and the next two digits give the corresponding hour. The red vertical bars denote where freaques waves might have occurred.
This part of the exercise is necessarily intuitive and subjective. Not all cases are as dramatically pronounced as the Draupner case. They are, in our visualization, at least potential freaque wave cases. With a few exceptions, their corresponding urtosis and their departure from Gaussian distribution tend to sustain our subjective visual choice. Clearly visual picks tend to find more cases than the conventional indicators. But who is in position to quibble which one really is or is not a true freaque wave when we don’t even have a tangible definition for it yet?

**Circumscribing freaque wave cases**

We proceed next to examine conventional approaches to circumscribe freaque waves. As alluded earlier the widely used approach is the use of the ratio of maximum wave height versus significant wave height in a given time series wave data. Based on the assumption of Gaussian and Rayleigh distribution theories, a ratio larger than 2 is generally regarded as possibly a freaque wave case. However, some ambiguity is implicated with this approach. One is that the size of time series data has never been specified. Different time length of data invariably leads to different results. The other is that the significant wave height, usually defined as the average of the highest one third wave heights in the data, has been mostly represented by four times the standard deviation in the data – again
a result of the assumption of Gaussian and Rayleigh distributions. The significant wave height, $H_{1/3}$, and the standard deviation wave height, $H_s$, are not always the same as we see in Figure 8 here. The North Sea data, represented by the points labeled as ns1520 and ns1620, show that $H_{\text{max}}/H_s$ and $H_{\text{max}}/H_{1/3}$ are basically close. But the Gueishantao data show that $H_{\text{max}}/H_s$ tend to underestimate $H_{\text{max}}/H_{1/3}$ by about 15 percent. This is possibly because The Draupner platform is in the deep North Sea, whereas Gueishantao buoy is more in the nearshore area which could be affected by shoaling effects. As a result, we see that there are 3 cases of $H_{\text{max}}/H_s$ greater than 2, whereas 6 cases of $H_{\text{max}}/H_{1/3}$ greater than 2. But our visually picked freaque wave cases seem to be indifference to the demarcation nevertheless, as there are plenty of cases show freaque wave occurrences with either ratios below 2 as shown by the data points of freaque wave cases enclosed by red circle in Figure 8.

Figure 8. Correlation of the ratios of $H_{\text{max}}/H_s$ with $H_{\text{max}}/H_{1/3}$. The blue line represents the 1:1 perfect fit. The red line is a best eyeball fit, 0.85:1 in this case. The points with a red circle around are the visually picked freaque wave cases.

We have also examined the data in connection with equation (1) discussed earlier that shown the theoretical relation between the ratio of wave heights and the number of trough-to-crest wave heights in the data. It is of interest and may even be comforting to note that the measured data fit the theoretical relation reasonably well for the most part. With one or two exceptions most of the identified freaque wave cases are clearly not part of the theoretical curve as expected. It is encouraging to see that while Gaussian and Rayleigh distributions can be useful in general but they are just not capable of representing cases when freaque waves are present. Furthermore, we found when $H_{1/3}$ and $H_s$ are not comparable, $H_{1/3}$, rather than $H_s$, should be used in the analysis.
A new freaque index

To further devise a viable approach to justify our subjective visual identification of freaque waves from the available data, we constructed a simple new empirical freaque wave index based on examining groupings of 18 consecutive waves. This is a purely empirical venture, we have not yet been able to put it in analytical form. The idea stems from the popularly fabled notion that every 7th wave is the highest. We generalize it into the consideration of a group of 18 consecutive wave heights. Clearly a freaque wave, being considered as unusually larger than those in its proximity both in time and space, should be rising up from one of these groups. Thus for every 1024 data point time series in the Typhoon Krosa wave data set, we looked at every group of 18 consecutive zero-crossing wave heights in the time series, and calculated the ratio of maximum to mean wave heights among them in each group. The highest of all these calculated ratios is the group index for 18 waves in that time series. The results are presented in Figure 10. It was through intuition and trial and error that led us to the size of 18 waves and a demarcation of 2.95, plotted as the middle red line in Figure 9, as best substantiated our visual picks. As shown in Figure 9 it is likely any time series data with a freaque index over 2.95 will contain a freaque wave.

![Image of calculated freaque index](image)

Figure 9  Calculated freaque index corresponding to the data shown in Figure 7.
As an independent corroboration, we calculated the freaque index for the North Sea Draupner data sets shown in Figure 10 as respective horizontal lines. The widely recognized freaque wave case occurred at hour 1520, January 1, 1995 that data produced a freaque index 3.9 shown as the top ns1520 line, whereas the hour 1620 case without a freaque wave produced a freaque index of 2.7, shown by the lower ns1620 line. Both fit our postulated criteria well. We are reasonably confident that this new freaque index will emerge as a viable, encompassing index for searching and exploring freaque waves.

Concluding remarks

Without any preconceived notion regarding whether or not freaque waves can occur during a typhoon or hurricane, we are surprised and encouraged that we are able to positively ascertain that their occurrences are clearly manifested. Although at this stage we are not certain that our findings can be generalized to all typhoons or hurricanes, we feel that it is quite possible that MV Derbyshire might have encountered an abnormal freaque wave during the 1980 Typhoon Orchid before their demise.

How often that freaque waves occur is still a question that has yet to be satisfactorily answered. A widely reported news item regarding a brief three-week radar satellite study carried out by the German Aerospace Centre in 2003 in which they found 10 monster waves around the world, ranging from 26 m to 30 m in height and concluded that “it looks as if freaque waves occur in the deep ocean far more frequently than the traditional linear model would predict.” Liu and Pinho (2004) studied wave measurements made from Campos Basin off the Brazil coast in South Atlantic Ocean also concluded that freaque waves are “more frequent than rare.” The Liu and Pinho study was based on cases that fulfill $H_{max} / H_s > 2$. Now that we have also found freaque wave cases for $H_{max} / H_s$ less than 2, we can certainly expect that what we are now considering as freaque waves may just be an integral part of the ocean surface process.

So in the midst of still more uncertainties along with more results for each new study, we wish to echo the recent call by Liu et al. (2008) for the need for more concerted wave measurements throughout the world’s oceans since “Without tangible measurements, no amount of modeling or theoretical simulations can truly divulge the reality of what is really happening during the passing of a typhoon or hurricane.”

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References


