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Design Wave Height Estimation under the Influence of Typhoon Frequency, Distance, and Intensity

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Abstract: The extreme sea conditions caused by typhoons pose a threat to the design safety of marine and coastal engineering structures. In the past, design wave height calculation models that only considered the frequency of typhoons ignored the influence of other hazard factors of typhoons, resulting in lower design standards. In this paper, typhoon frequency, intensity, and distance are selected, and dimensional influences of different factors are eliminated through standardization processing. Based on the correlation between different hazard factors, we have obtained a multi-dimensional discrete joint probability distribution of typhoon hazard factors and constructed a new design wave height that considers the comprehensive effects of typhoon frequency, intensity, and distance. Our results show that the design wave height values of the 50-year, 100-year, and 200-year events are 12.59%, 8.10%, and 3.14% higher than the Gumbel distribution, which is more in line with the distribution of the wave height of waves under severe typhoon conditions. The new model can fully reflect the impact of typhoons on wave height, which can provide a reference for the design safety of marine engineering in the South China Sea.

Keywords: typhoon-induced multiple hazard factors; design wave height; standardization; South China Sea

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1. Introduction

Typhoons are one of the important factors that induce various marine disasters. Under the combined influence of its own hazard factors, they often affect the wind, waves, and currents around the sea area, leading to extreme sea conditions. Such extreme sea conditions can easily cause structural failure, even overturning, and damage to marine and coastal engineering structures such as flood embankments and offshore platforms that have been working on the sea for a long time [1–3]. China is one of the countries most affected by typhoons in the world. The South China Sea and coastal provinces in the South China Sea are also the hardest-hit areas of typhoon disasters in China. Not only do many typhoons occur, they also occur frequently [4–6]. As the South China Sea is a rich area of marine resources in China, with important strategic significance in the marine economy [7,8], making the design safety of various marine and coastal engineering structures in the South China Sea particularly important. The currently employed design wave height model neglects the influence of typhoon intensity and typhoon distance, and only considers the influence of typhoon frequency. It is precisely because the impact of typhoons is not fully considered that the design standards of coastal engineering are low and the protection capacity is limited. Therefore, it is necessary to reasonably select representative hazard factors such as typhoon intensity, the shortest distance from typhoon center to sea area, and the frequency of typhoon occurrence. Then, the correlation between each hazard factor and its impact on marine environmental factors can be analyzed. On this basis, the design wave height calculation model of multiple hazard factors is established. At the same time, the design wave height of the South China Sea during the typhoon period can be calculated by using this model. It is of great research significance for the protection of various marine structures and the reduction of marine disasters in the South China Sea.

The research method of calculating design wave height is to select an extreme value model as the probability distribution of wave height, then use the measured sample data to determine the unknown parameters, and finally calculate the multi-year design wave height through the accumulation rate. Commonly used extreme value distribution models include Gumbel distribution [9], Weibull distribution [10], P-III distribution [11], lognormal distribution [12], and so on. The track and number of typhoons can change from year to year, resulting in a different number of typhoons affecting a certain ocean area each year. Therefore, the typhoon frequency caused by the change of typhoon track directly affects the statistical law of wave height under the influence of typhoon. The commonly used extreme value distribution model cannot consider this feature, and it is difficult to meet the statistical law of typhoon waves. The univariate compound extremum distribution, considering the frequency and intensity of typhoons, can more truly reflect the connotation characteristics of things than the probability distribution of a single factor, which accords with its probability and statistical characteristics. In 1980, Liu and Ma proposed a new probability distribution model—the compound extreme value distribution theory [13]—focusing on the characteristics of typhoons. The new theory deduced that a set of discrete distributions (typhoon frequency) and continuous distributions (wave height) can form different composite extreme distributions. Since then, the compound extremum distribution has been widely used in different regions at home and abroad, which has continuously verified the correctness of probability prediction results by using the compound extremum distribution [14,15]. In the 1987 Summary of Flood Research in the United States [16], this model is listed as one of the contributions of the United States to flood frequency analysis in the past 50 years. In recent years, some scholars have improved the compound extremum distribution from the perspective of parameter estimation methods, threshold selection, and model uncertainty, and generally improved the calculation accuracy of the compound extremum distribution [17,18]. With the increase of mathematical knowledge, it has become possible to use multiple variables to demonstrate the interaction between extreme weather such as typhoons and marine environmental parameters. Thereafter, the composite extreme value distribution has developed from one-dimensional to multi-dimensional [19].

The research on the calculation method of marine environmental factors has developed from the simple probabilistic prediction to the probabilistic prediction considering the influence of typhoons. Subsequently, the theoretical model has been developed from one dimension to multiple dimensions, and the combined probability prediction of multiple marine environmental factors under the influence of typhoons has been realized. The calculation of the design wave height, while considering the influence of typhoons on the sea area, is a great progress in the theoretical model of the design wave height calculation. However, the probabilistic prediction model of wave height only considers the influence of typhoon frequency and does not consider the influence of other typhoon factors on wind wave height. In fact, typhoon wind speed, pressure, frequency, distance will affect the accuracy of the design wave height calculation. The wind speed, pressure, frequency, and distance of typhoons all affect the accuracy of calculating design wave heights. The frequency of typhoon occurrence is the most common typhoon hazard factor in typhoon research, because typhoon occurrence inevitably causes extreme sea conditions. Therefore, the higher the frequency of typhoon occurrence, the more likely it is to have extreme marine environmental element values. The compound extremum distribution reflects the influence of typhoon frequency on wave height [20,21], but does not reflect the influence of other typhoon hazard factors on wind wave height. Typhoon intensity is one of the important hazard factors in typhoon research, which has a significant impact on the wave height. Generally, the stronger the typhoon intensity, the stronger the wind, and the higher the wave height caused. The distance between the typhoon center and the observation point is also one of the hazard factors of typhoons. Under the same typhoon intensity, the closer the typhoon center is to the observation point, the higher the wave height caused by the typhoon [22]. In addition, typhoon hazard factors such as typhoon moving speed, typhoon path, radius of maximum wind of typhoon, and pressure difference at typhoon center all have a certain impact on wave height [23–25]. Among the many typhoon hazard factors, it is necessary to determine the typhoon factor which has significant influence on the probability distribution of wave height. Only by selecting representative typhoon hazard factors can the effect of typhoon factors be fully reflected.

There are many hazard factors such as typhoon intensity, the shortest distance from the typhoon center to the sea area, and the frequency of typhoon occurrence. There are three key points when analyzing the distribution and calculation of wave height under the joint influence of multiple typhoon hazard factors: first, determining the representative typhoon hazard factors; second, eliminating the influence of differences in dimensions and value ranges among different hazard factors; third, the joint distribution of multi-dimensional typhoon disaster factors should be reasonably studied. Taking the maximum wind speed near the center at the bottom of a typhoon and the frequency of typhoon occurrences as examples, on the one hand, the two have different dimensions and units of measurement. On the other hand, the frequency of typhoon occurrences is a discrete variable of typhoon hazard factors, while the maximum wind speed near the center at the bottom of a typhoon is a continuous variable of typhoon hazard factors. Therefore, it is necessary to normalize the maximum wind speed near the center at the bottom of a typhoon to solve the comparability between data indicators; in addition, the correlation between different typhoon disaster factors is not simply independent of each other. For example, the shortest distance and frequency of typhoons vary with the location of the typhoon, which belongs to the external cause of typhoon hazard factors. Therefore, it should be a two-dimensional discrete distribution, rather than a simple independent distribution. Therefore, one of the focuses of this article is how to achieve the standardization of typhoon hazard factors to eliminate the impact of differences in dimensions and value ranges between different indicators. At the same time, based on the correlation between typhoon hazard factors such as typhoon intensity and typhoon frequency, a reasonable construction of a multidimensional joint distribution of typhoon hazard factors is also important.

Starting from the mechanism of the influence of typhoon hazard factors on wave height, this article identifies representative typhoon hazard factors that have a significant impact on the design wave height elements. Unify the standardization of typhoon hazard factors based on the differences in data types among different typhoon hazard factors, to solve the comparability problem between data indicators. Based on its correlation, establish a multidimensional joint probability distribution of typhoon hazard factors to comprehensively reflect the impact of typhoons. A new design wave height calculation model is proposed by combining the joint probability distribution of multi-dimensional typhoon hazard factors with the wave height distribution. The design wave height of the South China Sea is calculated once in a period of many years, and the obtained results are compared with the results calculated via existing models in multiple aspects to verify and demonstrate the superiority of the new model.

This article mainly comprises two aspects: firstly, the typhoon hazard factors represented by typhoon frequency, intensity, and distance are determined, and the joint probability distribution of typhoon hazard factors is established by eliminating the differences among different disaster factors. Secondly, the dimension of discrete distribution of compound extremum is extended, and the design wave height calculation model is proposed under the influence of typhoon frequency, distance, and intensity. The joint analysis of typhoon intensity, distance from typhoon center to observation point, frequency of typhoon occurrence, and calculation of design wave height not only provide new ideas for the study of the impact of typhoons on design wave height, but also provide certain reference value for the safety design of offshore structure in the South China Sea.

The structure of the remainder of this paper is as follows: in the second part, the corresponding mathematical model is given, and the multi-dimensional discrete composite distribution model is proposed. In the third part, taking the South China Sea where typhoons frequently occur as an example, the new model is used to estimate the design wave height near Naozhou Island in the South China Sea under the influence of typhoons. In the fourth part, the research of this paper is summarized.

2. Joint Analysis and Design of Wave Height Models for Typhoons' Multiple Hazard Factors

2.1. Determination of Typhoon Hazard Factors

The lower the internal pressure of a typhoon, the greater the pressure difference in the typhoon area. The lower the central pressure, the greater the energy of the typhoon, and the greater the central wind speed [26], which can lead to the occurrence of heavy rainstorms [27]. Therefore, in the typhoon process where typhoon factors affect wave height, the central minimum pressure, and maximum wind speed of the typhoon are important hazard factors. Research has shown that there is an approximate relationship between the pressure drop at the center of a typhoon and the maximum wind speed near its center, as follows [28]:

$$v_{max} = K(p_\infty - p_0)^{\frac{1}{2}} \tag{1}$$

where, K is a function of density. Near the center of a typhoon, the average K value is generally 5.7, p_0 is the lowest pressure at the center of the typhoon, and p_∞ is the atmospheric pressure in the surrounding environment of the typhoon.

Therefore, the relationship between the center minimum pressure and maximum wind speed of a typhoon is basically determined for a specific sea area. This indicates that only one needs to be considered for the center minimum pressure and maximum wind speed of a typhoon. The classification of tropical cyclones is based on the maximum wind speed at the bottom center of a typhoon, so the maximum wind speed at the bottom center of a typhoon is an important indicator of typhoon strength, and the minimum pressure at the center of a typhoon can also reflect its strength. Therefore, the intensity of a typhoon can fully represent its central minimum pressure and maximum wind speed. The difference in wave height caused by typhoons of different intensities is significant, and it is necessary to focus on considering typhoon intensity when calculating ocean design wave heights.

The occurrence of typhoons will inevitably lead to larger wave heights, and the higher the frequency of typhoons appearing in the research area, the greater the probability of generating harmful extreme wave heights. Typhoon frequency has been widely considered and applied in practical engineering. As early as 1987, Muir and El-Shaarawi [29] compared six probability distribution models widely used in the international ocean engineering community, and believed that the design wave height model considering typhoon frequency has the advantages of good agreement with measured data and reasonable prediction results. The frequency of typhoons has a significant impact on wave heights, which is a consensus in the engineering community. Therefore, when calculating ocean design wave heights, it is necessary to focus on the frequency of typhoons.

The shortest distance between the center of a typhoon and the sea observation point is a hazard factor that describes the impact of a typhoon on the research area. From the observed data of wave height, the maximum wave of the typhoon clearly appears near the center of the typhoon and decreases in all directions. The distance between the typhoon center and the studied sea area was divided into different levels by Fang Zhongsheng et al. to study the size of the wave height period generated under different distances [22]. The results showed that the smaller the distance between the typhoon center and the studied sea area, the higher the average wave generated. Therefore, when calculating the ocean design wave height, it is necessary to focus on the shortest distance between the typhoon center and the observation point.

In addition to typhoon frequency, distance, and intensity, moving speed and path also affect wave height. However, the influence of typhoon moving speed and typhoon track on wave height is limited [30]. Therefore, this paper focuses on the influence of typhoon frequency, distance, and intensity.

During the occurrence of typhoons, the abnormal changes in ocean wave height are related to the occurrence of typhoons, their impact range, and typhoon intensity. Therefore, this article considers the impact of typhoon frequency, typhoon intensity, and the shortest distance from the typhoon center to the observation point on the calculation of design wave height, comprehensively reflecting the role of typhoons. At the same time, data on typhoon intensity, typhoon frequency, and the shortest distance from the typhoon center to the observation point are easy to obtain, making the research method highly practical. Based on the correlation between typhoon intensity, distance, and frequency, a reasonable joint probability of multi-dimensional typhoon hazard factors is established, which is linked to the design wave height to comprehensively reflect the impact of typhoon factors on wave height.

2.2. Standardization of Typhoon Hazard Factors

Hazard factors such as typhoon intensity, distance from typhoon center to observation point, and frequency of typhoon occurrence often have different dimensions and units. In order to eliminate the impact of differences in dimensions and value ranges between different indicators, data standardization and standardization processing are needed to solve the comparability between data indicators. The processed indicators are in the same order of magnitude, which is suitable for comprehensive comparison and evaluation. Another question is that the frequency of typhoon occurrence belongs to discrete data, while the maximum wind speed of the typhoon and the shortest distance from the typhoon center to the observation point are continuous data. It is necessary to harmonize the typhoon hazard factors and uniformly conduct discretization processing. The standardization formula is [31]

$$x^* = \frac{x - \overline{x}}{\sigma} \tag{2}$$

where x is the original value of a hazard factor, $\overline{x}$ is the average of the data samples, σ is the standard deviation of the data samples, and x^* is the standardized value of the hazard factor.

The frequency of typhoon occurrence is discrete data. According to the statistical data of typhoon in the study area, it can be directly divided into several levels according to the frequency of typhoon occurrence to describe the influence of typhoon on the observation point.

Typhoon intensity can be measured by the maximum wind speed at the bottom center of the typhoon, or by the lowest pressure near the center of the typhoon. The typhoon intensity data is processed by standard to eliminate the difference of order of magnitude between it and typhoon frequency, typhoon distance.

After the standardization of typhoon intensity, its mean value is 0 and its variance is 1. The typhoon data is divided into different levels with an interval length of one standard deviation. The higher the level, the greater the danger.

The distance between the center of typhoon and the observation point can be calculated using latitude and longitude [32]:

$$\mathrm{S} = 2\mathrm{arcsin}\sqrt{\sin^2\frac{\mathrm{a}}{2} + \cos(\mathrm{Lat1}) \times \cos(\mathrm{Lat2}) \times \sin^2\frac{\mathrm{b}}{2}} \times \mathrm{R} \tag{3}$$

The latitudes of the typhoon center (point A) and the observation point (point B) are Lat1 and Lat2, with longitudes of Lng1 and Lng2. The latitude difference a = Lat1 − Lat2, and the longitude difference b = Lng1 − Lng2. R is the radius of the Earth and its mean value is 6378.137 km.

The longitude and latitude data of the typhoon center can be obtained from the typhoon path data, and the longitude and latitude of the observation point are known. Therefore, the distance (S: km) from point A to point B can be approximately calculated using Equation (3). Perform the above calculation for each path passing through a typhoon to obtain the shortest distance between the center of a series of typhoons and the observation point. Following the standardization steps mentioned above, the shortest distance between the typhoon center and the observation point can be divided into different levels to describe the impact of the typhoon on the observation point.

2.3. Skewness and Kurtosis

The skewness coefficient, S, and kurtosis coefficient, K, can be used, respectively, to describe the symmetry and steep shape of random sample distribution. Specifically, it can be defined as the third-order center distance and the fourth-order center distance of the sample, respectively. The skewness coefficient, S, is also a statistic that describes the distribution form of data, and it describes the symmetry of the distribution of the values taken by an aggregate. Kurtosis coefficient K is also a characteristic number that characterizes the peak value of probability density distribution curve at the average value, namely, a statistic that describes the steepness of the distribution pattern of all values taken in the aggregate. Intuitively, kurtosis K reflects the cusp of the data peak.

2.4. Design Wave Height Calculation Model Reflecting the Impact of Multiple Typhoon Hazard Factors

It is important when constructing a new design wave height model to explore the correlation between typhoon frequency, intensity, and distance and reasonably reflect the joint distribution of typhoon hazard factors. The strength of a typhoon is characterized by the maximum wind speed at the center of the typhoon's bottom layer (or the minimum pressure at the bottom layer). Although it may vary depending on the sea area it passes through, once a typhoon is generated, it has its own maximum wind speed and minimum pressure, which do not change depending on the sea area under consideration. It belongs to the inherent nature of a typhoon and is approximately independent of the external hazard factors of the typhoon. The frequency of typhoons and the shortest distance from the typhoon center to the observation point only occur due to the sea area under consideration, and the disaster factors affected by the study sea area, that is, the data of these hazard factors will vary depending on the region under consideration, belonging to the external hazard factors of typhoons. However, these two factors do not have a clear reference relationship and are in a relatively uncertain state, making it inappropriate to assume their independence. Therefore, typhoon intensity is approximately independent of typhoon frequency and distance, and there is a fuzzy relationship between typhoon frequency and distance. The joint probability expression of typhoon frequency, intensity, and distance is as follows:

$$p(i,j,k) = p(i) \cdot p(j,k) \quad (4)$$

where, $p(i)$ is the probability of typhoon intensity, $p(j,k)$ is the joint probability of typhoon frequency and distance, and, $p(i,j,k)$ is the joint probability of typhoon frequency, intensity, and distance.

Referring to the compound extremum model of a single hazard factor and combining with the joint probability distribution of typhoon frequency, intensity, distance as well as the probability distribution of wave height, a design wave height model for typhoon multiple hazard factors was established to calculate the design wave height under the joint influence of typhoon multiple hazard factors:

Definition 1. *Let (y_1, y_2, y_3) be a three-dimensional discrete random vector, and its probability distribution be $p_{ijk} = P(y_1 = i, y_2 = j, y_3 = k)$, ξ. Following the continuous distribution G(x), note*

$$F_0(x) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} p_{ijk} [G(x)]^{ijk} \quad (5)$$

We call it $F_0(x)$; it is a composite distribution composed of these two distributions.

Theorem 1. *Assuming $\xi, \eta_m (m = 0, \ldots, 6)$ is a continuous random variable, and η_m follows the distribution $Q_m(x)$, ξ Following the distribution $G(x)$, let y_1, y_2, y_3 be a random variable that is independent of both $\eta_m (m = 0, \ldots, 6)$ and ξ and takes a non-negative integer value, denoted as ξ_{ijk} is ξ When $y_1 = i, y_2 = j, y_3 = k$ Observation value at, denoted as*

$$p_{ijk} = P(y_1 = i, y_2 = j, y_3 = k),\ i, j, k = 0, 1, 2, \ldots, \tag{6}$$

Define random variables ζ

$$\zeta = \begin{cases} \eta_0, & \text{when } y_1 = 0, y_2 = 0, y_3 = 0 \\ \eta_1, & \text{when } y_1 = 0, y_2 = 0, y_3 > 0 \\ \eta_2, & \text{when } y_1 = 0, y_2 > 0, y_3 > 0 \\ \eta_3, & \text{when } y_1 = 0, y_2 > 0, y_3 = 0 \\ \eta_4, & \text{when } y_1 > 0, y_2 = 0, y_3 = 0 \\ \eta_5, & \text{when } y_1 > 0, y_2 > 0, y_3 = 0 \\ \eta_6, & \text{when } y_1 > 0, y_2 = 0, y_3 > 0 \\ \max\limits_{\substack{1 \le i \le y_1, \\ 1 \le j \le y_2, \\ 1 \le k \le y_3}} \left\{ \xi_{ijk} \right\}, & y_1, y_2, y_3 \ge 1 \end{cases} \tag{7}$$

Then, the distribution function of ζ is

$$F_0(x) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} p_{ijk} [G(x)]^{ijk} \tag{8}$$

Proof of Theorem 1.

$$\begin{aligned} F(x) = p\{\zeta < x\} \quad & = p\{\zeta < x, y_1 = 0, y_2 = 0, y_3 = 0\} + p\{\zeta < x, y_1 = 0, y_2 = 0, y_3 > 0\} \\ & + p\{\zeta < x, y_1 = 0, y_2 > 0, y_3 > 0\} + p\{\zeta < x, y_1 = 0, y_2 > 0, y_3 = 0\} \\ & + p\{\zeta < x, y_1 > 0, y_2 = 0, y_3 = 0\} + p\{\zeta < x, y_1 > 0, y_2 > 0, y_3 = 0\} \\ & + p\{\zeta < x, y_1 > 0, y_2 = 0, y_3 > 0\} + \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} p\{\zeta < x, y_1 = i, y_2 = j, y_3 = k\} \\ & = p\{\eta_0 < x\} p\{y_1 = 0, y_2 = 0, y_3 = 0\} + p\{\eta_1 < x\} p\{y_1 = 0, y_2 = 0, y_3 > 0\} \\ & + p\{\eta_2 < x\} p\{y_1 = 0, y_2 > 0, y_3 > 0\} + p\{\eta_3 < x\} p\{y_1 = 0, y_2 > 0, y_3 = 0\} \\ & + p\{\eta_4 < x\} p\{y_1 > 0, y_2 = 0, y_3 = 0\} + p\{\eta_5 < x\} p\{y_1 > 0, y_2 > 0, y_3 = 0\} \\ & + p\{\eta_6 < x\} p\{y_1 > 0, y_2 = 0, y_3 > 0\} \\ & + \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} p\left\{\zeta < x|_{y_1 = i, y_2 = j, y_3 = k}\right\} p\{\zeta < x, y_1 = i, y_2 = j, y_3 = k\} \\ & = Q_0(x) p_{000} + Q_1(x) \sum_{k=1}^{\infty} p_{00k} + Q_2(x) \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} p_{0jk} + Q_3(x) \sum_{j=1}^{\infty} p_{0j0} + Q_4(x) \sum_{i=1}^{\infty} p_{i00} \\ & + Q_5(x) \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} p_{ij0} + Q_6(x) \sum_{i=1}^{\infty} \sum_{k=1}^{\infty} p_{i0k} + \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} p_{ijk} [G(x)]^{ijk} \\ & = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} p_{ijk} [G(x)]^{ijk} - p_{000}(1 - Q_0(x)) - \sum_{k=1}^{\infty} p_{00k}(1 - Q_1(x)) \\ & = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} p_{ijk} [G(x)]^{ijk} - p_{000}(1 - Q_0(x)) - \sum_{k=1}^{\infty} p_{00k}(1 - Q_1(x)) \\ & - \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} p_{ij0}(1 - Q_5(x)) - \sum_{i=1}^{\infty} \sum_{k=1}^{\infty} p_{i0k}(1 - Q_6(x)) \end{aligned} \tag{9}$$

Denoted as $F_0(x) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} p_{ijk} [G(x)]^{ijk}$, easy to see $F(x) = F_0(x) - \epsilon(x)$.

$$\epsilon(x) = p_{000}(1-Q_0(x)) + \sum_{k=1}^{\infty} p_{00k}(1-Q_1(x)) + \sum_{j=1}^{\infty}\sum_{k=1}^{\infty} p_{0jk}(1-Q_2(x)) + \sum_{j=1}^{\infty} p_{0j0}(1-Q_3(x)) + \sum_{i=1}^{\infty} p_{i00}(1-Q_4(x)) + \sum_{i=1}^{\infty}\sum_{j=1}^{\infty} p_{ij0}(1-Q_5(x)) + \sum_{i=1}^{\infty}\sum_{k=1}^{\infty} p_{i0k}(1-Q_6(x)) \quad (10)$$

where, $F_0(x)$ is a three-dimensional discrete compound extremum distribution composed of $\eta_m(m=0,\ldots,6)$ distribution and ξ distribution. In practice, the three characteristic factors of typhoons must all be greater than 1 to have an impact on sea waves. If one of them is zero, for example, when the intensity of a typhoon is zero, and the frequency of typhoon occurrence and the shortest distance from the typhoon center to the measuring point are not zero, this situation cannot exist; $\epsilon(x)$ is obviously 0. Therefore, when we solve $F(x) = R$, we can replace it with $F_0(x) = R$, ignoring $\epsilon(x)$. This simplifies the problem. The proof process is similar to the one-dimensional discrete compound extremum distribution [33]. □

2.5. Study Design

Normalize the typhoon intensity (defined by the maximum wind speed at the bottom center of the typhoon), the shortest distance from the typhoon center to the observation point, and the frequency of typhoon occurrence, and classify them into levels. Based on the correlation between typhoon intensity, the shortest distance from the typhoon center to the observation point, and the frequency of typhoon occurrence, establish a multidimensional joint probability model of typhoon hazard factors, comprehensively reflecting the characteristics of the typhoon. At the same time, the design wave height is calculated based on the derived design wave height model that reflects the multiple hazard factors of typhoons. By comparing the calculation results with previous distribution models, the superiority of the new model is verified and demonstrated. The flow chart of the study design is shown in Figure 1.

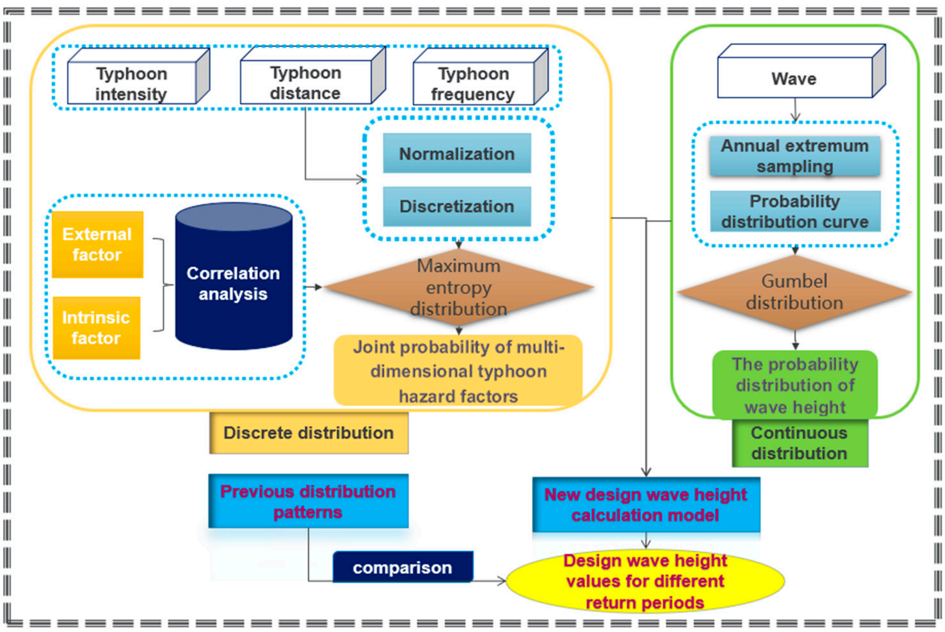


Figure 1. Flow chart.

3. Application in Engineering Examples

This article studies the joint effects of multiple hazard factors of typhoons in the South China Sea on design wave heights. The main collection and use of typhoon statistics from the Naozhou Ocean Observatory and Naozhou Island (21°16′ N, 110°22′ E) from 1990 to

2016 were wind wave data and typhoon data. The geographical location map of the study area is shown in Figure 2.

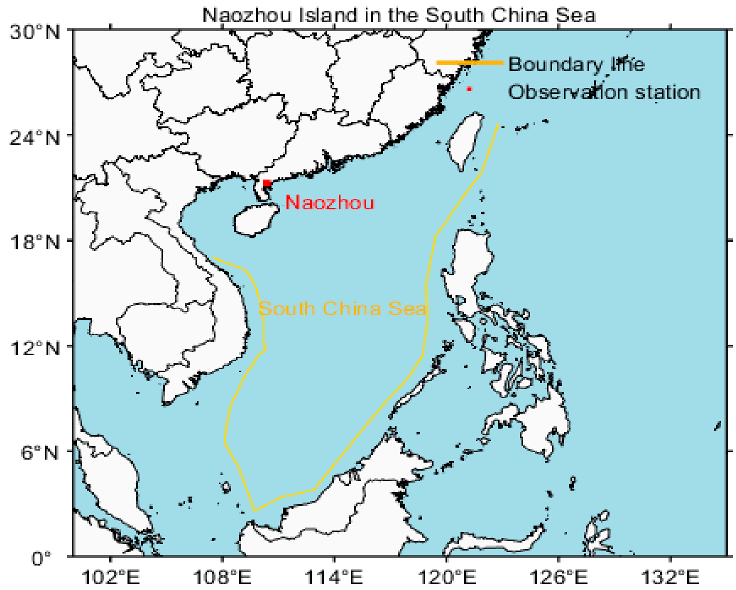


Figure 2. Geographical location map.

3.1. Typhoon Multiple Hazard Factors Joint Distribution

Due to the consideration of the maximum values of ocean waves under extreme conditions, the wave height data in the Naozhou Island (21°16′ N, 110°22′ E) of the South China Sea from 1990 to 2016 and the typhoon data corresponding to the annual extreme wave heights was selected for analysis, as shown in Table 1. Complete typhoon data is available through "The CMA Tropical Cyclone Database", which can be accessed at https://tcdata.typhoon.org.cn/index.html (accessed on 12 March 2023).

Table 1. Annual strongest typhoon data near Naozhou Island from 1990 to 2016 (partial).

Year	Number	X_1 (m/s)	X_2 (km)	X_3 (m)
1990	9004	25	96	2.8
1991	9111	48	72	4.6
1992	9205	35	187	4.3
1993	9323	20	116	2.8
......	......	......	......	......

X_1 represents maximum wind speed at the bottom center of a typhoon (m/s); X_2 represents shortest distance from typhoon center to observation point (km); X_3 represents annual maximum wave height (m).

Where the maximum wind speed is the maximum typhoon wind speed corresponding to the annual extreme wave height, typhoon frequency refers to the proportion of the annual number of typhoons in the total number of typhoons in the study area from 1990 to 2016.

To understand the impact of typhoons, we consider their intensity, the distance from typhoon centers to observation points, and frequency of occurrence to describe their impact on wave heights. According to Formula (2), the typhoon intensity, the shortest distance from the typhoon center to the observation point, and the frequency of typhoon occurrence during 1990–2016 were standardized. Since the standardized data mean is 0 and the standard deviation is 1. We divide the data into different levels by one standard deviation interval. The results are shown in Tables 2–4, respectively.

Table 2. Standardized typhoon intensity.

Level	1	2	3	4	5
Number of Times	2	6	8	8	1

Table 3. Standardized shortest distance from typhoon center to observation point.

Level	1	2	3	4	5
Number of Times	15	6	2	1	1

Table 4. Standardized typhoon frequency.

Level	1	2	3	4	5
Number of Times	2	6	7	5	4

In order to illustrate the characteristics of typhoon data and further explore the potential information, the skewness coefficient S and kurtosis coefficient K can be used, respectively, to describe the symmetry and steep shape of random sample distribution. Statistical analysis was conducted on the standardized data of typhoon intensity, the shortest distance from typhoon center to observation point, and typhoon frequency. The corresponding skewness coefficient S and kurtosis coefficient K are shown in Table 5.

Table 5. Characteristic coefficients of different typhoon hazard factors.

Characteristic Parameters	Typhoon Intensity	Typhoon Distance	Typhoon Frequency
skewness coefficient S	−0.2263	1.7101	0.1983
kurtosis coefficient K	2.2929	5.306	2.2447

From the perspective of skewness, the typhoon intensity is left-biased, while the shortest distance from the typhoon center to the observation point and the frequency of typhoon occurrence are both right-biased. From the perspective of kurtosis, the intensity and frequency of typhoons are both smoother at the peak than the normal distribution, while the shortest distance from the typhoon center to the observation point is steeper at the peak than the normal distribution.

The commonly used discrete distributions are Poisson distribution, binomial distribution, discrete maximum entropy distribution, etc. The study used Poisson distribution and discrete maximum entropy distribution to fit standardized typhoon intensity, the shortest distance from typhoon center to observation point, and typhoon occurrence frequency data. The fitted figures are shown in Figure 3, respectively.

From the above fitting graphs, both the discrete maximum entropy distribution and the Poisson distribution are good in fitting the frequency of typhoon occurrences, but in fitting the typhoon intensity and the shortest distance from the typhoon center to the observation point, the discrete maximum entropy distribution is relatively good. Therefore, the study will use discrete maximum entropy to fit the disaster factors of each typhoon.

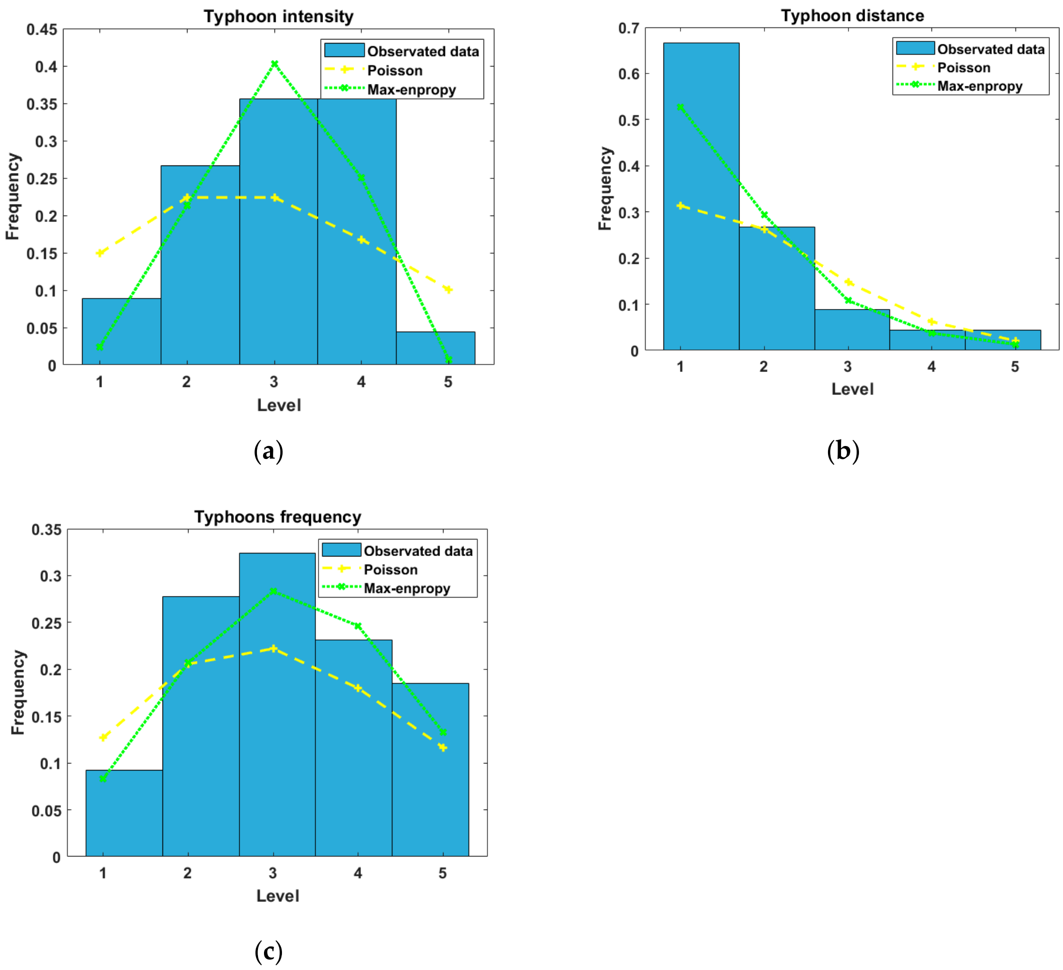


Figure 3. (**a**) Fitting of typhoon intensity; (**b**) fitting of typhoon distance; (**c**) fitting of typhoon frequency. The green curve represents discrete maximum entropy distribution; the yellow curve represents Poisson distribution.

In order to describe typhoon variables reasonably, the maximum entropy distribution can be used to make the most reasonable inference of the unknown relation, provided that some knowledge is known. The maximum entropy distribution function does not make any restrictive assumptions about typhoon parameters and maintains the maximum uncertainty of unknown information while constraining known information. By replacing the joint probability distribution of typhoon hazard factors established by the maximum entropy distribution into the discrete distribution of the new model, the relation between typhoon factors and wave height can be established. According to the fact that typhoon intensity belongs to the internal factors of typhoons, the discrete maximum entropy Equation (11) [34,35] is used for fitting, and the estimated parameters are shown in Table 6. Where, α, γ, β, and ξ are the parameters of the discrete maximum entropy distribution to be fitted to data:

$$p(i) = exp\left\{\alpha - 1 - \beta i^{\xi} + \gamma lni\right\} \tag{11}$$

Table 6. Parameter estimate of typhoon intensity.

α	γ	β	ξ
−2.72	3.2438	0.00248	4.884

Based on the correlation between the frequency of typhoon occurrence and the shortest distance from the typhoon center to the observation point, a two-dimensional discrete maximum entropy equation (Equation (12) [36]) was used to fit the shortest distance from the typhoon center to the observation point and the frequency of typhoon occurrence. The parameter estimation results are shown in Table 7. Where, α, t_2, t_3, t_4, m_1 and m_2 are the parameters of the two-dimensional discrete maximum entropy distribution to be fitted to data:

$$p(j,k) = \alpha(jk)^{t_2} e^{-t_3 j^{m_1} - t_4 k^{m_2}} \tag{12}$$

Table 7. Parameter estimate of typhoon occurrence frequency and shortest distance.

α	t_2	t_3	t_4	m_1	m_2
0.5472	2.181	2.634	0.1101	0.81	2.07

Based on the correlation between typhoon intensity, frequency of occurrence, and the shortest distance from the typhoon center to the observation point, the joint probability distribution of multiple hazard factors for typhoons is constructed as Equation (4). The results shown in Tables 6 and 7 are the estimated values of each parameter in the joint probability distribution.

3.2. Wave Height Distribution and Parameter Estimation

According to the Gumbel distribution used to calculate the design wave height of the South China Sea in the past [37], this paper conducts Gumbel goodness-of-fit test on the wave height data on Naozhou Island. Meanwhile, Weibull distribution and P-III distribution were added for comparison in order to verify the best fitting degree between Gumbel distribution and wave height. The parameters of each extreme value distribution are shown in Table 8.

Table 8. The parameters of each extreme value distribution.

Parameters	Gumbel	Weibull	P-III
position parameter	$\mu = 3.7799$	$\mu = 0.5000$	$\mu = -1.5423$
scale parameter	$\sigma = 1.2709$	$\beta = 2.9891$	$\beta = 2.8665$
shape parameter		$\alpha = 4.4293$	$\alpha = 17.1942$

Where, the position parameter is the statistical parameter that affect the starting position of a curve. The scale parameter is the statistical parameter that changes the vertical and horizontal coordinates of the curve and the steepness of the curve. The shape parameter is the statistical parameter that controls the shape of the distribution curve.

Then, the KS test method was used to test the goodness of fit of each extreme value distribution, and the results are shown in Table 9.

Table 9. K-S test.

Distribution Model	p	D_n	D_0 (0.05)	Compare	Result
Gumbel	0.7644	0.1275	0.2641	$D_n < D_0$	accept
Weibull	0.6086	0.1461	0.2641	$D_n < D_0$	accept
Pearson-III	0.8035	0.1226	0.2641	$D_n < D_0$	accept

Where, the p value in the K-S test is a test for the difference in cumulative distribution, D_n is test value, and D_0 is critical value (0.05). As shown in Table 9, all the test values are less than the critical value and the p value is greater than 0.05, which indicates that the Gumbel, Weibull, and P-III distributions all fit well with the distribution of the actual wave height.

The image method can also be used to visualize the fit of each distribution. The probability plot, quantile plot, return level plot, and density plot of all extreme value distributions are shown in Figures 4–6.

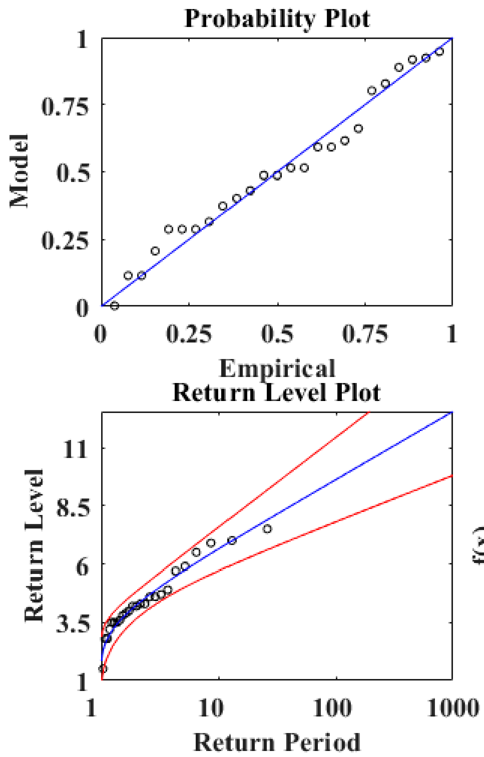


Figure 4. Gumbel goodness-of-fit test.

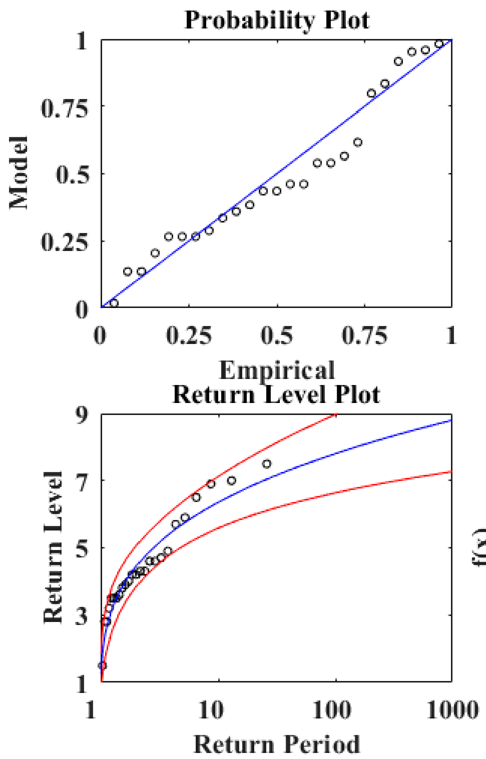


Figure 5. Weibull goodness-of-fit test.

The blue lines in Probability Plots(P-P) and Quantile Plot(Q-Q) are diagonal lines, and the blue curves in Return Level plots and density plots are data fitting curves. The red curve represents the 95% confidence interval and the points are observed data.

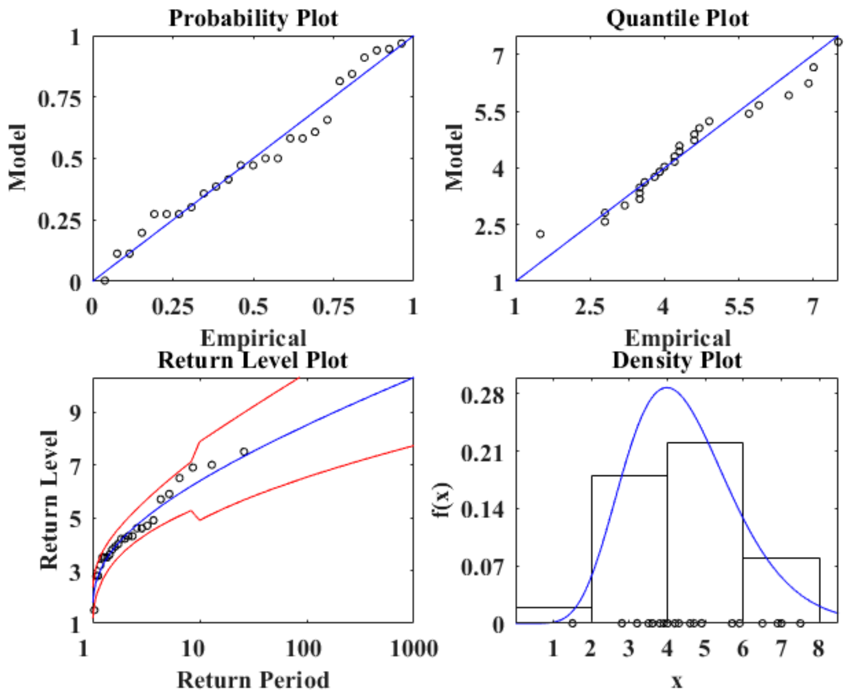


Figure 6. P-III goodness-of-fit test.

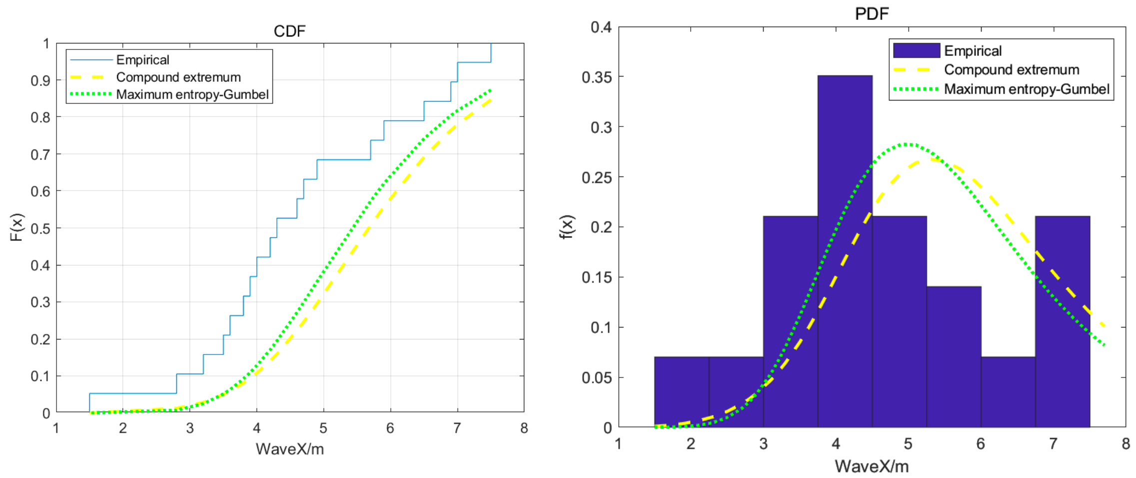
As shown in Figures 4–6, the P-P and Q-Q plots show that the wave height data are basically consistent with the theoretical distribution. The measured data in the return period plot are within a 95% confidence interval, and the probability density plot fits the actual distribution well. By comparing the P-P plot and Q-Q plot of each extreme value distribution, it can be found that the point data fit the Gumbel distribution better, which indicates that the Gumbel distribution fits the measured wave height data better than other distributions.

3.3. Design Wave Height Calculated by the New Model

Because the Gumbel distribution fitted the measured wave height data better than other distributions, it was used as a continuous distribution. Combined with the discrete distribution of typhoon disaster factors, all parameters and display expressions of the new design wave height model can be obtained. Its distribution function and probability density function are shown in Figure 7 below:

Figure 7a shows the comparison between the maximum entropy Gumbel distribution function that reflects typhoon intensity, distance, and frequency, as well as the compound extremum distribution function that only considers typhoon frequency and the measured data. It is evident from the figure that the fitting of the maximum entropy Gumbel distribution function is more reasonable, and the degree of fitting is slightly higher than that of one-dimensional distribution, which is more in line with the actual situation. Figure 7b shows a comparison of probability density maps. It is evident that the three-dimensional discrete maximum entropy Gumbel probability density is better than the one-dimensional one, and the reproduction level has been changed to be more in line with the actual situation.

Based on the parameters shown, calculate the design wave height values for different return periods calculated by different design models, as shown in Table 10.



(a) (b)

Figure 7. (**a**) Probability density diagram of maximum entropy Gumbel distribution and compound extremum distribution; (**b**) cumulative distribution diagram of maximum entropy Gumbel distribution function and compound extremum distribution. The green curve represents maximum entropy Gumbel distribution function, and the yellow curve represents compound extremum distribution.

Table 10. Design wave height values for different return periods calculated via different design models (m).

T-Year Return Periods	Gumbel	Compound Extremum	Maximum Entropy Gumbel
20	7.56	8.89	8.74
50	8.74	9.84	9.90
100	9.63	10.41	10.75
200	10.51	10.84	11.56

3.4. Discussions

According to the analysis in Section 3.2, the Gumbel distribution fits the wave height well among the other classical extreme value distributions. In general, the calculated design wave heights for different recurrence periods can be used as reference for engineering design. Considering the influence of typhoon frequency, the design wave height derived from the compound extremum distribution is higher than that of the Gumbel distribution. As shown in Table 10, the design wave height values of the 50-year, 100-year, and 200-year events are 12.59%, 8.10%, and 3.14% higher than the Gumbel distribution, respectively. The new model takes into account the influence of typhoon frequency, distance, and intensity, and its design value of multi-year wave height design value is slightly higher than other methods. As shown in Table 10, the design wave height values of the 50-year return period, 100-year return period, and 200-year return period are 13.27%, 11.63%, and 10.00% higher than the Gumbel distribution, respectively, and 0.61%, 3.27%, and 6.64% higher than the one-dimensional compound extremum distribution. Obviously, the multi-year return period wave height obtained by the three-dimensional discrete maximum entropy Gumbel distribution is higher than other distributions. If the three-dimensional discrete maximum entropy Gumbel distribution is used as the design standard, the calculated design wave height will be higher, which is more strict and safer compared with the Gumbel distribution and compound extreme value distribution. At the same time, the three-dimensional discrete maximum entropy Gumbel distribution contains all the information of the one-dimensional complex extreme value distribution, which is a more fully used model.

According to the calculation of design wave height, the findings of this paper show that considering the influence of typhoon frequency, distance, and intensity on wave height can improve the design standard of offshore engineering buildings. On the one hand, future research and development should move towards the direction of multi-dimensional marine environmental factors, such as studying the joint probability prediction of wave height and water level under the influence of typhoon frequency, distance, and intensity. On the other hand, the research can consider more typhoon hazard factors and calculate design wave height more accurately.

4. Conclusions

This article has determined the typhoon hazard factors in the South China Sea, comprehensively considered the effects of typhoon frequency, intensity, and distance, and conducted statistical correlation analysis on them. Different reference indicators have been processed through dimensionality and standardization, and based on the correlation relationship, a multidimensional discrete joint probability distribution of typhoon disaster factors has been obtained. A new design wave height calculation model and display expression have been proposed and applied to the South China Sea to calculate the annual wave height under the influence of typhoons in the South China Sea. Through multiple comparisons with traditional models, it has been verified that the new model has more advantages over traditional models and can provide a reference for the study of design wave heights under the influence of typhoons in the South China Sea. The main conclusions of this article are as follows:

(1) In the impact of typhoon hazard factors on the wave height in the South China Sea, three representative typhoon disaster factors have been determined—the frequency of typhoon occurrence, the shortest distance from the typhoon center to the sea area, and the maximum wind speed at the bottom center of the typhoon.

(2) The frequency of typhoons and the shortest distance from the typhoon center to the observation point are external factors of typhoons. Typhoon intensity is an intrinsic factor of typhoons, and its relationship with external factors can be approximated as independent. Compared with the Poisson distribution, the discrete maximum entropy distribution is suitable for fitting various typhoon hazard factors.

(3) The new design wave height model calculates a higher multi-year wave height value compared to other methods. The actual wave height values of the 50-year, 100-year, and 200-year return periods are 13.27%, 11.63%, and 10.00% higher than the Gumbel distribution, respectively, and 0.61%, 3.27%, and 6.64% higher than the one-dimensional compound extremum distribution, respectively. If the new model is used as the design standard, the calculated design wave height will be higher, which is more strict and safer compared with the Gumbel distribution and compound extreme value distribution.

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