ABSTRACT: It is common at international level to predict the extreme wind speed with mature typhoon numerical model. And it is necessary to analyze the radial wind-pressure field and radial wind-speed field of typhoon in numerical simulation before the prediction. The paper analyzes the analytic model, proposed by Holland, for the radial wind-pressure field and radial wind-speed field of typhoon and discusses what influence the different values of $\beta$, distribution coefficient of radial typhoon pressure (also referred to as Holland parameter $\beta$), introduced by Holland, will produce on radial distribution of typhoon pressure and speed and it also reviews and concludes existing formulas, which have been proposed by numerous scholars, for calculating wind-pressure distribution coefficient $\beta$. We have studied and compared the values of $\beta$, which had been computed by various formulas, and their impacts on calculating results of radial typhoon pressure distribution and also compared it with the data fitting conclusions of measured pressure from ground stations, according to the Holland empirical analytic model for wind-pressure field and wind-speed field of typhoon and by using the actual air pressure data from hundreds of ground stations in Zhejiang province, China. Since the maximum wind-speed radius, central pressure differential, latitude of typhoon center and surface temperature of the ocean, all of these can affect the value of wind-pressure distribution coefficient $\beta$, further study and verification are needed to figure out which method to calculate $\beta$ will work out best fitting precision for radial wind-pressure distribution of typhoon.

KEYWORDS: Typhoon; Wind-pressure field; Maximum wind-speed radius; Central pressure differential

1 INTRODUCTION
Long-span and towering structures have sprung up in coastal areas in the past few years. All of these structures are sensitive to extreme wind speed within their service life. Therefore, it is really necessary to predict the extreme typhoon speed reasonably during the recurrence life of target structures and thus figure out reasonable basis for safety design and risk assessment of building structures. In addition, mature prediction for extreme typhoon speed with numerical modeling is commonly used at international level. In the numerical simulation process of typhoon, it is critically important to simulate and calculate the wind field of typhoon or the radial speed distribution of typhoon (also referred to as radial wind profile of typhoon). Research results [1, 2], which are based on the sensitivity analysis method, suggest that the typhoon pressure distribution coefficient $\beta$ impacts the determination of the design wind speed during the recurrence interval at the engineering site. Therefore, we make use of the actual pressure data from the hundreds of ground stations in Zhejiang province, China, study and compare the values of the coefficient $\beta$, which have been figured out by different formulas, as well as their influence on the calculated results of radial typhoon pressure distribution, and we also compare it with the fitting results of measured data from ground stations.

An accurate calculation of the radial wind profile of typhoon plays a very important part in the prediction of the extreme typhoon speed and the evaluation of typhoon disasters. Thus, a
great number of scholars have proposed their models to calculate the radial typhoon profile. However, most of the previous scholars have based the statistical fitting on measured data. They usually present the empirical formulas, such as Schloemer [3] and Atkinson [4], to calculate the radial wind profile. In 1980, Holland [5] innovatively combined the empirical function for typhoon pressure distribution, which had been obtained by Atkinson, Holliday and Dvorak [6], with the equilibrium equation of radial pressure gradient of typhoon cyclone, and thus figured out the analytic function model of radial typhoon speed distribution. The analytic model is better by having only one parameter, namely the typhoon radial wind pressure distribution coefficient $\beta$. But it also relies on measured data to estimate the value of $\beta$. In conclusion, the fitting results, from the numerical simulation calculation of typhoon in the Atlantic and Australia by Holland analytic model, are more accurate than those of empirical function models.

2 HOLLAND ANALYTIC MODEL

A great deal of actual measurement for radial wind pressure distribution of typhoon has been made and many measured data and information have been obtained in early years. The measured data of typhoon pressure is standardized, to remove the influence from different typhoon centers and different air pressures on the variability of measured results, shown as below:

$$P_{at} = \frac{(P_r - P_c)}{(P_a - P_c)}$$

In which, $P_r$ means wind pressure at the distance of $r$ away from the typhoon center; $P_c$ is central pressure of typhoon; $P_a$ is natural air pressure, it is theoretically the pressure where $r$ is infinitely great.

On the basis of measured data, many scholars, such as Depperman [7] and Schloemer [3], have used researches to suggest that the radial wind pressure distribution of typhoon complies with the negative exponent relationship. Holland presents them all in the following functional expression:

$$P_{at} = \frac{(P_r - P_c)}{(P_a - P_c)} = \exp \left[ -\left(\frac{R_{max}}{r}\right)^{\beta}\right]$$

(2)

In the above formula, $P_a$-$P_c$ is low pressure differential $P$; $R_{max}$ is maximum radius of wind speed; $\beta$ wind pressure distribution coefficient, also named as Holland parameter. Eq. (2) can be transferred to Schloemer equation when $\beta = 1$.

Equilibrium equation of radial pressure gradient of typhoon cyclone:

$$\frac{1}{\rho_A} \frac{\partial P}{\partial r} = \frac{V^2}{r} + fV$$

(3)

In the equation, $\rho_A$ = air density, kg/m$^3$; $P_r$ = wind field pressure distribution function, hPa; $r$ = radius from typhoon center, km; $V$ = average tangential wind speed of air micelle, m/s; $f$ is Coriolis coefficient, $f = 2\Omega\sin\Psi$, in which $\Omega$ (radian/ s) represents the revolving speed of the earth and $\Psi$ is the latitude of the air micelle.

It can be learned from equation (3):

$$V = \sqrt{\frac{r \cdot \frac{\partial P}{\partial r} + \frac{1}{4} f^2 r^2 - \frac{1}{2} fr}{\rho_A}}$$

(4)
\[ V = \sqrt{\frac{\beta}{P_a}} \left( \frac{R_{\text{max}}}{r} \right)^{\beta} \cdot [100] \cdot (P_r - P_c) \]  
\hspace{1cm} (5)

\[ V_{\text{max}} = \sqrt{\frac{\beta \Delta P}{e P_a}} \]  
\hspace{1cm} (6)

Coriolis strength is much smaller than the gradient pressure of cyclone and its centrifugal force in the maximum speed region of typhoon, so the Coriolis strength is ignored. The functional expression for average tangential wind speed \( V \) at \( r \) away from typhoon center is worked out from equation (2) and (4). When \( r = R_{\text{max}} \) is obtained from \( \partial V / \partial r = 0 \), the average tangential wind speed reaches the maximum value.

In the equation, \( e = 2.71828 \), it is the base number of natural logarithm. \([100] = \text{hPa}\) is converted into \( \text{Pa}\).

Thus it can be seen that if typhoon central pressure \( P_c = 950 \text{ hPa}\), natural air pressure \( P_a = 1010 \text{ hPa}\), maximum wind speed radius \( R_{\text{max}} = 20 \text{ km}\), radial air pressure distribution and radial wind speed distribution of typhoon vary to the coefficient \( \beta \), as is shown in Fig. 1 a) and b). According to Fig. 1 a), when the value of \( \beta \) is enlarged, the eye of typhoon becomes bigger and the wind distribution curves intersect at the maximum wind speed radius. According to Fig. 1 b), as the value of \( \beta \) is enlarged, horizontal wind profile changes a lot and the wind speed becomes larger within the maximum wind speed radius but smaller beyond it. On the basis of measured data and the upper limit of the air boundary layer, Holland determined that the wind pressure distribution coefficient \( \beta \) be between 1.0 and 2.5. Since the wind pressure distribution coefficient \( \beta \) introduced by Holland numerical model takes many values, Holland numerical model applies to a larger field. It can simulate different typhoons to such a good degree that most scholars accept it.

![Figure 1](image-url)  
Fig. 1. The variation of radial pressure and wind speed distribution with various value of \( \beta \).
3 COMPUTING METHOD OF WIND PRESSURE DISTRIBUTION COEFFICIENT

The value of wind pressure distribution coefficient $\beta$ influences the computing accuracy of numerical simulation of typhoon, so scholars have made a lot of researches on it. But such researches are still few in China. There are mainly two methods to estimate the wind pressure distribution coefficient $\beta$: one is to make regression analysis on the data of ground air pressure and then to estimate the values of parameters; the other is to get the gradient velocity from the equilibrium equation of barometric gradient and then to compare it with the data of wind speed of the upper frictional layer. Vickery and others [8] compared the two methods. In the first method, the parameter $\beta$ changes in different phases of typhoon and at different sites of wind field. Thus the value of Holland parameter $\beta$ is hard to determine. However, this method demonstrates the varying pattern of Holland parameter $\beta$ to some degree. And in the other method, Holland parameter $\beta$ can be expressed by the function of central air pressure differential and maximum wind speed radius. The formulas to calculate typhoon pressure distribution coefficient $\beta$, suggested by various scholars, are introduced briefly as follows.

3.1 Love & Murphy

Love & Murphy [9], according to measured data of typhoon pressure from northern Australia, suggested:

$$\beta = 0.25 + 0.3 \ln(\Delta P)$$

(7)

In the formula, $\Delta P$ is the central pressure differential.

3.2 Hubbert and etc.

When they analyzed the typhoon that attacked Australian coasts, Hubbert and others [10] proposed that wind pressure distribution coefficient parameter $\beta$ and the smallest central pressure of typhoon $P_c$ comply with linear relation. The expression is shown below:

$$\beta = 1.5 + (980 - P_c) / 120$$

(8)

3.3 Holland & Harper

Holland & Harper [11] suggested that, as to Australian tropical cyclone, parameter $\beta$ is a liner function of central pressure differential. They also proposed an empirical equation:

$$\beta = 2.0 - (P_c - 900) / 160$$

(9)

3.4 Jakobsen

By using the empirical relationship between the maximum wind speed and the central pressure differential as well as the equation of motion, Jakobsen [12] considered the function of Coriolis force and thus put forward a formula to calculate the Holland parameter $\beta$: 
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\[ \beta = \frac{e}{r_2^2} \frac{\rho_A}{[100] \Delta P} (V_{\text{max}})^2 \]  
(10)

\[ V_{\text{max}} = \left[ \frac{1}{3.6} \right] K_p (\Delta P)^\gamma \]  
(11)

In the formula, \( e = 2.71828 \), it is the base number of natural logarithm; \( r_2 = 1.05 \); \( \rho_A = 1.15 \) kg/m\(^3\); \( \Delta P \) = central pressure differential, hPa; \([100]\) = the value of central pressure differential when it is changed from hPa to Pa; \( V_{\text{max}} \) = the maximum wind speed within one minute at 500 m above sea level; \( K_p \) and \( \gamma \) are regression parameters, \( K_p = 12.36 \), \( \gamma = 0.73 \).

3.5 FEMA

The technical manual, in the Hazus typhoon disaster analysis software of the American Federal Emergency Management Agency (FEMA), also suggested a computing method of parameter \( \beta \). This is a linear relational expression of central pressure differential and maximum wind speed radius.

\[ \beta = 1.38 + 0.00184 \Delta P - 0.00309 R_{\text{max}} \]  
(12)

3.6 Holland

In 2008, Holland [14] proposed a new formula to calculate the wind pressure distribution coefficient \( \beta \). He said that many factors, such as central pressure of typhoon and its variation to time, its moving speed, its wind speed profile and the longitude and latitude of typhoon center. The computing expression is as follows:

\[ \beta = b_2 (v_{mg} / v_m)^2 \rightarrow 1.6b_2 \]  
(13)

\[ b_2 = -4.4 \times 10^{-4} (\Delta P)^2 + 0.01 \Delta P + 0.03 \frac{\partial p_c}{\partial t} - 0.014 \psi + 0.15 V_r x + 1.0 \]  
(14)

\[ x = 0.6(1 - \Delta P / 215) \]  
(15)

In the formula, \( \frac{\partial p_c}{\partial t} \) = variation of central pressure strength, hPa/h; \( \psi \) = absolute value of the central latitude of typhoon; \( V_r \) = moving speed of cyclone, m/s; \( V_{mg}/V_m \) = conversion factor from gradient wind to surface wind.

4 COMPARISON OF METHODS BASED ON AIR PRESSURE OBSERVATION

4.1 Introduction to Air Pressure Data from Observation Stations in Zhejiang Province

To study and verify the analytic model for radial typhoon pressure and speed distribution proposed by Holland, we compare the mentioned functional expressions for computing the typhoon
pressure distribution coefficient $\beta$, study the influence from different methods on computing results of radial typhoon pressure distribution and compare them with the fitting results of air pressure data from ground stations. A good deal of data on typhoon pressure is needed. Now we have collected a lot of measured data on wind pressure of the No.8 tropical storm Morakot from ground stations in 2009. It is demonstrated briefly as follows.

The No. 8 tropical storm Morakot was born at approximately 1,000 km away from the eastern Philippines on August 2, 2009. Its minimum central pressure was 945 hPa and the maximum average speed was 43.1 m/s (in 10 minutes). And few typhoons in the history had had such strength. Typhoon Morakot pass through Zhejiang province from south to north. It is tracked in Graph 2. The abundant air pressure data, which has been measured by observation stations, is typical. Additionally, there are 1,000 and more ground observation stations in Zhejiang province and 270 and more stations at most recorded the landing process of Typhoon Morakot completely. Graph 3 shows the locations of these stations. Each station recorded from 21:00 on August 8 to 20:00 on August 11 and produced every hour a group of data, which includes: date, time, serial number of station, name of station, latitude ($^\circ$), longitude ($^\circ$), altitude (0.1 m, -9,999 means the altitude has not been measured.), average wind direction in 10 minutes (0 ~ 359), average wind speed (m/s) within 10 minutes, maximum wind speed (m/s) in one hour, extreme wind speed (m/s) in one hour, and air pressure of this station (-9,999 means the altitude has not been measured). The yearbooks [15] of tropical cyclones present the longitude and latitude and pressure of the center of Typhoon Morakot in every hour from 11:00 on August 6 to 20:00 on August 11.

4.2 Values of Coefficient $\beta$ Calculated by Various Methods and Their Comparison

As is known, the maximum wind speed radius $R_{max}$ is needed when we calculate the typhoon pressure distribution coefficient $\beta$ with different methods and study their influence on the computing results of radial wind pressure distribution of typhoon. But measured data and yearbooks for tropical cyclones do not record the measured value of the maximum wind speed radius $R_{max}$. Therefore, the value of $R_{max}$ can be determined by the empirical functional relation, which has been obtained by Yasui [16] through fitting of measured records, between central pressure differential and maximum wind speed radius of typhoon. The following is the conditions for this relation:
(1) Central pressure of typhoon shall be smaller than 980 hPa;
(2) Distance from the center of typhoon to the engineering site shall be between 100 km and 500 km;
(3) Ground air pressure in the engineering site shall be smaller than 1,000 hPa.

\[ E(R_{\text{max}}) = 2.06 \times 10^4 \Delta P^{-1.27} \]  \hspace{1cm} (16)

\[ \sigma(R_{\text{max}}) = 4.4 \times 10^4 \Delta P^{-1.76} \]  \hspace{1cm} (17)

In the formula, \( E() \) represents the average value of \( R_{\text{max}} \) and \( \sigma() \) the variance.

On the basis of Holland distribution function for typhoon speed and pressure, the empirical function for \( R_{\text{max}} \) determined by Yasui and yearbooks of tropical cyclones, we use calculate the value of the typhoon pressure distribution coefficient \( \beta \) by various functional expressions and compare the values of \( \beta \). Fig. 4 shows the values of the wind pressure distribution coefficient \( \beta \), which have been computed by various methods, throughout the process of Typhoon Morakot. As is seen is the graph, the values of \( \beta \) computed by two methods of Jakobsen and Holland change intensely while those computed by the four methods of Love & Murphy, Hubbert and etc., Holland & Harper and FEMA are relatively stable; the central pressure differentials differ a lot before 3:00 on August 10. The value of \( \beta \) computed by Jakobsen’s method is largest and that computed by FEMA’s method is smallest and the former is almost twice the value of the latter; as strength of typhoon and central differential reduces in the process, all of the values of \( \beta \) computed by the six methods tend to decrease.

Figure 4. Values of wind pressure distribution calculated by various methods throughout typhoon Morakot.

4.3 Influence from Different Computing Methods on Radial Typhoon Pressure Distribution

Radial wind pressure and speed distributions of typhoon refer to the functional relationship between the wind pressure and wind speed on some profile in the center of typhoon and their distance to the center of typhoon. Fig. 5 presents the two-dimensional wind field and the radial wind speed profile of typhoon. Actually, ground observation stations cannot distribute or gather on a radial profile in the special structure of typhoon and the radius of the round vortex is usually from 500 km to 1,000 km. Typhoon can usually reach the lapse limit (15 ~ 20 km) vertically at most. The ration between the vertical and horizontal dimensions is around 1:50. Typhoon is a flat, cyclone and vertical air mass. Therefore it is considered that the wind pressure data of observation stations in two close plane regions is as same as that on a radial profile. On Fig. 6, a real point is a ground observation station; the two dotted oblique lines refer to two special planes;
the full oblique lie between the two dotted lines mean the radial wind profile of typhoon; the dots between the two oblique lines are selected ground observation stations; the quadrant box in the center refers to the center of typhoon; the wind pressure data from ground stations corresponding to these dots is exactly that of the radial wind profile; the two dotted curves represent stations furthest away from the center of typhoon and also the circle that takes the distance as its radius. In the disposal and calculation of wind pressure data from ground observation stations, we take 15 km as the distance between two planes and also between two straight lines. In consideration of landing of typhoon, its central pressure and its intense, we study the radial wind pressure distribution of typhoon at 00:00 on August 9 (before landing), 16:00 on August 9 (landing) and 16:00 on August 10 (after landing). And we reject abnormal wind pressure data from ground stations, in consideration that typhoon pressure shall be not smaller than central pressure and not bigger than barometric pressure.

Figure 5. Wind Field Profile of Typhoon.

Figure 6. Selection and Disposal of Station Locations.

At 00:00, August 9, Typhoon Morakot did not land. Its center was 25.5° at northern latitude and 120.5° at eastern longitude. Its central pressure \( P_c \) was 965 hPa. At that time, 278 stations recorded it completely. Natural air pressure \( P_a \) was 1,010 hPa. Therefore, computing results are shown by Fig. 7a) and 7b). At the same time, the distance between two planes is considered
to be 15 km, covering 26 ground stations at most. Abnormal data is removed. And the wind pressure coefficient $\beta$ is computed as 0.72 through fitting. It can be seen in Fig. 7b) that the wind pressure distribution curve, which is calculated according to Holland typhoon pressure distribution function and Yasui’s empirical function of $R_{\text{max}}$ and functional expressions of wind pressure distribution coefficient $\beta$ of various scholars, differs a lot from that obtained through removal of abnormal points and fitting of measured wind pressure data. The wind pressure distribution coefficient of typhoon $\beta=1.93$, which is calculated by Jakobsen’s method, is the largest one. In this method, the radius of typhoon’s eye is biggest and the typhoon pressure is smallest within the region of the biggest speed but it is largest beyond this region; in FEMA method, coefficient $\beta = 1.0$, is the smallest one; radius of typhoon eye is smallest; the pressure is biggest in the region of the largest speed but smallest beyond the region. These are more similar to the measured data.

When Typhoon Morakot was landing at 16:00 on August 9, the center was 26.5° at northern latitude, 119.9° eastern longitude. The central pressure $P_c = 970$ hPa. At that time, 252 ground stations recorded it completely. And the natural air pressure $P_a$ was considered as 1,010 hPa.
hPa. As a result, the computing results are shown by Fig. 8a) and 8b). At the same time, the distance between two planes is considered to be 15 km, covering 90 measuring stations at most. Abnormal points are disposed and the wind pressure distribution coefficient $\beta$ is calculated as 0.43 through fitting. Fig. 8b) shows that the wind pressure distribution curve, which is calculated according to Holland typhoon pressure distribution function and Yasui’s empirical function of $R_{max}$ and functional expressions of wind pressure distribution coefficient $\beta$ of various scholars, differs a lot from that obtained through removal of abnormal points and fitting of measured wind pressure data, similar to the situation before landing. The wind pressure distribution coefficient of typhoon $\beta=1.82$, which is calculated by Jakobsen’s method, is the largest one. In this method, the radius of typhoon’s eye is biggest and the typhoon pressure is smallest within the region of the biggest speed but it is largest beyond this region; in FEMA method, coefficient $\beta = 0.87$, is the smallest one; radius of typhoon eye is smallest; the pressure is biggest in the region of the largest speed but smallest beyond the region. These are more similar to the measured data. However, it is still more than twice the value of the typhoon pressure distribution coefficient $\beta$ computed by fitting measured data.

Typhoon Morakot has landed at 16:00 on August 10. Its center was 29.1° at northern latitude, 120.3° at eastern longitude, close to the center of Zhejiang province. Central pressure $P_c$ was 992 hPa. At that time, Typhoon Morakot has decreased and become a tropical storm. 275 ground stations recorded it completely. The natural air pressure $P_a$ was considered as 1,010 hPa. Thus the computing results are shown by Fig. 9a) and 9b). At the same time, the distance between two planes is considered to be 15 km, covering 25 measuring stations at most. Abnormal data is removed and the wind pressure distribution coefficient $\beta$ is computed as 1.33. Among all the methods to calculate the wind pressure distribution coefficient $\beta$, Holland’s method considered it as 1.66 and it is the largest one; while FEMA considered it as 0.80, the smallest one.

![Figure 9. The selection of stations and fitting process of pressure distribution (After landfall)](image-url)
In Fig. 10, the general variation of $\beta$ with the state of typhoon landfall are illustrated and compared with the other empirical results. Totally, the suggested curve from U.S.A. Manual of FEMA has the similar tendency with the observed curve, the fitted expressions of Eqs. (16) and (17) from the on-spot measurement can refinelly show the detailed change related to the state of typhoon landfall.

$$\beta = -2.365 + 0.0573\Delta P + 0.0035R_{\text{max}} \quad (\text{Before landfall})$$

$$\beta = 0.4899 + 0.0178\Delta P \quad \text{(After landfall)}$$

### 5 CONCLUSIONS

For the reasons given above, by the analysis of Holland’s functional model of radial wind speed and pressure distribution and on the basis of Holland’s function of typhoon speed and pressure as well as Yasui’s empirical function and measured data of $R_{\text{max}}$ and through the comparison of the influence from various computing functional expressions for typhoon pressure distribution coefficient $\beta$, the following conclusions can be drawn:

1) The value of the typhoon pressure distribution coefficient $\beta$, which is introduced by Holland’s functional model, influences the computing result to a large degree. It is necessary to analyze and determine the value of wind pressure distribution coefficient $\beta$ at the engineering site on the basis of measured data.

2) The values of the coefficient $\beta$ computed with different functional expressions differ a lot from each other. And the largest is likely to be twice the smallest one.

3) The wind pressure distribution curve, which is calculated according to Holland typhoon pressure distribution function and Yasui’s empirical function of $R_{\text{max}}$ and functional expressions of wind pressure distribution coefficient $\beta$ of various scholars, differs a lot from that obtained through removal of abnormal points and fitting of measured wind pressure data. It is necessary to work out a functional expression, which suits China’s coast situation, to compute wind pressure distribution coefficient $\beta$. 

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**Figure 10. The variation of $\beta$ with the state of typhoon landfall.**

In Fig. 10, the general variation of $\beta$ with the state of typhoon landfall are illustrated and compared with the other empirical results. Totally, the suggested curve from U.S.A. Manual of FEMA has the similar tendency with the observed curve, the fitted expressions of Eqs. (16) and (17) from the on-spot measurement can refinelly show the detailed change related to the state of typhoon landfall.
4) Comparison between computing results and measured data shows that the computing method for the coefficient $\beta$, which is proposed by the technical manual of the Hazus typhoon disaster analysis software of the FEMA, can be used if the data of radial profile of air pressure is out of access. The wind pressure distribution curve obtained by this method is very similar to that obtained through fitting of measured data. But this conclusion needs studying and verifying further.

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7 REFERENCES