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THE FREAK WAVE POTENTIAL OF TYHOON SWELL

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Key words: freak wave, typhoon, moving wind system, swell accumulation effect, freak wave potential index.

ABSTRACT

Freak waves are so-called rogue waves, which are considered nearly impossible according to traditional ocean wave theory and sometimes cause coastal and sea wrecks. There are already some hypotheses that explain freak wave occurrence. However, the moving wind system generates swells which can be enhanced by swell energy flux accumulation. A newly-defined parameter "Freak Wave Potential Index" Φ for the typhoon swell can manifest the possibility for a freak wave occurrence. This index can be correctly estimated, because actual typhoon datum is already known. The "Freak Wave Potential Index" concept may also be used for other moving wind systems.

I. INTRODUCTION

There are many wave hazards around the Taiwan coast. These dangerous waves have been studied by Taiwanese ocean engineers and named as giant waves, dangerous waves or freak waves [2, 3, 20]. Those waves can be categorized into four types [6]. The first type may be regarded as extreme values of the statistical probability distribution tail. The second type is due to interaction between the waves and current. The third one is due to the wave-wave non-linear interaction. The fourth type is due to the superposition of waves of different frequency components. The first and fourth types belong to the statistical point of view, while the second and third types are pertaining to physical aspects. The nonlinear process is modeled using a wave equation known as the nonlinear Schroedinger equation. In this equation a wave begins to 'soak' energy from the waves immediately fore and aft. In such a case, an unusual, unstable wave type may form a single wave that 'sucks' energy from other waves [4, 8, 19]. A simple statistical definition of the freak wave, which does not include steady current focusing, is a wave height that exceeds twice the significant wave height [10, 11].

Munk and Snodgrass [18] discussed the swell height enhancement due to a moving storm. They proposed energy amplification μ which is a function of the wave spectrum, storm movement speed and storm & wave station positions, without the wind condition. Dysthe and Harbitz [7] studied big waves from polar lows, which have a rather limited horizontal extent of the order of 100 km but do not move slowly. As the movement speed is close to the wave group velocity, this phenomenon is called group velocity quasi-resonance. Donelan and Magnusson [5] studied the probability of rogue wave occurrence due to mixed seas from two different wind systems, in which at least one of mixed sea components is swelling. They named this event meteorological focusing.

II. TYPHOON SWELL PREDICTION SCHEME

Following Munk and Snodgrass's goal, this author proposed a swell prediction scheme for a moving typhoon [12]. A typhoon or hurricane is a tropical atmospheric cyclone that may generate huge waves within its domain. The swell usually propagates faster than the typhoon itself and appears outside the typhoon. The typhoon can be regarded as a wave generator. Two semi-empirical equations were verified several times. The final form is as follows:

$$H_S = \lambda C_1 H_R \sqrt{\frac{R_7}{DD}} \tag{1}$$

$$T_S = C_2 T_P \tag{2}$$

in which H_S is the swell height in meters, H_R the estimated wave height in feet at the typhoon's radius of maximum wind speed R, R_7 the typhoon's radius of Beaufort's scale No. 7 wind in km, DD the distance between the typhoon center and the wave station in nautical mile, T_S the swell period, T_P the estimated wave peak period at R.

There are three parametric typhoon/hurricane wave forecasting methods, i.e. the methods proposed by Bretschneider and Tamaye [1], Young [22] and Hsu [9]. Hsu's method is the simplest. He used only the maximum wind speed to determine wave heights. Young needed the maximum wind speed U_R,

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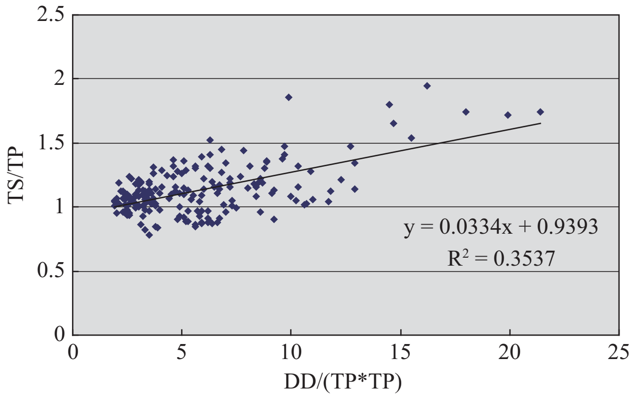

Fig. 1. Regression line for C_2.

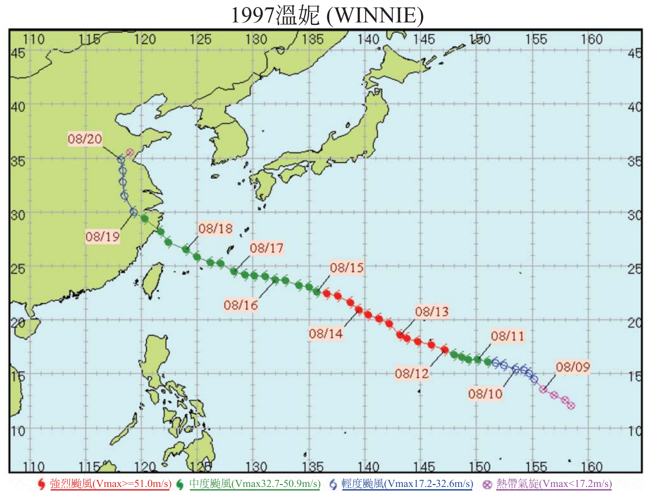

Fig. 2. Track of Typhoon Winnie in 1997 (Reproduced from Central Weather Bureau Website).

the radius of maximum wind speed R and the hurricane moving speed V_F. Bretschneider and Tamaye employed the central atmospheric pressure, the radius of the maximum wind speed R and the hurricane moving speed V_F. Bretschneider and Tamaye's method is more complicated and the results are proven to be reasonable. The author uses Bretschneider and Tamaye's method to estimate H_R in feet and T_P in seconds without considering the hurricane movement speed as in the following equation

$$H_R = K'\sqrt{RdP} \tag{3}$$

$$T_P = 0.347\tanh\left\{\ln\left[\frac{1+\dfrac{40H_R}{(0.865U_R)^2}}{1-\dfrac{40H_R}{(0.865U_R)^2}}\right]^{0.5}\right\}^{0.6}\times U_R \tag{4}$$

where dP is the atmospheric pressure reduction from normal in inches of mercury and K' is a coefficient proposed by Bretschneider and Tamaye [1]. A regression equation is as follows [16]:

$$K' = 7.59 - 41.21\left(\frac{fR}{U_R}\right) + 160.51\left(\frac{fR}{U_R}\right)^2 - 219.32\left(\frac{fR}{U_R}\right)^3 \tag{5}$$

where the geostrophic wind speed in knots

$$U_R = K\sqrt{dP} - 0.5\,fR,$$

in which K is given in a table by Bretschneider and Tamaye [1] and a regression equation is as follows [16]:

$$K = -\frac{\phi}{7.5} + 70 \tag{6}$$

where ϕ is the latitude of typhoon center.

Because the maximum wind speed radius R is not provided by the weather authority, a 'trial and error' method is used to estimate it by inputting the radius from Beaufort's scale No. 7 wind (R_7) and the maximum wind speed into the equation:

$$\frac{U_r}{U_R} = -\frac{1}{2}\frac{fR}{U_R}\frac{R_7}{R} + \left(\left(1+\frac{fR}{U_R}\right)\frac{R}{R_7}\exp\left(1-\frac{R}{R_7}\right) + \left(\frac{1}{2}\frac{fR}{U_R}\frac{R_7}{R}\right)^2\right)^{\frac{1}{2}} \tag{7}$$

where U_r is the wind speed from Beaufort scale No. 7, e.g. 30.5 knots, U_R the maximum wind speed provided by the weather agency and f is the Coriolis force coefficient. C_1 and C_2 are empirical constants, in which C_1 is then 0.106 and C_2 is a regression equation from 197 data [17]. The empirical equation is the following (Fig. 1).

$$C_2 = 0.9393 + 0.0334\frac{DD}{T_P^{\,2}} \tag{8}$$

Because $T_P^{\,2}$ has a measure of wave length, $\dfrac{DD}{T_P^{\,2}}$ is a relative distance from a station to a typhoon center. It is obvious that C_2 increases as the relative distance increases. To verify the above-mentioned typhoon swell prediction scheme, Typhoon Winnie in 1997 and the wave measurement at Hualien Harbor (23.98°N, 121.64°E) are used. The typhoon track is shown in Fig. 2 and comparisons between measurements and estimates are then shown in Figs. 3 and 4. Both swell heights and period match quite well. Moreover, λ is the swell height modification coefficient which is very important and will be addressed in the following section.

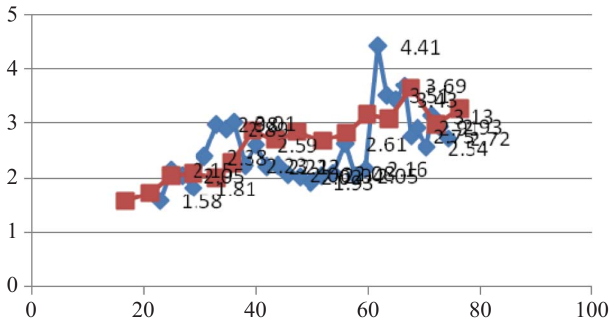

Fig. 3. Comparison of hindcast (squares) and measured swell height for Typhoon Winnie at Hualien Harbour.

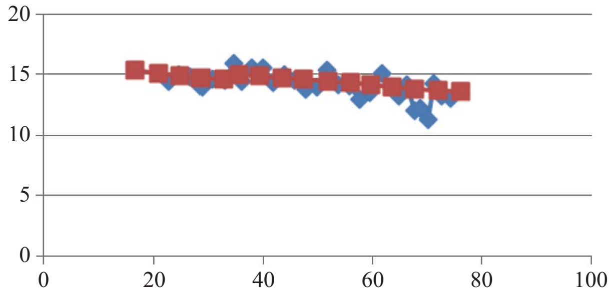

Fig. 4. Comparison of hindcast (squares) and measured swell period for Typhoon Winnie at Hualien Harbour.

III. SWELL ACCUMULATION EFFECT OF A MOVING TYPHOON

As the typhoon is stationary, the situation is different from that approaching a station. As the typhoon approaches the observer, the travel time for the wave energy becomes shorter. This results in an increase in the wave energy flux. Another possibility is that the typhoon strength variation will change the wave period and hence alter the travel time. Under the energy conservation assumption and a stable wave height within a short period of time, the wave height modification factor used to multiply the swell height estimated from a stationary typhoon is as follows [13]:

$$\lambda = \sqrt{T_D / T_D^{'}} \tag{9}$$

in which T_D is the swell appearance time period for a stationary typhoon, $T_D^{'}$ that for a moving typhoon. T_D is the time lag for the successive typhoon data stream. $T_D^{'}$ is equal to $T_D - \Delta T_{lag}$. ΔT_{lag} is the time difference between the swell propagation times for two successive typhoon data. Due to the assumption of a stable wave height in deriving Eq. (9), the time difference of two successive typhoon data should be less than 0.5 hour. Therefore, interpolated typhoon data and T_S data will be employed to estimate the successive lag times, i.e. T_{lag1} and T_{lag2}. As ΔT_{lag} approaches T_D, i.e. the latter swell has almost caught the former swell, then $T_D^{'}$ approaches zero. Following Eq. (9), the wave height modification factor λ will be infinite. Of course it should not be infinite in reality but large. The definition of a freak wave is that the ratio of $H_{\max}$ to $H_{1/3}$ is larger than 2. Therefore, as the significant wave height $H_{1/3}$ is larger, then according to the 1st, 3rd and 4th type freak wave, a destructive freak wave is probable. Like the 2nd type freak wave λ makes the significant wave height larger. This makes sense! Other than typhoons or hurricanes, there are other wind systems that always move, such as extra-tropical cyclone, polar lows, etc. All of these wind systems may have the same potential to generate freak waves.

IV. THE FREAK WAVE POTENTIAL OF TYPHOON SWELL

As $T_D^{'}$ is smaller than T_D, λ becomes greater than one. As the distance between the typhoon center and wave station decreases and as C_g, i.e. a function of wave period, increases, $T_D^{'}$ would be smaller than T_D. Tulin, Yao and Magnusson [17] discussed the evolution and structure of energetic wind waves using Eq. (7) in their paper and wrote: "In certain complex circumstance, as in the case of spatially enhanced waves due to gusts or squalls, ray focusing can occur in the front of the formation ($(C_g)_x < 0$), causing enhanced energy growth." $(C_g)_x$ is the derivative of C_g along the wave ray. This also asserts the reason λ is greater than one that the later wave period is larger than the former one. Because λ is very sensitive to $T_D^{'}$, as the latter is small. As ΔT_{lag} is larger than T_D, i.e. the latter swell has overrun the former swell, then $T_D^{'}$ is negative and Eq. (9) is not applicable. Usually typhoon data are scattered. Any little typhoon data perturbation, such as positions of the typhoon center, central pressures, the radius of Beaufort scale No. 7 wind (R_7), ocean current, etc., may change the wave period and hence $T_D^{'}$, which may change from positive to negative. Hence, the estimated the wave height may not be emphasized but its occurrence potential. Once the absolute value of $T_D^{'}$ is less than a small fraction of T_D, say one fourth, there is a high probability to have a freak wave. ΔT_{lag} is the time difference between the swell propagation times for two successive typhoon data series. Then

$$\Delta T_{lag} = T_{lag1} - T_{lag2} \tag{10}$$

$$T_{lag} = \frac{DD}{C_g + V} \tag{11}$$

in which DD is the distance between the swell source and a site in ocean, C_g the wave energy propagation speed which is proportional to the swell period and V the ocean current speed component in the swell direction. Freak Wave Potential Index Φ is defined as follows:

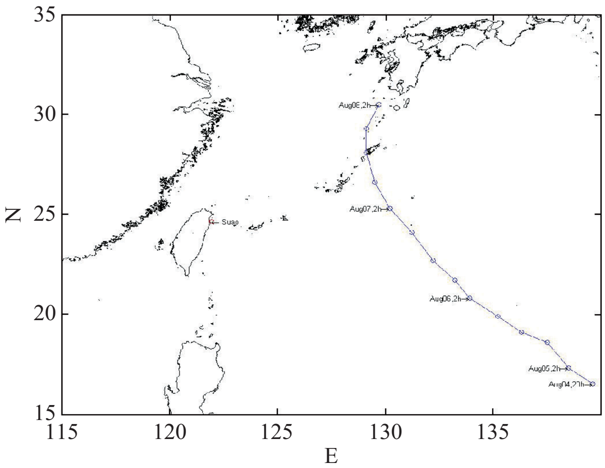

Fig. 5. Track of Typhoon Jenis in 1992.

$$\Phi = \sqrt{\frac{T_D}{\left|T_D^{'}\right|}} \tag{12}$$

Because $T_D^{'}$ becomes negative, as the latter swell overruns the former, an absolute value is employed. As $T_D^{'}$ is small, any change in the wind system may change its sign.

The index Φ can be predicted. Once it is larger than 2 for any site at a time, a freak wave is highly probable. A freak wave accident example is introduced as follows [14]: After 4 a.m. on August 7, 1992, four fishing ships were totally destroyed by sudden huge waves in the vicinity of Suao Harbor (24.63°N, 121.93°E) on the east coast of Taiwan. One man died, two persons were missing and five fishermen were injured. As the accident was close to the harbor, some of the wrecks drifted to shore. One fisherman said that he had never confronted such a big wave in his 40 year fishing career. Two days before, a medium scale typhoon Janis had been in the area around 19°N, 136°E and moved fast toward Taiwan. The typhoon Janis' track is shown in Fig. 5. From 14 h to 20 h, Aug. 5, the typhoon central pressure decreased quickly from 970 hPa to 955 hPa. This made the latter wave period larger than the former one. The estimated "Freak Wave Potential Index" Φ is 3.8! There was unfortunately no wave measurement. The source was at 20 h, Aug. 5 and 790 nautical miles away, i.e. the 5th typhoon center from right in Fig. 5. This was 32 hours before the accident. Actually one could predict this rogue wave!

V. DISCUSSION AND CONCLUSION

Although Typhoon Winnie is much stronger than Janis, however, the former's moving speed is slower and the swell group speed is larger. Therefore, the ratio of moving speed to group speed for Winnie is much small than that of Janis. As the ratio is closer to 1, the process is more approaching to a resonance. Hence, the Freak Wave Potential Index Φ for Winnie is around 1.3. There were no accident reports. Typhoon Janis did not invade Taiwan. Hence, no information is available in the Central Weather Bureau Website. An abrupt large wave without alarm is the most dangerous!

Unfortunately on September 1st, 2011 three rock fishing enthusiasts lost their lives at Tou-Cheng, I-Lan owing to freak waves. From Aug. 25 till Sept. 4, tropical storm Talas, which is a weak typhoon was in the Western Pacific, moved to the north and was about 2000 km away from Taiwan. In the meantime Central Weather Bureau did not announce any typhoon alarm. However, Harbor Research Center's wave meter record at Suau Harbor reveals that the significant wave height is about 1.2 meter and the wave period is approximately 12 seconds. The estimates are also similar. The unexpected long wave may be the main reason, because the long wave can generate higher run-up and result to a larger backwash.

The index Φ is defined as the square root of a ratio, which is the swell appearance time for a stationary wind system divided by that for a moving and changing strength one, where an absolute value is taken for the denominator. As the denominator is positive, i.e. the later swell does not overrun the former, the index Φ reveals a wave height amplification coefficient. As the index Φ is large, it is sensitive to the swell appearance time for a moving wind system (the denominator), which is a function of the wind system strength and its approaching speed to the site. Usually the actual wind system data fluctuates around their mean values. Hence, the index Φ can be a measure of freak wave potential. As the "Wave Potential Index" is larger than 2, a freak wave is highly probable. This index can be correctly calculated because the historical typhoon datum is available. Furthermore, "Freak Wave Potential Index" concept may also be used for other moving wind systems.

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