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A Study on the Development of Wind and Wave Model of Typhoon

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Abstract : *In this paper, after analyzing other models with their advantages and disadvantages, we proposed a simple parametric model for calculating wind speed & direction and wave height & direction at any location around the typhoon at sea. The proposed wind-field model of typhoon is asymmetric, and consists of a circular symmetric wind-field caused by the pressure gradient of stationary typhoon and a moving wind-field caused by the movement of typhoon. By verifying this model through observed data, we found that it is accurate enough to develop the simulation software for training students and seafarers so as to take appropriate actions while being faced with the typhoon at sea.*

Key words : *simulation for avoiding typhoon, wind-field model, wave-field model*

1. Introduction

Tropical cyclones are warm core, non-frontal low-pressure systems of synoptic scale that develop over tropical or subtropical waters and have a definite organized surface circulation. Tropical depressions, tropical storm and typhoons are all forms of tropical cyclones, differentiated only by the intensity of the winds associated with them. In this paper, these systems are called typhoon for convenience. Typhoon always causes very great threat to vessels navigating at sea, and tends to make a lot of life losses and damages to property.

In order to prevent striking from typhoon or to reduce the losses and damages caused by typhoon, many researchers have been engaging in studying typhoon, but they still cannot make completely clear of its structure, including its wind-field and wave-field distributions. Typhoon is a very complicated system, and it is difficult to find out an accurate mathematical model to depict it. Anyway, many researchers have been trying to make the model for typhoon with various approaches for their own purposes. All these models can be generally classified into three categories : analytical models, numerical models and parametric models. Analytical models have closed form solutions to the momentum equation in a simplified fashion and their accuracy may be reduced owning to some simplified processes. Numerical models solve the equation of motion by numerical methods and these models generally have good accuracy while requiring significant computational efforts. Parametric models were introduced to approximate numerical solutions by functional forms of the typhoons' characteristics, and these models have better numerical accuracy than analytical models and greater computational efficiency than numerical models.

In view of that there is only past typhoon's track data information available for us to utilize, we have to find out a simple parametric model for calculating wind speed & direction and wave height & direction at any location around the center of typhoon. This model could be used to develop a simulation software for training students and seafarers to avoid typhoon's strike at sea.

2. Wind-field model of typhoon

The wind-field of a typhoon is normally asymmetric, and asymmetrical processes in parametric wind-field models are arising mainly from typhoon's movement. Therefore, for simulating the asymmetric characteristic of wind-field of typhoon, we used to consider the wind-field model of typhoon could be made of two wind-fields. One is circular symmetric wind-field which is caused by the pressure gradient of stationary typhoon, and the other is moving wind-field which is caused by the weather system surrounding typhoon.

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2.1 Circular symmetric wind-field

The wind-field of typhoon are generally calculated or forecasted from the pressure gradient of typhoon or model-typhoon wind-field. While providing that surface pressure field has circular symmetric distribution, the gradient wind of typhoon can be calculated as follows(Zhu, 2002);

$$V_g(r) = -\frac{1}{2}fr + \sqrt{\left(\frac{fr}{2}\right)^2 - \frac{r}{\rho}\frac{dP}{dr}} \tag{1}$$

where, $V_g(r)$ is gradient wind of stationary typhoon, $\frac{dP}{dr}$ is pressure gradient, r is radial distance from the center of typhoon, ρ is the air density and f is the Coriolis parameter ($f = 2\Omega\sin\varphi$, Ω is the rotation rate of the Earth and φ is the latitude of central position). Obviously, the calculation of gradient wind is somewhat complicated, while the wind-field of model typhoon is relatively simple and easy to be applied.

In general, these wind-fields are functions of the following typhoon characteristics(central pressure difference, maximum winds, forward speed, radius to maximum winds, site-to-eye distance, site-to-eye angle and Coriolis factor) and the relative location of site. These kinds of parametric wind-field models usually consist of two terms, a maximum magnitude term related to the maximum wind speed $V_{\max}$ and a decaying term related to the radius to maximum wind $R_{\max}$.

In our database(Guo-Zhu Jin, 2004) of past typhoon track data(Source: *The Best Track Data from the Joint Typhoon Warning Center* of U.S.A.), most of records have the values of $V_{\max}$. If $V_{\max}$ is not available, it can be calculated from the following regression equation(Atkinson and Holliday, 1977).

$$V_{\max} = 6.7\,(1010 - P_0)^{0.644} \tag{2}$$

where, the unit of $V_{\max}$ is *m/s* and P_0 is the minimum sea level pressure(*hPa*). Eq.(2) was yielded from analyzing maximum wind measurements of typhoons for 28 years in the Western North Pacific.

$R_{\max}$ is a significant parameter but can not be available in our database. $R_{\max}$ is relating to many factors such as the intensity, the basin, the center position and so on. It is not a fixed value but a variable one from typhoon to typhoon, time to time and basin to basin. However, several studies have been done to formulate $R_{\max}$. Empirically $R_{\max}$ could be determined by Eq.(3) as a function of maximum wind speed and latitude of central position of typhoon (Willoughby and Rahn, 2003).

$$R_{\max} = 46.29exp\,(-0.0153\,V_{\max} + 0.0166\varphi) \tag{3}$$

where, the unit of $R_{\max}$ is ㎞ and φ is the latitude of typhoon central position.

Various equations have been suggested to such kind of wind-field model and there appear to as many models as there are researchers working in the field. We shall describe here only three for comparison.

The first is a straightforward description of wind-field, which has its roots in the writings of Leonardo da Vinci, and was first applied to tropical cyclones by Depperman in 1947. This is so called Rankine-combined or modified potential vortex(Holland, 1997).

$$\begin{cases} V_{Ran} = V_{\max}\left(\dfrac{r}{R_{\max}}\right) & \text{if } r \le R_{\max} \\ V_{Ran} = V_{\max}\left(\dfrac{R_{\max}}{r}\right)^x & \text{if } r > R_{\max} \end{cases} \tag{4}$$

where, x is a shape parameter of the wind-field outside R, and its value has $0 < x < 1$, typically reasonable range of values is $0.3 < x < 0.8$.

As shown in Fig.1, because the decay rate of wind speed is too large, the wind speed V_{Ran} calculated from Rankine model tends to be lower than others, especially near the area of maximum wind radius.

In order to overcome the shortage of Rankine model, Jelesnianski proposed the following wind-field model (Jelesnianski, 1966).

$$V_{Je} = 2\,V_{\max}\frac{R_{\max}/r}{(R_{\max}/r)^2 + 1} \tag{5}$$

This wind-field model is better than Rankine Model, but the wind speed V_{Je} in the far area tends to be higher because the decay rate of wind speed is small. Therefore, Chen proposed an improved wind-field model as follows(Chen, 1994);

$$\begin{cases} V_{Rch} = V_{\max}\,(r/R_{\max})^{2/3} & \text{if } r \le R_{\max} \\ V_{Rch} = V_{\max}\,(R_{\max}/r)^{2/3} & \text{if } r > R_{\max} \end{cases} \tag{6}$$

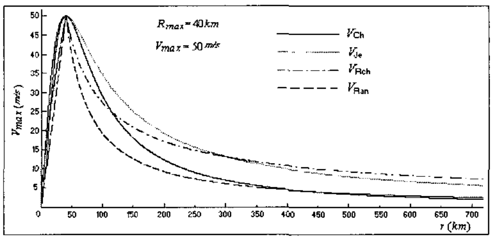


Fig. 1 Profiles of circular symmetric wind-field

This wind-field model is more actual and reasonable, but wind speed still tends to higher than measured wind speed data in the area far away from the center of typhoon. Based on the analyses above mentioned, a more realistic wind-field model is further proposed as follows;

$$\begin{cases} V_{Ct} = V_{\max}\dfrac{r}{R_{\max}} \cdot \dfrac{3}{(R_{\max}/r)^{1/2} + r/R_{\max} + (r/R_{\max})^{5/2}} & r \leq R_{\max} \\ V_{Ct} = V_{\max}\dfrac{R_{\max}}{r} \cdot \dfrac{3}{(r/R_{\max})^{1/2} + R_{\max}/r + (R_{\max}/r)^{5/2}} & r > R_{\max} \end{cases} \tag{7}$$

Expressions of Eq.(7) can be integrated one equation as follows;

$$V_{Ct} = V_{\max}\frac{3\,(R_{\max}r)^{3/2}}{R_{\max}^3 + r^3 + (R_{\max}r)^{3/2}} \tag{8}$$

As shown in Fig.1, the profile of wind speed by this model locates between those of Rankine and Jelesnianski model, and decays far away at a reasonable rate. Hence, referring to Fig.3, at any location $O(r,\theta)$ within stationary typhoon region, the wind speed can be calculated from equation (9a), and its wind direction with an inward angle α(around 20°) from its isobar tangent can be calculated from equation (9b).

$$V_{Ct}(r,\theta) = V_{Ct} = V_{\max}\frac{3\,(R_{\max}r)^{3/2}}{R_{\max}^3 + r^3 + (R_{\max}r)^{3/2}} \tag{9a}$$

$$D_{Ct}(r,\theta) = \theta - 90^\circ - \alpha \tag{9b}$$

The wind-field due to the pressure gradient of stationary typhoon can be determined by equations (9a) and (9b).

2.2 Moving wind-field

The magnitudes of the speed of moving wind-field are different from site to site within typhoon area. Several models for moving wind-field of typhoon have been developed by researchers, and the main of them are as follows(Chen, 1994);

Miyazaki model: $V_{SM} = V_S exp(-\pi r/500)$ (10)

Jelesnianski model: $V_{SJ} = V_S[R_{\max}r/(R_{\max}^2 + r^2)]$ (11)

Uenomuhu model: $V_{ST} = V_S exp\left(-\dfrac{\pi}{4}\dfrac{r - R_{\max}}{R_{\max}}\right)$ (12)

where V_S is forward speed of typhoon, r and $R_{\max}$ are the same meaning with the foresaid.

As shown in Fig.2 with V_S = 10 ㎧ and $R_{\max}$= 40 ㎞, V_{SM} curve shows that moving wind speed is maximum (equal to V_S) at typhoon center, and then it is reduced promptly $0.53V_S$ at the distance $R_{\max}$ from the center, $0.043V_S$ at the distance 500km from the center. V_{SJ} curve indicates that moving wind speed is zero at typhoon center, and reaches maximum (equal to half of V_S) at the distance $R_{\max}$ from the center and then decays very slowly. In V_{ST} curve, moving wind speed at typhoon center is $0.456V_S$ and achieves maximum(equal to V_S) at the distance $R_{\max}$ from the center, then decays promptly. These three moving wind-field models are not so reasonable and with some problems somewhat.

In view of this condition, at any location $O(r,\theta)$, a model for wind speed of moving wind-field is proposed as follows;

$$V_m(r,\theta) = V_S\frac{3\,(rR_{\max})^{3/2}}{R_{\max}^3 + r^3 + (rR_{\max})3/2} \tag{13a}$$

As shown in Fig.2, V_M curve shows that moving wind speed is zero at typhoon center and reaches maximum value (equal to V_S) at r = $R_{\max}$, and then decays at a moderate rate. Therefore this model is more reasonable than the others above mentioned.

The directions of moving wind-field at any location $O(r,\theta)$ within typhoon's region is same with that of typhoon's forward movement. If the direction of typhoon's forward movement is β, the directions of moving wind-field are;

$$D_m(r,\theta) = \beta \tag{13b}$$

The wind-field due to the movement of typhoon can be determined by Eqs (13a)~(13b).

2.3 Wind-field model of typhoon

Providing that the magnitudes of circular symmetric winds are determined by Eq.(9a) and their directions have an inward angle(around 20°) with isobar tangent(such as vector $\overrightarrow{OA}$ shown in Fig.3), and the magnitudes of winds of moving wind-field are determined by Eq.(13a) and their directions are all same with that of typhoon movement (such as the vector $\overrightarrow{AB}$ in Fig.3). The actual winds ($\overrightarrow{OB}$) of typhoon can be expressed as;

$$\overrightarrow{OB} = \overrightarrow{OA} + \overrightarrow{AB} \tag{14}$$

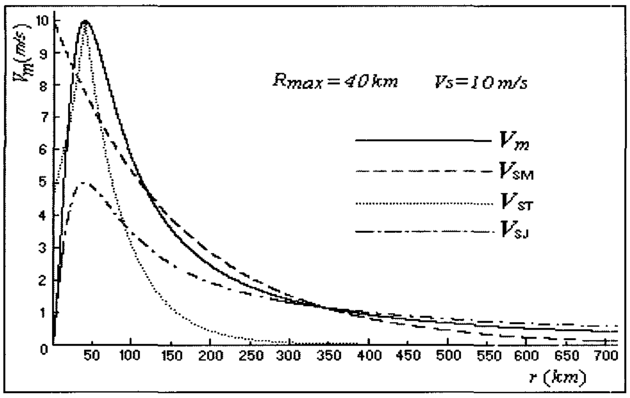


Fig. 2 Profiles of moving wind-field

If the direction angle of typhoon's movement is β and the magnitude(speed) of moving wind-field is V_S, the magnitude $V(r,\theta)$ of wind speed at position $O(r,\theta)$ could be calculated as follows;

$$V(r,\theta)=\frac{3(rR_{\max})^{3/2}}{R_{\max}^3+r^3+(rR_{\max})^{3/2}}\sqrt{V_{\max}^2+V_S^2+2V_{\max}V_S\sin(\theta-\alpha-\beta)} \qquad (15)$$

and its direction $D(r,\theta)$ can be calculated as follows;

$$D(r,\theta)=\tan\left(\frac{V_S\sin\beta-V_{\max}\cos(\theta-\alpha)}{V_S\cos\beta+V_{\max}\sin(\theta-\alpha)}\right) \qquad (16)$$

In Fig.4, owing to adding the effects of typhoon movement to the symmetric wind-field, the modeled wind-field is asymmetric and the winds in the right side of the movement direction are stronger than those in the left, the winds in the rear right quadrant are strongest. These results agree well with the condition of the real wind-field distribution(Note : in this Fig. 4, the arrows only denote the directions of winds).

By verifying this wind-field model through observed data(source: Third Institute of National Oceanography, China), we found that the average rate of relative prediction error is 13.5% and it is enough to be permitted and accepted for our purpose.

3. Wave-field model of typhoon

Since there are only past typhoon track data available for use and the basic characteristics of wind and wave fields of typhoon are requested to simulate only, the empirical method for calculating the wave-field of typhoon is applied in this study.

In this method, the observed wave data from Ocean Data Buoy Stations of Japan Meteorological Agency during the years of 1974~1996 are applied. These stations are moored at the nearby waters of Japanese and at the Western North Pacific. The method classified the data into several classes according to the typhoon central pressure, the distance from observation point to the typhoon center and the azimuth angle from the direction of typhoon's movement, and then calculated the mean values of wave height, wind speed and wave period in each class.

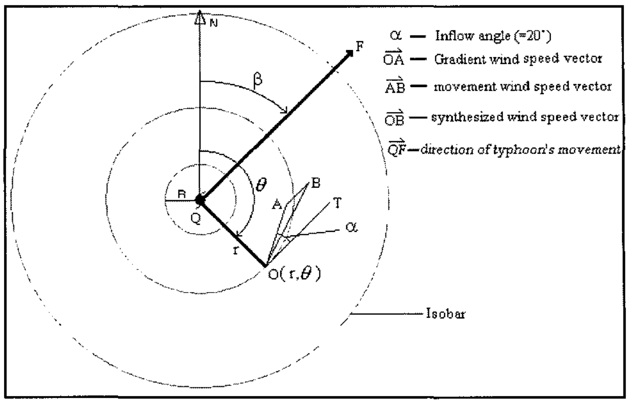


Fig. 3 Synthesized vector of wind-field

In order to derive the empirical relationship among the significant wave height, wind speed and other parameters, this method carried out the regression analysis and dimensionless analysis and yielded Eqs.(17)~ (18) to predict conveniently significant wave height by using the wind speed and the radial distance(Fang and Jin, 2003).

$$H_S=2.96\times10^{-3}V_{10}^{1.44}r^{0.279}\ ,\ P_0\le955hPa \qquad (17)$$

$$H_S=2.74\times10^{-3}V_{10}^{1.39}r^{0.305}\ ,\ P_0>955hPa \qquad (18)$$

where, H_S means significant wave height(m), V_{10} is wind speed at 10-meter high level(m/s) and r indicates radial distance from typhoon center(m).

As to periods of significant waves(T_S), there are several existing equations available, but they are based on the common ocean weather condition. In view of the particular circumstance of simulation system (that is, Typhoon -Avoidance), it is better to find out an equation used to calculate the wave periods in typhoon's area.

Bretschneider proposed the equation (19) according to the observed data of thirteen hurricanes occurred in the eastern waters of U.S.A.. Hurricanes and typhoons have the same weather phenomenon, so periods of significant waves(T_S) also can be calculated as follows (Yang, 2000) in our simulation system.;

$$T_S=3.83\sqrt{H_S}\ \text{(sec)} \qquad (19)$$

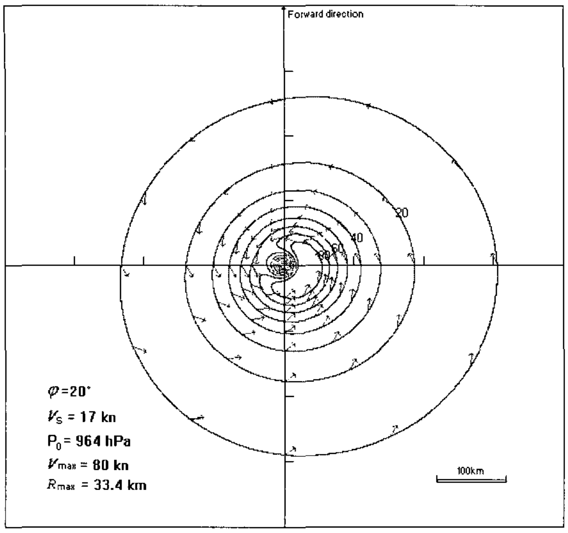
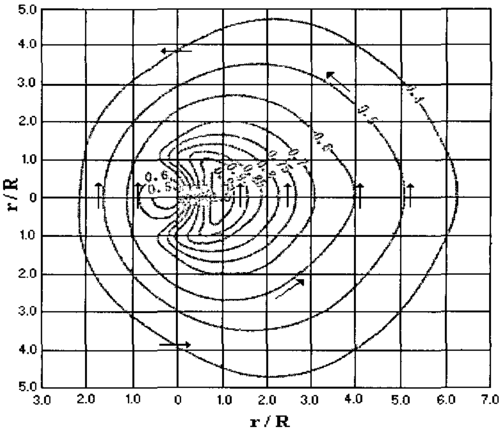


Fig. 4 Wind-field of typhoon



R----- the disatance from typhoon center to maximun wave height zone.

r ------the distance from typhoon center to observation point.

Fig. 6 Wave-field by Bretschneider

In this study, for simplicity, we consider that the wave direction is same with the direction of the corresponding wind roughly even though the wave directions in typhoon region was known to be very complicated. The value of V_{10} can be calculated according to Eq.(15) and the significant wave heights H_S can be predicted according to Eqs.(17)~(18).

The average of the absolute value of the relative error of predicted results is 15% by using whether Eq.(17) or Eq.(18). By verifying it through other observed wave data, both equations can be used to predict typhoon wave height rationally on the whole.

Provided that the parameters of typhoon are the same with those in Fig.4, the significant wave filed is shown as in Fig5. The form of Fig.5 is very similar to the wave field of hurricane developed by Bretschneider in 1957 as shown in Fig.6(Traffic Ministry, 2001).

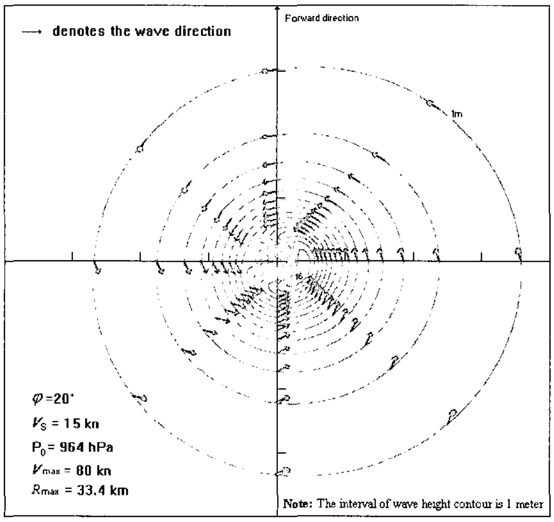


Fig. 5 Wave-field of Typhoon

We applied No.14 typhoon formed on 17th August of 1997 to these wind-field and wave field models. Fig.7 is an example screen which shows wind speed and wave height at some locations in the typhoon region. Actually, in our software, the information of wind and wave at any location within typhoon region can be shown to trainees at the right down corner of the computer screen as shown in Fig.7 while the mouse is moving. It is very intuitive and convenient for trainees to take appropriate avoiding action.

4. Conclusion

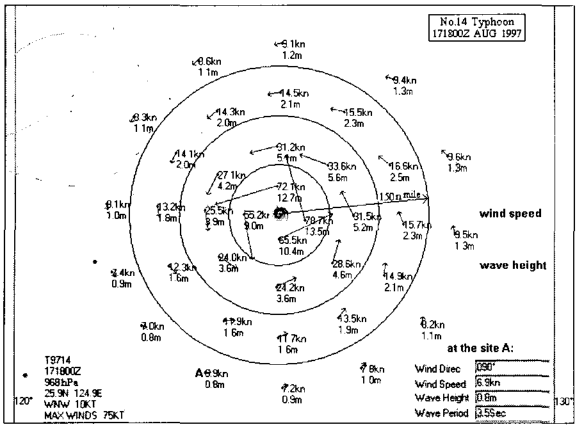
In this paper, we proposed a simple parametric model for calculating wind speed & direction and wave height & direction at any location around the typhoon at sea.

The proposed wind-field model of typhoon is asymmetric, and consists of a circular symmetric wind-field caused by the pressure gradient of stationary typhoon and a moving wind-field caused by the movement of typhoon.

An empirical method with the regression analysis and dimensionless analysis was applied to produce the wave-field of typhoon by using only wind speed and radial distance.

By verifying this model through observed data, we found that it is accurate enough to develop the simulation software for training students and seafarers so as to take suitable actions while being faced with the typhoon at sea.

In the near future, after making a method for evaluating trainee's actions with sea-keeping performance, we will develop a typhoon avoiding simulation system for training mariners so that they can take suitable actions to evade the typhoons.



at the site A:

Wind Direc 090°
Wind Speed 6.9kn
Wave Height 0.8m
Wave Period 3.5Sec

Fig. 7 An example screen of wind and wave fields

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