

## ON THE CHARACTERISTICS OF OBSERVED COASTAL FREAK WAVES

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The purpose of this study is to describe the characteristics of occurrence of coastal freak waves and to investigate their statistical and spectral structures. According to Ochi's definition of freak wave, 175 coastal freak waves were obtained from a long-term full scale wave data bank, in which there are more than 4500 wave records. The probability distribution of occurrence of coastal freak waves was investigated. The goodness-of-fit testing shows that the Rayleigh distribution is more appropriate for describing the occurrence probability of coastal freak waves when the ratio of its wave height to the corresponding significant wave height is more than 2.4. However, the occurrence probability of coastal freak waves remains below the Rayleigh distribution. The relationship between coastal freak waves and the related sea states shows that the occurrence possibility of coastal freak waves may significantly increase in the sea of grouping waves or in the wave field of bimodal spectra. Wavelet Transform was applied to the *in situ* wave records to investigate the energy distribution on the time-frequency domain. It justified the previous conclusions and demonstrated that the wave groups and superposition of the swell and wind wave energy, which occupies 70% of the coastal freak samples, play major roles of inducing the coastal freak waves.

*Keywords:* Extreme waves; freak waves; field observation; wavelet transform analysis.

### 1. Introduction

Taiwan, which is located at the rim between Asian continent and Pacific Ocean, is a small island with a dense population of 23 million residents. The main island of Taiwan, slightly smaller than the Netherlands, is about 36 thousand square kilometres in area. However, more than two-third of this island is covered by rugged and towering mountains, only an estimated 30% of the area of Taiwan is arable. The dramatic growth of land demands for habitation, recreational and economic

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activities occurred over the past decades in Taiwan. Under the increasing pressure of meeting the vacancy craving, coastal zones around Taiwan were reclaimed and being utilized, which exacerbated the collisions between human and nature, such as the frequently occurred coastal disasters.

Among all coastal disasters, the event of coastal freak waves is one of the frequent and serious hazards around Taiwan coast. This kind of waves occur suddenly from the rather relatively calm neighbourhood without any advance warnings. Act as mantraps, the coastal freak waves often cause lives to be lost by abruptly engulfing people into the sea, even when one is on the seashore regions such as breakwaters, shore rocks or beaches. Furthermore, it was reported that vessels had been attacked and destroyed as well. The highly unpredictable nature makes them well known by the Taiwanese fishermen as “rabid-dog waves”.

According to the historical “rabid-dog waves” events, 140 eyewitness reports have been retrieved from the Taiwanese newspapers from 1949 to 1999. Relevant reports show that more than 496 people lost their lives and more than 35 crafts were capsized in the past 50 years due to the nearshore freak waves. The statistics of the occurrence locations and time demonstrated significant regional and seasonal variability, still events of “rabid-dog waves” occurred everywhere around the coastal line of Taiwan. Being one of the most dangerous threats of coastal activities in Taiwan area, they endangered the population more than the tsunami or shark attack.

To mitigate this kind of hazard, it is important to investigate the causes of coastal freak waves to achieve a better understanding. In this present study, long term full-scale observed wave data are analyzed. It is the aim to describe the statistical structure of the occurrence of coastal freak waves and to investigate the characteristics of them.

There are few studies on coastal freak waves; herein the scope of relevant literature review has been extended to previous studies on freak waves and extreme waves. Previous studies suggested the causes of freak waves or extreme waves could be categorized into four types (Dysthe, 2000). The first type can be regarded as the extreme values of the tail of statistical probability distribution. The second type is due to the interaction between the waves and current. The third one is due to the wave-wave non-linear interaction and the last type is due to the superposition of waves of different frequency components. Waves of the first type were often named as “Extreme Waves”, while waves of other types were more referred to “Freak Waves”.

Concerning the previous studies by statistical approach, Kimura & Ohta (1994) derived the occurrence probability of freak waves to be  $1/3600$ . Sand *et al.* (1990) had collected a few records of extreme waves in the coast of Denmark, and proposed that the probability distribution of the wave heights, which consisted of extreme waves satisfy the modified Rayleigh distribution with positive skewness. Wolfram *et al.* (2000) applied probability analysis to the waves recorded in the North Sea between 1994 and 1998. It concluded that the rogue waves were 50%

steeper than the significant steepness. Magnusson *et al.* (1999) demonstrated from the statistical analysis of field data from buoy measurements in the North Sea that the occurrence probability is somewhat less than the prediction of statistical model.

The interaction of waves and current has been recognized as one of the mechanisms of the occurrence of freak waves in some area, such as the south-east coast of South Africa (Agulhas current) as well as the Kuroshio area in the south of Japan. The blockage, which took place when the waves propagate in the opposite direction to the current, will concentrate the wave energy in some caustic location and induce freak waves. On the other hand, in the cases of waves propagating in the direction perpendicular to the current, the non-homogeneous current may deflect the wave and concentrate the wave energy (Smith, 1976; White and Fornberg, 1998).

Concerning the third type, the wave-wave non-linear interaction of narrow-band waves could be another mechanism of causing freak waves. Relevant studies, which were originated by Peregrine (1985), mainly focused on the numerical computation of Non-linear Schrodinger Equation (NSL) (Peregrine, 1985; Dole *et al.*, 1986 and Henderson *et al.*, 1999). Hung (1985) also discussed the resonance effect, which is due to the non-linear wave-wave interaction of the waves of arbitrary wave length and propagation directions. It was pointed out that huge waves might occur due to the resonance effect. Sand (1990) and Yasuda *et al.* (1992, 1994) had tried to simulate the extreme waves. The results showed that the non-linear wave-wave interaction might be one of the mechanisms of causing the extreme waves. Dean (1990) approved with their viewpoint. The last type of extreme wave mechanisms can be divided into (1) the superposition of waves propagating in different directions; and (2) the coalescence of waves that propagate in the same direction. A numerical model of Korteweg-de Vries (KdV) equations was utilized by Pelinovsky *et al.* (2000) to simulate the coalescence.

Some other related studies focused on the case study of extreme wave events. Thieke *et al.* (1992) discussed the mechanism of an event that occurred at Daytona Beach in Florida in 1992. Continuous energy transfer to waves from storms, which moved in proximate speed with wave celerity, may be the cause of the event. After interviewing survivors of the hazardous extreme waves disasters, Chen (1999) described the phenomenon of the occurrence of extreme wave.

To sum up, the possible causes of freak waves might be categorized as the following two types:

- (a) Due to the impacts of environmental changes such as
  - (1) continuous energy transfers from the moving storm to waves;
  - (2) wave transformation due to humpy bottom;
  - (3) interactions between waves and currents;
  - (4) wave energy concentration due to deflections, reflections and inflections; and which are caused by bathymetric change.

- (b) Due to the wave-wave interaction:
- (1) linear energy superposition; and
  - (2) nonlinear wave-wave interaction.

Some of them may be the inducing conditions of coastal freak waves and will be discussed in this study.

In the present study, *in situ* wave records, selected from a long-term field observation and satisfied the definition of coastal freak wave, were analyzed and discussed from both time and frequency domains. Firstly, the goodness-of-fit testing was applied to the comparison between probability distribution of coastal freak waves and different hypothesized distributions to have an appropriate probability distribution on describing the occurrence of coastal freak waves. Secondly, the probability of occurrence of coastal freak waves was then discussed together with different wave parameters to investigate the relationship between coastal freak waves and related sea states. Finally, Wavelet Transform was applied to the selected wave records to investigate the mechanisms of coastal freak waves.

## 2. Data Acquisition and Selection

The coastal ocean monitoring network around Taiwan was set up in 1996. The network consists of 6 data buoy stations, 3 pile stations and 4 underwater acoustic stations. The field data were observed from Cheng-Kung wave stations, which is located in the Pacific Ocean off the eastern coast of Taiwan as illustrated in Fig. 1. The station, at a water depth of 43 m, equipped with an under-water acoustic wave gauge. The signal that sent by the up ward looking wave gauge reflects when it propagates through the media with different density. The time that required for the signal transmitting from the gauge to the water surface serves to locate the elevation. Time series of water elevation was obtained directly from the gauge and stored in the data acquisition unit in a nearby shore station. The measurements were carried out 58 minutes every single hour. The sampling rate was set to 5 Hz.

A whole year *in situ* wave data of 1996 were selected for analysis. A prerequisite to the analysis is an assessment of quality control criteria of data records, one of which is to check the vertical acceleration. If the vertical acceleration of water particles in wave orbital motion, derived by taking double differential of the water elevation, exceeds the gravitational acceleration, the data was regarded as false data. 4565 records were then selected at last. Each record contains water elevation of 58 minutes in an hour. Totally, more than two million waves were analyzed in the present study.

The terms “rabid-dog waves” or “freak waves” are used to express unusual high single wave. However, a common recognition of the definition may not have been established yet. The definitions of freak waves are somewhat obscure since neither the cause of the occurrence nor the phenomena of the freak waves have been clarified. Chen (1999) interviewed eyewitness to lethal coastal freak waves and quoted their

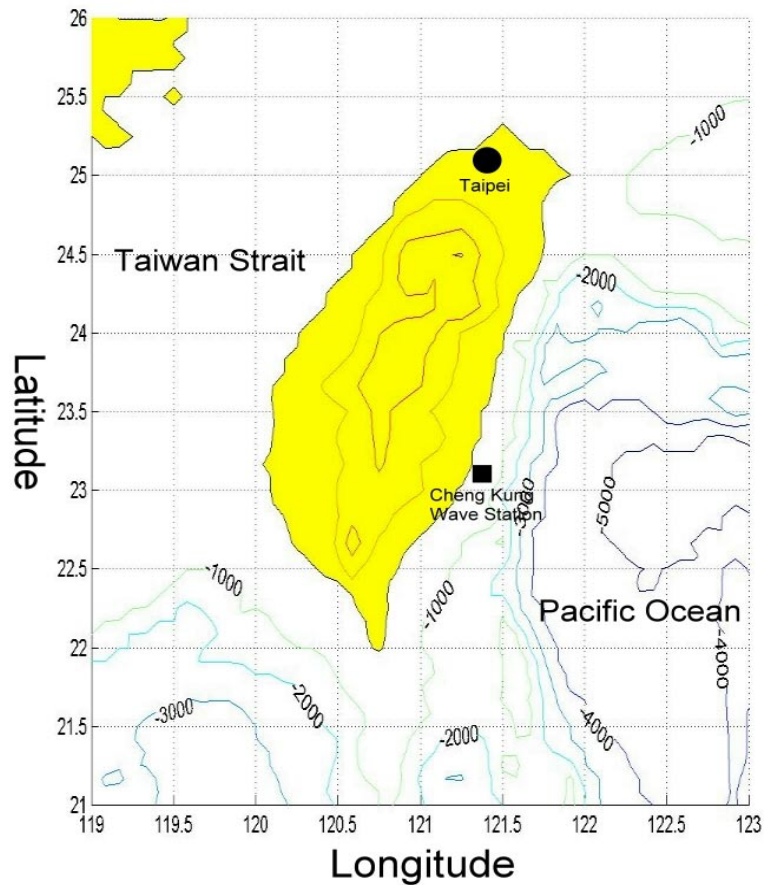


Fig. 1. The location of Cheng-Kung wave station.

statements of the freak wave: “It is a mammoth short crested wave with apparently little relation to the average and neighbouring waves. It comes with a wall-like high crest but not necessarily a corresponding pronounced trough”. Coincide with the description above, Kliting and Sand (1987) defined the freak wave as:

- (1) It is twice higher than the significant wave height.
- (2) It is twice larger than the fore-going and the following wave heights.
- (3) Its wave crest is larger than 65% of its wave height.

Besides, Kjeldsen (1993) defined a freak wave, when the measured wave height  $H$  exceeds twice the significant wave height and simultaneously is larger than 10.0 m. The use of Kjeldsen’s definition was recommended by the IAHR/PIANC for statistical interpretation of real sea state as well. In present study, due to the limited number of the large wave records ( $H_S > 10.0$  m) in Cheng-Kung area, the waves that satisfy the following conditions are selected for analysis:

- (1) All waves exceeding twice the significant wave height.
- (2) The wave height is larger than 2.0 m.

The adoptive definition in the present study enables sufficient data population for statistical and spectral analysis to be obtained. Consequently, 175 isolated coastal freak waves were retrieved according to the definition.

### 3. Probability of Occurrence of Coastal Freak Waves

#### 3.1. Probability structure of coastal freak waves

In the past thirty years, US and European oil companies had installed numerous oil/gas platforms from nearshore to offshore zones. Two most active zones are the North Sea and Gulf of Mexico. Since these offshore platforms are frequently subjected to high wind and large waves, works of wave measurements and statistical analysis of extreme waves were done from 1970 to 1990. According to the long-term field studies of the water surface elevation, there are several publications that deal with the statistical evaluation of irregular sea states in specific locations (e.g. Kjeldsen, 1984; Nickerson, 1993; Rozario *et al.*, 1993; Yasuda *et al.*, 1997).

In the present study, the field observed coastal data is analyzed to investigate the statistical distribution. Rayleigh extreme distribution and envelope concept probability models are utilized to predict the occurrence probability and then compared with the field measurements. Previous studies have already proved that the mean maximum wave height is highly related to the probability distribution of wave heights. If the distribution for the zero-crossing deep-water irregular waves agrees well with the Rayleigh distribution, the mean maximum wave height can be derived by the equation (e.g. Isaacson *et al.*, 1981):

$$(\bar{H}_{\max})/H_{1/3} = \frac{1}{\sqrt{2}} \left( (\ln N_0)^{1/2} + \frac{\gamma}{2} (\ln N_0)^{1/2} - \frac{\pi^2 + 6\gamma^2}{48(\ln N)^{3/2}} \right) \quad (1)$$

in which,  $N_0$  is the number of waves,  $\gamma$  is the Euler constant, which equals to 0.5772. Goda (1985) reported the measured wave data show slightly larger occurrence probability than the Rayleigh distribution in the tail part of the distribution. Yasuda *et al.* (1992) showed the non-linearity brings nearly no significant difference on the wave height distribution when the waves are fully developed. However, the goodness of fitting of the data and the distribution model in the part of large  $\bar{H}_{\max}/H_{1/3}$  of wave height has not been sufficiently investigated yet.

The estimation of the mean maximum wave height mentioned above was derived theoretically as a probability distribution of wave amplitude in the case of narrow banded spectrum with a constant frequency and the magnitude of the wave height varies slowly with time. However, it may be questionable to estimate the freak wave height by the Rayleigh extreme distribution due to the fact that typical freak wave is characterized as a single and steep extreme wave, which is quite different from

the waves under a narrow banded Gaussian process. In fact, Kimura & Ohta (1994) tried to derive the probability distribution of the wave height on the basis of its definition of zero-crossing wave height. The results showed considerable difference from the Rayleigh distribution when the wave spectrum is wide.

Based on the concept of the envelope process, numerous studies on the probabilistic analysis of random waves have been carried out. Nolte and Hsu (1972) have developed a method to evaluate the statistical properties of group waves and proposed a distribution to describe the probability distribution of wave height. The mean maximum wave height can be estimated accordingly by the following equation:

$$\frac{\bar{H}_{\max}}{H_{1/3}} \approx 0.682(\ln N_0)^{0.468} \left[ 1 + \frac{\gamma}{2.138 \ln N_0} \right] \quad (2)$$

The agreements of the wave height distributions that obtained from above theories and the field data were not comprehensively examined especially for the parts when the wave heights are larger than twice the mean wave height. In order to realize the occurrence probability of coastal freak waves, this section aims at investigating the wave height distribution in very large part.

Figure 2 demonstrates the occurrence probability that is obtained from the field data analysis and the estimations according to Eqs. (1) and (2). The goodness-of-fit test by Chi-square test shows that the measured data could be considered to be Gaussian random process at the 5% level of significance. From the results, it can be found that the envelope concept contributes well to estimate the occurrence probability of coastal freak waves when  $H_{\max}/H_{1/3} < 2.4$ . As the value of  $H_{\max}/H_{1/3}$  gets to exceed 2.4 and further increases, the tendency is revealed that occurrence probability is better described by Rayleigh extreme distribution. Nevertheless, the Rayleigh extreme distribution still over estimates the occurrence

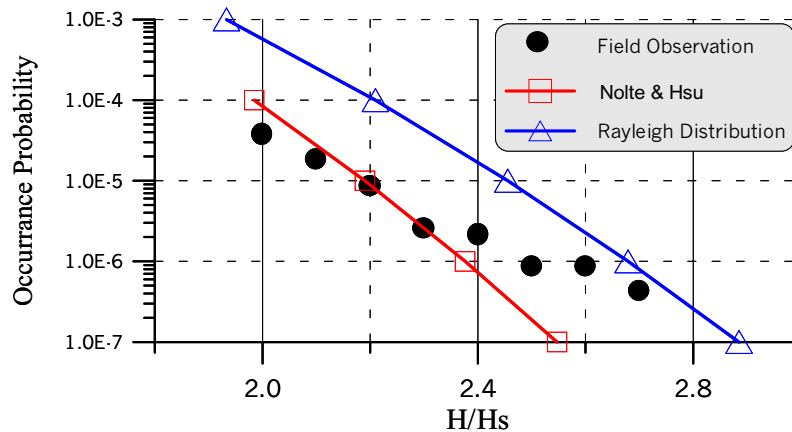


Fig. 2. The occurrence probability of field measured nearshore freak waves and the comparison of it with the estimations of Rayleigh and Nolte & Hsu (1972) distributions.

probability of coastal freak waves. The present conclusion is coincident with the statistical properties of the data measured in Japan Sea by Yasuda *et al.* (1997).

### 3.2. The relationship between occurrence probability and sea states

Instead of a constant value, the occurrence probability of coastal freak waves varies seasonally. From the results of statistical analysis of field data, a statistically significant difference of the mean occurrence probabilities of coastal freak waves in the winter and summer season could be identified. The occurrence probability is larger in the winter than in summer. This seasonal dependence indicates the existence of the relationship between the probability and the sea states. It is of great interests to demonstrate whether the probability could be a function of sea states such as wave profile, spectral shapes, wave groupiness, non-linearity or other wave properties.

In this section, the 4565 full scaled field data were categorized according to the above mentioned sea states. The significant wave height and the wave steepness are used to represent the profile of the waves. Spectral peakedness parameter is used to describe the shape of the unimodal spectrum. The probability of the existence of bimodal spectrum is also discussed. Groupiness Factor ( $GF$ ) is used to represent the characteristics of wave grouping. Bicoherence parameter ( $b^2$ ) is used to represent the non-linearity involved in the wave spectrum in order to evaluate the statistical properties of waves in finite water depth. The definitions of those parameters are listed as follows:

$$\text{wave steepness} = H_{1/3}/L \quad (3)$$

where  $L$  is wave length calculated from measured  $T_{1/3}$  according to linear dispersion relationship. Spectral peakedness parameter proposed by Goda (1985) is defined as

$$Q_p = \frac{\int_0^\infty f[S(f)]^2 df}{(\int_0^\infty S(f) df)^2} \quad (4)$$

Goda (1985) showed that the larger value of  $Q_p$ , the narrower is the spectrum shape. The normalized bicoherence is defined as:

$$b^2(f_i, f_j) = \frac{|B(f_i, f_j)|^2}{E[|X(f_i)X(f_j)|^2]E[|X(f_{i+j})|^2]} \quad (5)$$

in which,  $B(f_i, f_j)$  is the bispectrum,  $X(f)$  is the Fourier transform of the water elevation  $\eta(t)$ . The value of bicoherence ranges from 0 to 1. The larger the value, the stronger non-linearity of the waves is. The definition of the Groupiness Factor is:

$$GF = \sqrt{\frac{1}{T} \int_0^T [E(t) - m_0]^2 dt / m_0} \quad (6)$$

where  $E(t) = \frac{1}{T_p} \int_{-T_p/2}^{T_p/2} \eta^2(t + \tau) d\tau$ .



To grasp the 4565 data picture, it is the first step to group the data into classes. The class interval was selected according to Sturges' formula:

$$M = 1 + 3.3 \log n \tag{7}$$

where  $M$  is the number of classes,  $n$  is the number of coastal freak waves and the logarithm to the base 10 is used.

The occurrence probabilities of coastal freak waves are estimated by the ratio of occurrence number of coastal freak waves to total wave number in each interval. Figure 3(a) is the diagram of occurrence probability via significant wave

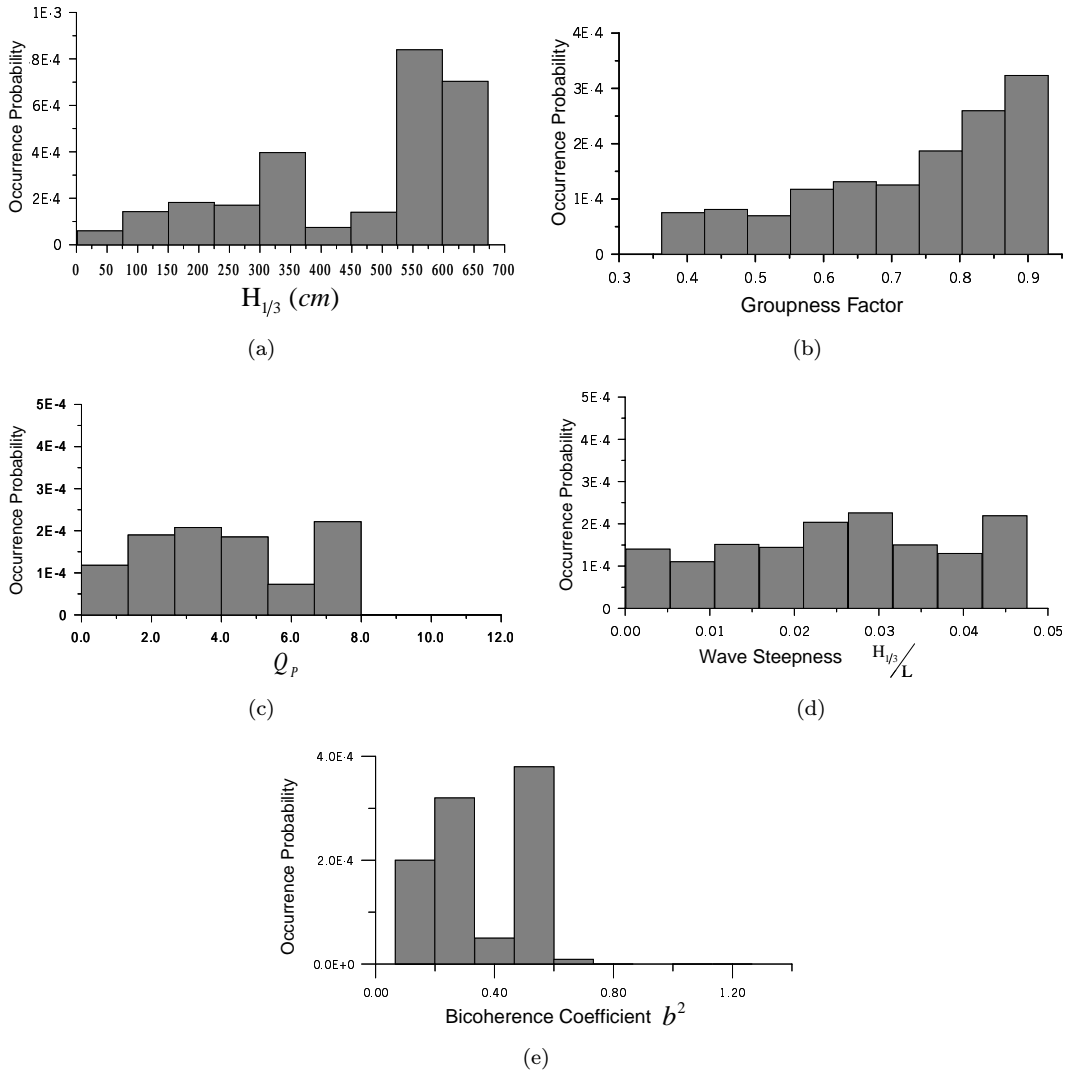
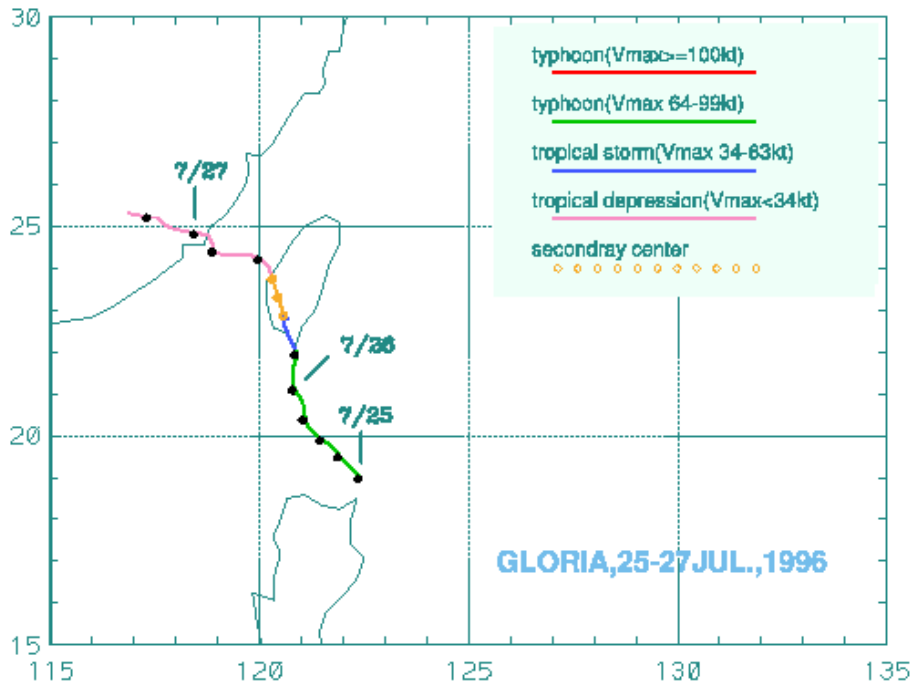
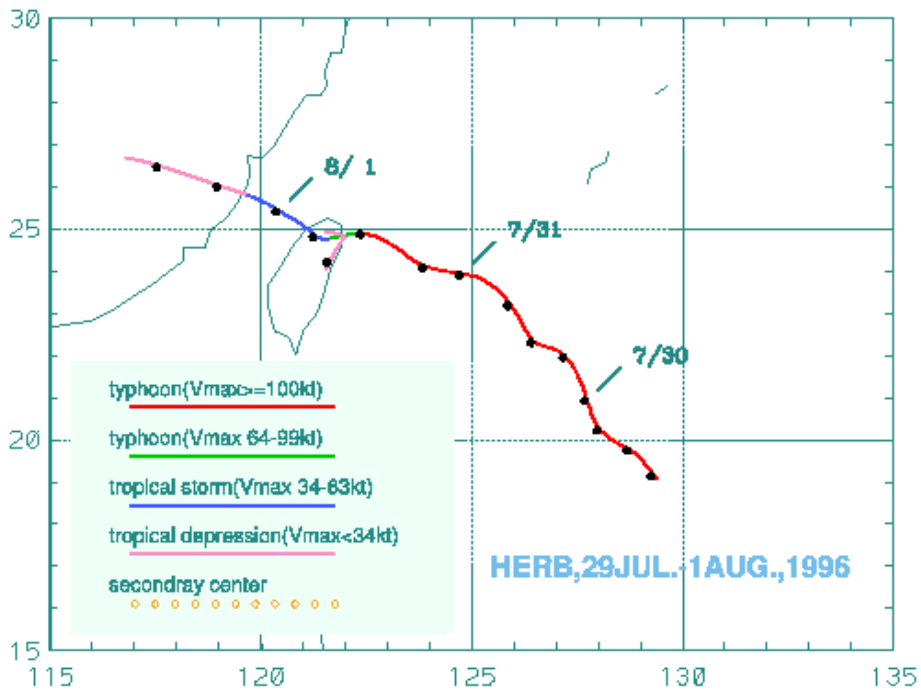


Fig. 3. The occurrence probability of field measured coastal freak waves via different sea state conditions: (a) Significant wave height; (b) Groupiness factor; (c) Spectral peakedness parameter  $Q_p$ ; (d) Wave steepness; (e) Nonlinear bicoherence coefficient  $b^2$ .



(a)



(b)

Fig. 4. The paths of typhoon Gloria (a) and Herb (b).

height. It demonstrates independent relationship between the occurrence probabilities with the wave heights less than 525 cm. However, quite large probability for  $H_{1/3} > 525$  cm is identified. A question arises that are there different mechanisms distinguishing those high freak waves from the others? The field station locates in the eastern coast, which was attacked by 5 typhoons in 1996, the influence of typhoon waves and swells from the western Pacific Ocean might not be ignored. It is revealed by examining the data that all of the high waves were occurred and observed during typhoon Gloria (25–27 July, 1996) and Herb (29 July–1 August, 1996). The paths of typhoon Gloria and Herb are illustrated in Fig. 4. In fact, most of the sever sea states in Cheng-Kung area are dominated by typhoon waves. The fact indicates that wave height itself might not be responsible for the occurrence of coastal freak waves, but yet the typhoon affected waves may play important role.

Figure 3(b) is the occurrence probability of coastal freak waves via Groupiness factor. It shows a very clear tendency. The GF of the field data collected at Cheng-Kung area ranges from 0.25 to 0.95. The occurrence probability increases rapidly with the increasing GF value. It demonstrates the strong relationship between wave groups and the occurrence of coastal freak waves. To clarify whether the highly grouping waves are also influenced by the typhoons, analysis of the waves observed during typhoon Gloria and Herb were carried out. Figure 5 is the diagram of examples of the water level records when freak waves occurred. These water elevation time series were measured during the typhoon Gloria from July 26, 1996 0000UTC to 0300UTC. It is obvious that the wave groups account for the occurrence of coastal freak waves in these cases. Considering the effect of typhoon induced sever sea, which is mentioned previously, the typhoon waves pronounce huger and stronger wave grouping nature when the typhoon eyes were approaching the station in these cases. However, it is still inconclusive to interrelate the occurrence of coastal freak waves with typhoons due to the fact that measurable portion (39 of the 93 records) of highly grouping waves ( $GF > 0.7$ ) freak waves occurred during monsoons.

On the other hand, previous studies have shown that the non-linear interaction might be one of mechanisms of coastal freak waves. Figure 3(e) shows that coastal freak waves rarely occur in the sea states of high non-linearity. Considering the wave amplitudes of the data, the 43 m water depth could be regarded as deep water and hence the bottom effect does not contribute to nonlinear wave-wave interaction. To assess the role that resonance play, further investigations are needed to evaluate this phenomenon. Figures 3(c) and (d) show no significant trends exist of the occurrence probability via wave steepness or spectral peakedness, respectively.

Concerning the spectral shape of the records of coastal freak waves, it was found during the  $Qp$  value analyzing process that there were more bimodal spectra than normal cases in a certain degree. The definitions of bimodal or multi-modal spectrum are:

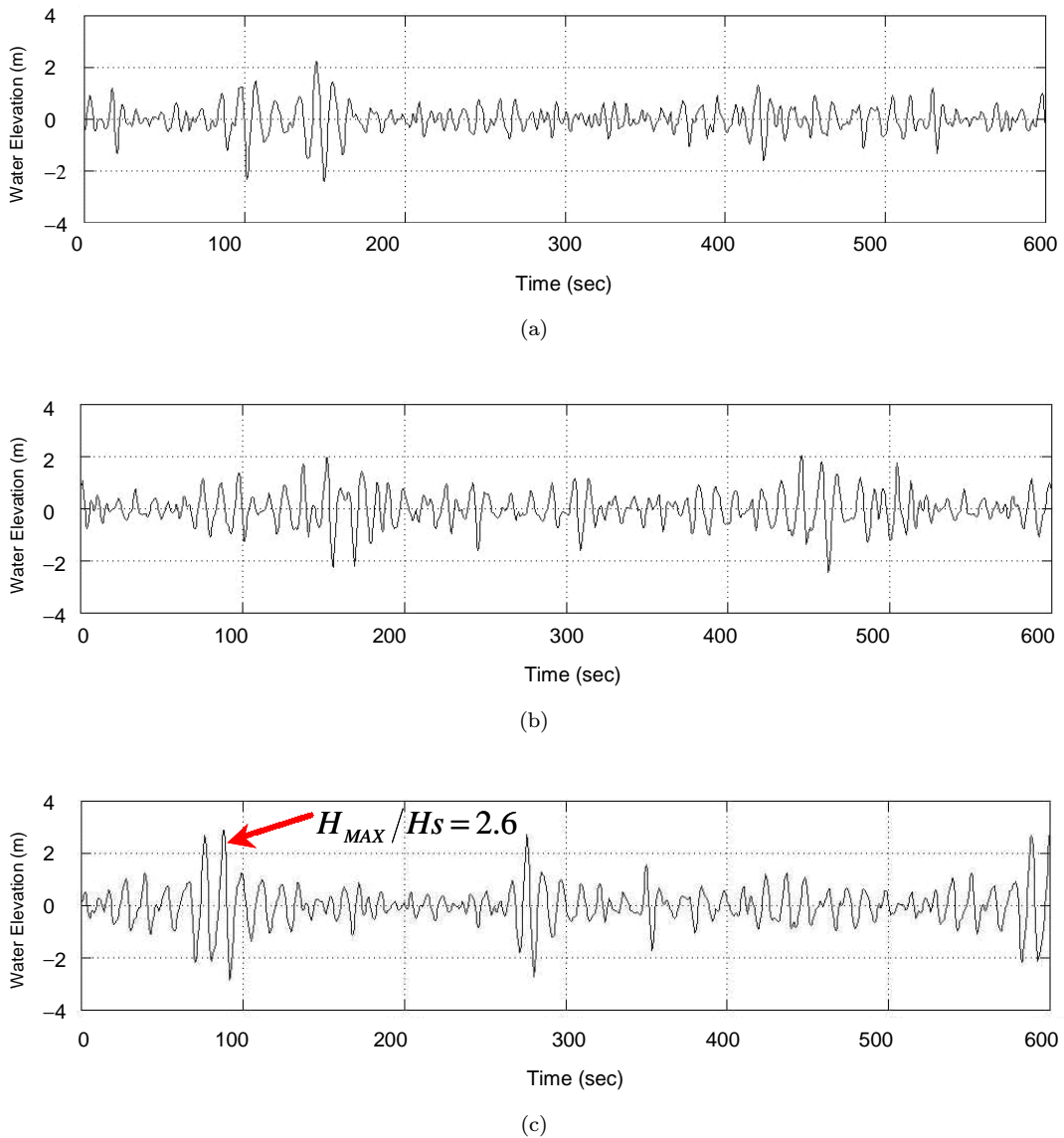


Fig. 5. Time series of water elevation measured during Typhoon Gloria 1996 July 26 from 0000UTC to 0003UTC. (a) Data measured at 0000UTC. The corresponding  $H_{1/3}$  is 160 cm.  $GF = 0.76$ ; (b) Data measured at 0100UTC. The corresponding  $H_{1/3}$  is 143 cm.  $GF = 0.81$ ; and (c) Data measured at 0200UTC. The corresponding  $H_{1/3}$  is 201 cm.  $GF = 0.83$ .

- (1) The difference between main wave period, which is the inverse of peak frequency and the secondary wave period is larger than 2 seconds; and
- (2) The peak value of the secondary largest portion of spectrum is larger the 30% of the peak value of energy density on the main frequency.

In Cheng-Kung area, 21.1% of 175 coastal freak waves have bimodal or multimodal spectra, while only 2.0% of field data that do not consist of coastal freak

waves have bimodal or multi-modal spectra. That is, there is significant difference on the spectrum shape when the coastal freak waves occur.

It is also found that 51.4% of 175 coastal freak waves come with a pronounced wave grouping phenomenon of GF value higher than 0.7. And, most of coastal freak waves of GF smaller than 0.4 are spectral bimodal or multi-modal. Only 2.2% of coastal freak waves happen in a wave field with both high GF and bimodal or multi-modal spectrum. To sum up, the statistical analysis demonstrates that 70.3% of coastal freak waves occur in the wave field of wave groups or bimodal spectrum. It suggests that the probability of occurrence of coastal freak waves may increase when the wave conditions with strong groupiness or bimodal spectrum become obvious. In the following section, Wavelet Transform will be implemented to justify their spectral structures.

#### 4. The Spectral Structures of Coastal Freak Waves

The occurrence of coastal freak waves is an extremely non-stationary phenomenon. In order to investigate the structure of the coastal freak waves, a proper method to analyze the temporal and spectral characteristics is needed. Most of the traditional methods of spectral analysis such as Fourier Transform are inappropriate for analyzing non-stationary signals. Wavelet Transform has been proven to be a much better tool on representing the non-stationary wave energy in time and frequency, simultaneously.

##### 4.1. The wavelet transformation

The Wavelet Transform that was used in the present study is the “Continuous Wavelet Transform” (CWT). Before applying the Wavelet Transform, the window function should be determined first. The window function, which is also named as mother wavelet, is a waveform of effectively limited duration that has an average value of zero. Given a mother wavelet, the wavelet functions are defined as:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}} \Psi \left( \frac{t-b}{a} \right) \quad (8)$$

where  $a$  and  $b$  are functions of scale and position. The CWT can be considered as sum over all time of signal multiplied by scaled, shifted versions of the mother wavelet:

$$CWT(a, b) = \int_{-\infty}^{\infty} \eta(t) \cdot \Psi^* \left( \frac{t-b}{a} \right) dt \quad a, b \in R, a \neq 0 \quad (9)$$

The central points and the widths of the time-frequency window are  $t^*$  and  $\omega^*$  in the time and frequency domain respectively. Chui (1992) introduced a parameter  $Q$ , which is the ratio of any arbitrary frequency and the width of the time-frequency

window:

$$Q = \frac{\omega^*/a}{2\Delta_\omega/a} = \frac{\omega^*}{2\Delta_\omega} \quad (10)$$

From the above equation, the value of  $Q$  is only related to the mother wavelet. For a fixed mother wavelet, the  $Q$  is a constant. The parameter  $Q$  can be regarded as the number of oscillation of the mother in the window.

There are numerous mother wavelet functions that have been created for practical application, from which, the Morlet function was proven to feature appropriate resolution in both time and frequency domain for wave signal analysis comparing to other frequent used mother wavelet functions such as Paul wavelet function and Gaussian Type function (Ou, 1996). In the present analysis, we selected Morlet function as mother wavelet. The Morlet function in the frequency domain and time domain can be expressed respectively as:

$$\hat{\Psi}_{\text{Morlet}}(\omega) = \frac{1}{\pi^4} [e^{-(\omega-\omega_0)^2/2} - e^{-\omega^2/2} e^{-\omega_0^2/2}] \quad (11)$$

$$\Psi_{\text{Morlet}}(t) = \frac{1}{\pi^4} (e^{-i\omega_0 t} - e^{-\omega_0^2/2}) e^{-t^2/2} \quad (12)$$

#### **4.2. Wavelet transform of coastal freak waves**

The results of Sec. 3 show that the occurrence of coastal freak waves is related to the wave groupiness and spectral shape. To investigate the mechanism of coastal freak waves, Wavelet Transform is applied to the 175 coastal freak wave data. The analyzed results could be categorized into three major patterns: the strongly wave grouping type, the spectral bimodal type and the third type, which has scattered and non-distinguished features. Examples of analyzed results of patterns 1, 2 and 3 are chosen and discussed in the following.

A typical result of applying the Wavelet Transform to the data of uni-modal spectrum and strong grouping phenomenon is illustrated in Fig. 6. The data was measured at 08:00 on July 30, 1996 at Cheng-Kung station. Meanwhile, there was a super typhoon Herb in the southwestern Pacific Ocean. The typhoon centre was about 400 km away from the wave observation station. Typhoon Herb landed on the eastern coast of Taiwan 24 hours later. The time-frequency information of the wave record is represented by the two-dimensional contour. The wave heights of coastal freak wave and significant wave height were 486 cm and 180 cm respectively. The ratio of coastal freak wave height to significant wave height is 2.7. It is found that the spectral shape was very narrow at the moment of coastal freak wave. The peak frequency is located at 0.075 Hz. There is no transient frequency change in the whole process. The coastal freak wave occurs in the middle of wave grouping envelope. The calculated Groupiness Factor is 0.87. From the viewpoint of engineering applications, the occurrence of wave groups and extreme waves together create a more serious

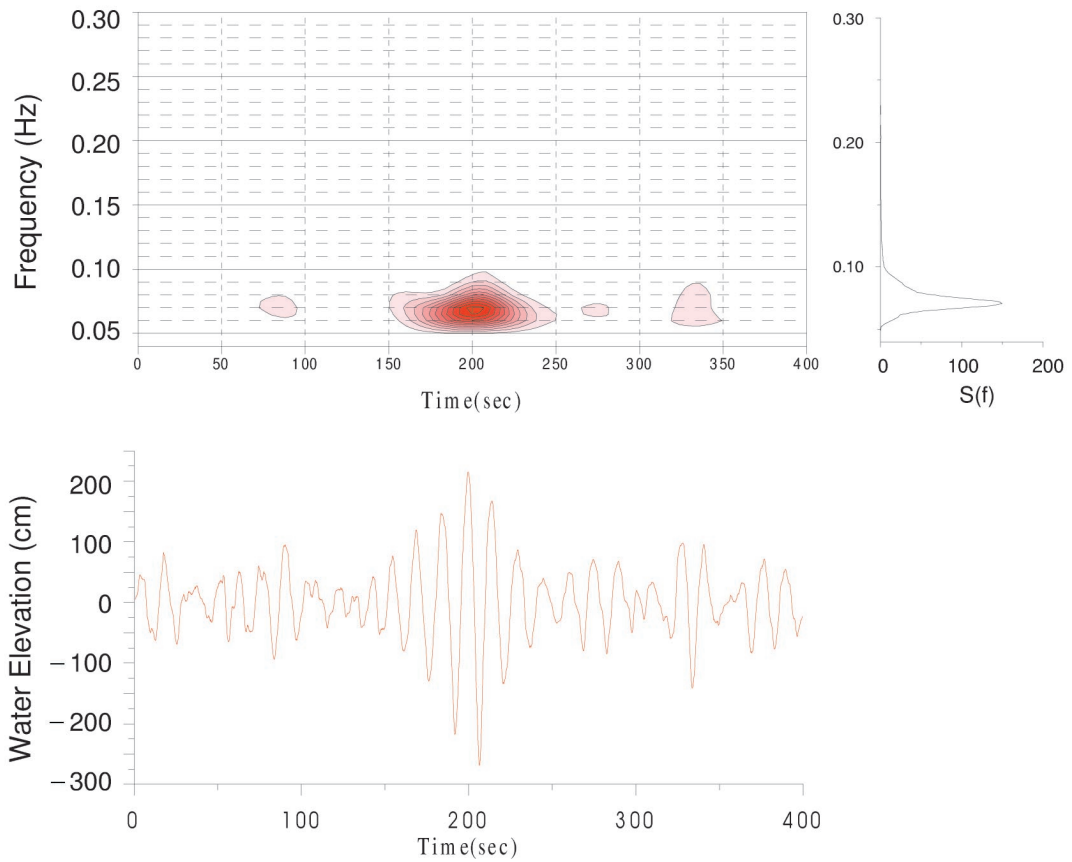


Fig. 6. Wavelet Transform Analysis of coastal freak wave record with strong grouping phenomenon. This record was measured by Cheng-Kung station at 0800UTC of July 30, 1996.

situation. Several statistical theories available for wave groups and extreme waves can be referred to Ochi (1998). Concerning the possible dynamics that underline these wave features, only very little studies had been done. The concept of extreme wave group was proposed by Su (1984), in which one wave group containing the largest wave in each wave record during 30 minutes was collected and analyzed. Su found that the envelope of the extreme wave groups statistically fit well with the envelope of a wave group at the height of nonlinear wave evolution due to Type I instability. The largest wave in such wave group often reaches the stage of breaking. That agreement further suggested the significance of the nonlinear wave dynamics in the analysis of ocean waves during heavy storms (Su, 1986).

Besides the effect of wave groups, coastal freak waves also occur at the situations of bimodal or multi-modal spectra. In the second pattern, the superposition of different wave systems may play an important role on inducing the coastal freak wave.

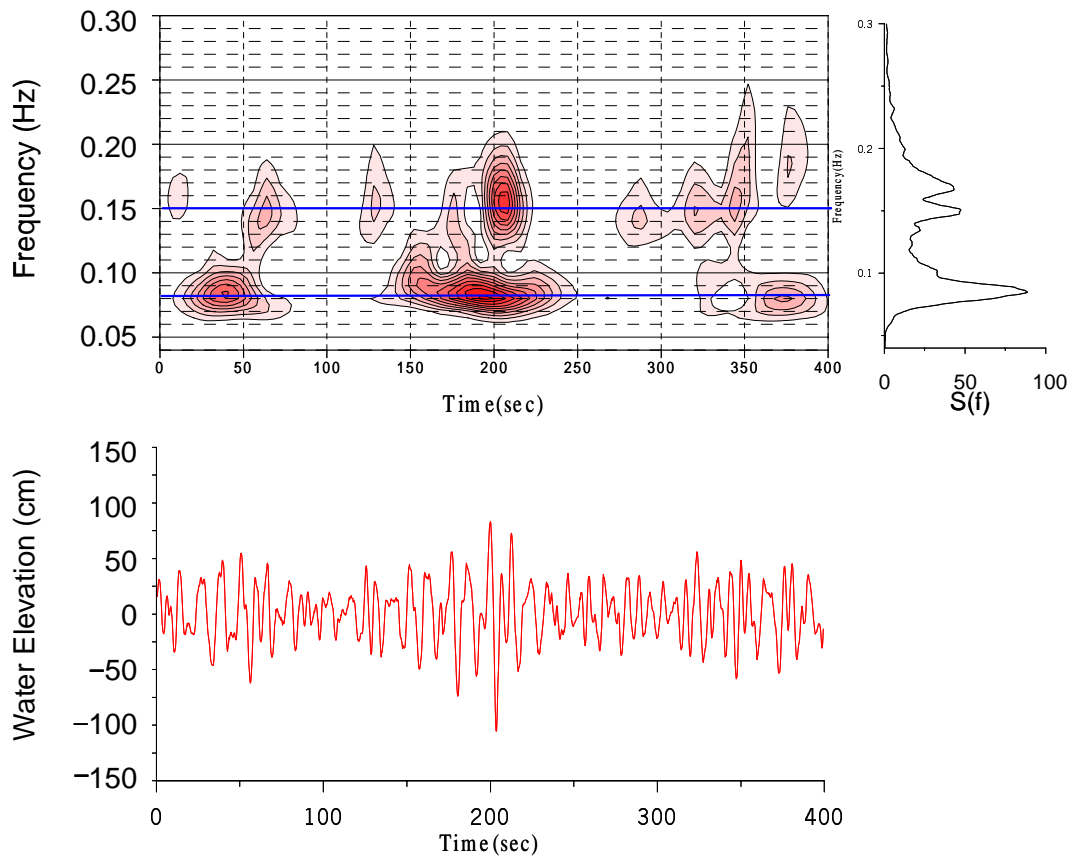


Fig. 7. Wavelet Transform Analysis of coastal freak wave record with bimodal spectral data. This record was measured by Cheng-Kung station at 1700UTC of October 9, 1996.

Figure 7 is a typical result of applying the Wavelet Transform to the wave data of bimodal spectrum. The data is observed at 1700 UTC on October 9, 1996. The wave height of coastal freak wave, occurred in the middle of the time history diagram, is 212 cm while the significant wave height is 94 cm in this record. The ratio of coastal freak wave heights to significant wave is 2.15. There are two major energy concentrations on Wavelet spectrum: one swell system of peak frequency at 0.08 Hz and the other wind wave system at 0.15 Hz. At the moment, when coastal freak wave occurs, there was no energy founded at the harmonic frequencies of swell frequency or wind wave frequency. Obviously, the occurrence of coastal freak wave was caused by the coalescence of two energy systems. Pelinovsky *et al.* (2000) carried out a numerical experiment of the coalescence of shallow water waves based on the KdV equation. He pointed out that the extreme waves could be a result of the coalescence when the Ursell number is smaller than  $1/6$ . Therefore, the coalescence can be basically regarded as linear superposition.



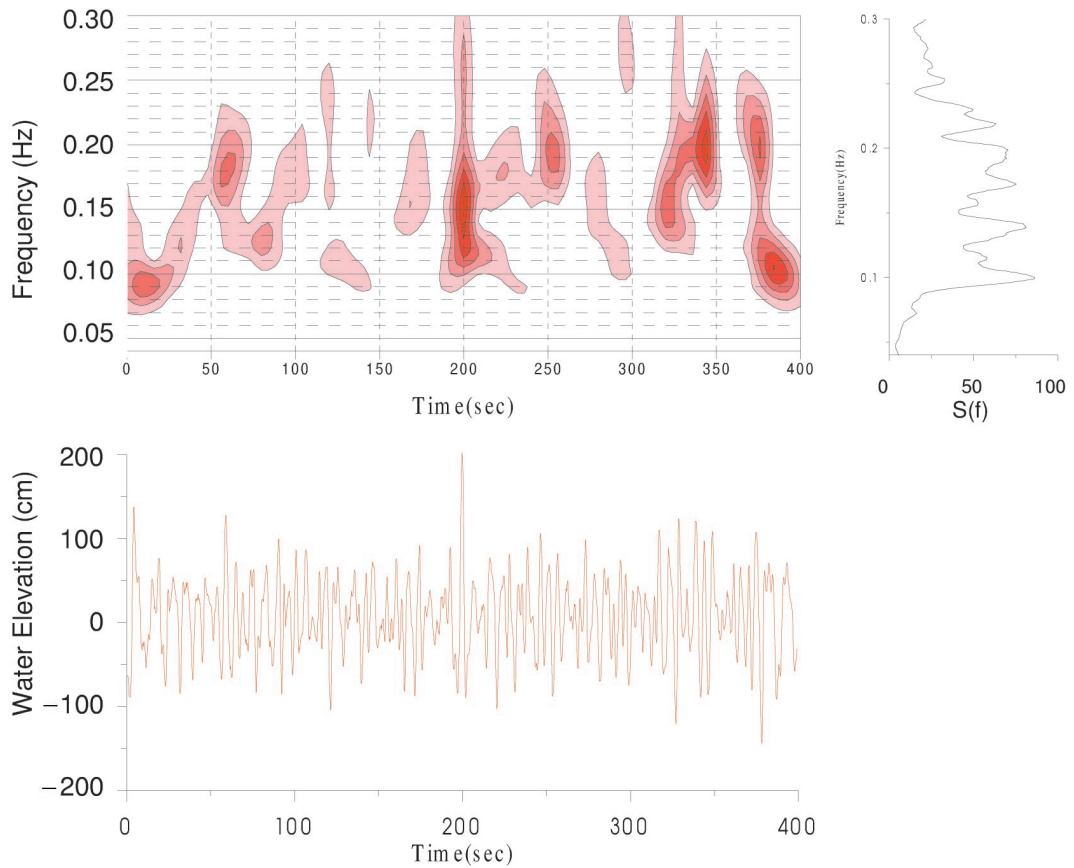


Fig. 8. Wavelet Transform Analysis of coastal freak wave record with multi-modal spectral data. This record was measured by Cheng-Kung station at 1800UTC of March 5, 1996.

Figure 8 is another typical example of coastal freak wave of multi-modal spectrum. The data was observed at 1800 UTC on March 5, 1996. The coastal freak wave is highly asymmetric on wave profile. Its wave crest is much larger than wave trough. The Fourier spectrum shows that there are complex energy systems in the seas. At the moment, for coastal freak wave, the Wavelet spectrum covers a wide frequency range. The result indicated that there might be non-linear effects on inducing the coastal freak wave. However, as mentioned previously, parameter of non-linear, bicoherence, is small in this sample. The reason that the bicoherence does not reflect the degree of non-linear may be due to the fact that the bicoherence is a time-average parameter. Hence, a new parameter that could more precisely represent the instantaneous non-linearity may be requisite. Herein, the third category is regarded as a non-distinguished ones.

Among the above mentioned three patterns, the first one, which features group with no superposition occupies about 50% of the population, and the second superposition pattern occupies 20%. The third category occupies the rest.

## 5. Conclusion

Coastal freak waves are hazardous to people and marine vessels in coastal zone. In order to investigate the characteristics of coastal freak waves, statistical and spectral structures of them are investigated by the analysis of long-term full scale field data.

The results show that the occurrence probability of coastal freak waves remains below the Rayleigh distribution. Moreover, its occurrence probability is highly dependent on the wave groupiness factor. With stronger wave grouping phenomenon, the occurrence probability increases rapidly. Concerning the local wave climate around the coast of Taiwan, the highly grouping waves are often measured as the swells that propagate to the nearshore from where the western Pacific typhoons locate. It is revealed that typhoon waves and swells might be one of the situations of occurrence of the coastal freak waves. This might explain that higher freak wave occurrence probability is yielded with large significant wave height. On the other hand, wave frequency spectra of the records, which contain freak waves, consist of more bimodal feature. Spectral bimodal feature originates from the existence of different wind-wave or swell systems in the wave field.

The results of Wavelet Transform analysis of the measured coastal freak waves has shown that wave groups, superposition of the swell and wind wave energy play major roles of inducing the coastal freak waves. The data with bimodal spectrum and that with strong wave groupiness are statistically independent. This implies either the typhoon swell or the complexity of wave field cause the coastal freak waves in the coastal zone of Taiwan. These two trends cover more than 70% of the occurrence probability and should be vigilantly cautioned.

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