PREDICTION OF STORM SURGE INTENSITY IN COASTAL DISASTER EVALUATION

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In coastal area, serious storm surge disasters are frequently caused by the higher tidal level and concomitant huge wave heights toward shoreline. Qingdao is located at the southern tip of Shandong Peninsula of China. The storm surge disaster in Qingdao depends on various influencing factors such as the intensity, duration, and route of the passing typhoon. In order to make up the defects of the warning water level, a Poisson Bi-variable Gumbel Logistic Distribution is presented to predict storm surge intensity. On the basis of observed records of tidal level and simultaneously occurred wave height series that are sampled from typhoon processes in Qingdao coastal area of China since 1949, the return periods of typhoon surge are estimated by this model. Then a new criterion is put forward to classify intensity grade of disaster-induced typhoon surges. A practical case indicates that the new criterion is clear in probability concept, easy to operate, and fits the calculation of typhoon surge intensity. Thus the procedure with the proposed statistical model will be a reference for the disaster mitigation in the other coastal area influenced by typhoons.

INTRODUCTION

Storm surge disasters occur frequently and result in the most serious economic loss in China. Especially serious storm surge disasters frequently cause serious damage to the economic development of the society and become one of the primary factors that restrict the development of the coastal area. How to calculate the storm surge intensity and to describe the magnitude of storm surge disaster is one of the main research topics of the surge prevention and disaster mitigation problem. As a kind of ocean dynamic phenomenon, storm surge has its natural attribute. While as a kind of disaster, it has social attribute. At present, there are several kinds of storm surge grade classification in China (Xu and Tan 1998, Gan 1991, Shi et al. 2000): (1) Intensity grade based on the set-up caused by the storm surge, (2) Intensity grade based on the extreme total water level, (3) Disaster degree grade based on disaster damage. The first grade lists the storm set-up as first when discussing the harm factors of the storm surge. The second grade, which takes account of not only the single storm set-up, but also the joint distribution of the astronomical tide and flood, takes the final water level together with various coefficients as the criterion. The third grade establishes the corresponding disaster degree grade from the view of disaster loss. Besides these, some researchers discussed the relationship between the intensity and the disaster degree of the typhoon storm surge (Xu and Tan 1998).

Recently some scholars suggest that the damage of the storm surge disaster should not be considered as the same as that of the typhoon disaster, although the serious storm surge disaster in China is primarily caused by typhoon (Le 1998). Actually the boundary of the storm surge disaster and the disaster directly caused by the strong wind of typhoon is easily separated. The disaster directly caused by sea water can be defined as storm surge disaster in principle. More and more researches show that serious storm surge disasters are frequently caused by the higher tidal level and concomitant huge wave heights toward shoreline (Li 1998). But the above-mentioned 1st and 2nd grading criteria only take account of water setup or total tide level. The 2nd grading criterion is also called warning water level. Once the total tide level exceeds this critical value, disaster prevention measures should be taken by local government. However, the warning water level has not taken into account the influence of a concomitant wave on disaster. Since the warning water level only includes the information of water setup and astronomical tide, it can hardly reflect overall the magnitude of a storm surge disaster. The loss of a storm surge disaster is divided into direct loss (such as loss of property and life) and indirect loss (such as input of repair and reconstruction, input of disaster relief, influence on ecological environment). Among them, direct loss mainly depends on the storm surge intensity and its influence area. The later is related with the economic development level, topography, and the ability of disaster prevention. In China, there is no standard for storm surge disaster statistics up to now. The fact that there is a reliability problem in the investigation of disasters greatly

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affects the accuracy of the third disaster degree grade. Before the relationship of the storm surge intensity and disaster degree is established, storm surge disaster magnitude must be identified correctly.

In this paper, on the basis of observed data of tidal level and simultaneously occurred wave height series that are sampled from typhoon processes in coastal area of Qingdao, China, including the occurrence frequency of typhoon, a bi-variable compound extreme distribution is presented to predict the typhoon surge intensity. Contrasted with the existing typhoon surge disaster data, a novel criterion is put forward to classify intensity grade of disaster-induced typhoon surges. This lays a foundation for the social economic risk evaluation of the storm surge.

TYPHOON SURGE DISASTER IN QINGDAO

Qingdao is located at the southern tip of the Shandong Peninsula (35°35'~37°09'N, 119°30'~121°00'E), see Figure 1.
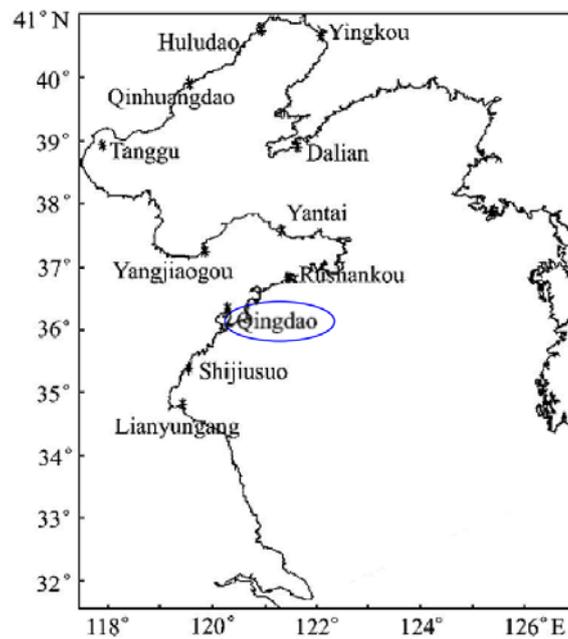
Figure 1. Location of Qingdao City

There are 77 typhoons affecting Qingdao in 53 years since 1949 to 2001 (which means its center enters the area north to 35°N). Statistics tell that three times every two years on average and 87.1 percent of them occur during July and September of the year, especially in August which accounts for 39.0 percent (see Figure 2). Although there are 1.5 typhoons every year that affect Qingdao, typhoon surge does not occur every year. The storm surge disaster intensity in Qingdao depends on various influencing factors such as the intensity, duration, and route of the passing typhoon. Especially when strong storm surge happens, the joint tidal level could be high enough and the concomitant huge wave height toward shoreline could be large enough.
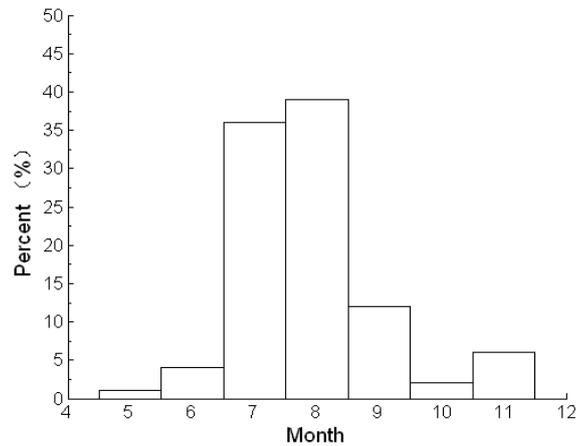
Figure 2. Typhoon monthly occurrence distribution in Qingdao area

Despite of these, there are still over ten typhoon surges that occurred in Qingdao area. Especially between 1985 and 2000, three continuous serious typhoon surges caused serious influence on the economic development of Qingdao. Table 1 shows their main disaster conditions.

Table 1 Three most serious typhoon surge disasters in Qingdao area			
typhoon number	8509	9216	9711
start-stop time	1985.8.14-1985.8.20	1992.8.27-1992.9.2	1997.8.10-1997.8.21
highest level (cm)	531	548	551
one-tenth largest wave height (m)	5.5	5.0	5.2
largest wind speed (m/s)	35.6	28.8	25.8
direct economic loss (10^8RMB)	5.08	6.80	2.17

POSSION BI-VARIABLE GUMBEL LOGISTIC DISTRIBUTION

Since single variable compound extreme distribution was provided (Liu and Ma 1980), it has been extensively applied in coastal and offshore engineering in China (Liu 1982, Langley and El-Shaarawi 1986, Dong et al. 2000, Dong et al. 2003). Recently Poisson Bi-variable Compound Gumbel distribution was given by Liu, et al (2002), which is proposed to estimate the joint action of typhoon wind and concomitant wave on oil platform in East China Sea. Dong, et al (2005) presented a Poisson Bi-variable Log-normal distribution to determine different design criteria of ocean environmental conditions. Dong, et al (2008) utilized the Bi-variable Pearson Type III distribution to estimate joint return values of simultaneously occurred extreme wind speed and wave height. In order to get a statistical analysis of extreme water level and corresponding wave height in the process of typhoon surge, this paper puts forward a Poisson Bi-variable Gumbel Logistic Distribution (PBGLD), which is supposed to grade typhoon surge intensity.

Suppose that the occurrence frequency n of typhoon every year in Qingdao is a discrete random variable, of which the distribution probability is P_k, while the extreme water level and corresponding wave height in the process of typhoon surge is (ξ, η), and the extreme water level and corresponding wave height without typhoon surge is (ζ, γ). Here assume (ξ, η) and (ζ, γ) are two dimensional continuous random variables, and their joint distribution functions are respectively $G(x, y)$ and $Q(x, y)$. The joint probability density function of (ξ, η) is $g(x, y)$, and the distribution function of ξ is $G_x(x)$. Given (ξ_i, η_i) as the *ith* observation value and n as a not negative integral random variable independent with (ξ, η), its distribution function can be denoted by:

$$\begin{cases} P\{n=k\}=P_k, & k=0,1,\cdots \\ \sum P_k = 1 \end{cases} \tag{1}$$

Random vector (X, Y) is defined as:

$$(X,Y) = \begin{cases} (\zeta,\gamma), & n=0 \\ (\xi_j,\eta_j) \mid \xi_j = \underset{1\le i\le n}{Max}\ \xi_i, & n\ge 1 \end{cases} \tag{2}$$

Therefore,

$$F(x,y) = P_0 \cdot Q(x,y) + \sum_{k=1}^{\infty} P_k \cdot k \cdot \int_{-\infty}^{y}\int_{-\infty}^{x} G_x(u)^{k-1} g(u,v)dudv \tag{3}$$

Equation 3 is called bi-variable compound extreme distribution composed of discrete distribution P_k and continuous distribution $G(x, y)$ (Liu et al. 2002).

In Qingdao coastal area, the tide level and corresponding wave height without typhoon surge is generally small. From the physical meaning of (ζ, γ), one can see that: there is one (ζ_0, γ_0) that satisfies $P\{(\zeta>\zeta_0)\cup(\gamma>\gamma_0)\}=0$, namely $Q(x, y)=1$. Supposing that the occurrence frequency n of typhoon agrees with the Poisson distribution, and λ is the occurrence number of typhoon, expression of bi-variable compound extreme distribution is obtained from Eq.3:

$$F(x,y) = e^{-\lambda}(1 + \lambda\int_{-\infty}^{y}\int_{-\infty}^{x} e^{\lambda\cdot G_x(u)} g(u,v)dudv) \tag{4}$$

In this paper the bi-variable continuous distribution $G(x, y)$ is supposed to agree with the bi-variable Gumbel logistic distribution, and the marginal distribution density functions of random variable x and y are expressed as follows (Gumbel 1960):

$$\begin{cases} G_x(x) = \exp[-\exp(-\dfrac{x-\mu_x}{\sigma_x})] \\[2mm] G_y(y) = \exp[-\exp(-\dfrac{y-\mu_y}{\sigma_y})] \end{cases} \tag{5}$$

where μ_1, σ_1 is respectively the location and scale parameter of the Gumbel distribution for the random variable series x_i ($i=1,2\cdots n$), μ_2, σ_2 respectively the location and scale parameter of the Gumbel distribution for random variable series y_i ($i=1,2\cdots n$). The joint probability density function of x and y is expressed as follows:

$$g(x,y) = \frac{1}{\alpha\sigma_1\sigma_2} A^{\frac{1}{\alpha}} B^{\frac{1}{\alpha}} (A^{\frac{1}{\alpha}} + B^{\frac{1}{\alpha}})^{\alpha-2} \cdot [\alpha(A^{\frac{1}{\alpha}} + B^{\frac{1}{\alpha}})^{\alpha} - (\alpha-1)] \cdot G(x,y) \tag{6}$$

where $A = \exp(-\dfrac{x-\mu_1}{\sigma_1})$, $B = \exp(-\dfrac{y-\mu_2}{\sigma_2})$, α is the correlation coefficient. By substituting Eq.6 into Eq.4, the PBGLD model is obtained.

With Eq.6 as the joint probability density function, the joint occurrence probability P assuming $X \ge x$ and $Y \ge y$ is given by

$$P = \int_x^\infty \int_y^\infty f(x, y) \, \mathrm{d}y \, \mathrm{d}x \qquad (7)$$

The reciprocal of P is the joint return period T corresponding to P.

DISTRIBUTION OF DISASTER-INDUCED TYPHOON SURGE

On the basis of observed record of tidal level and simultaneously occurred wave height sampled from typhoon processes in the Qingdao coastal area since 1949 (Li 1998), see Figure 3, the long-term bi-variable series are formed. The occurrence frequency number n of typhoon agrees with the Poisson distribution at the 0.05 significance level by χ^2 test (Papoulis 1991), see Figure 4.

| (1) Water level | (2) Wave height |
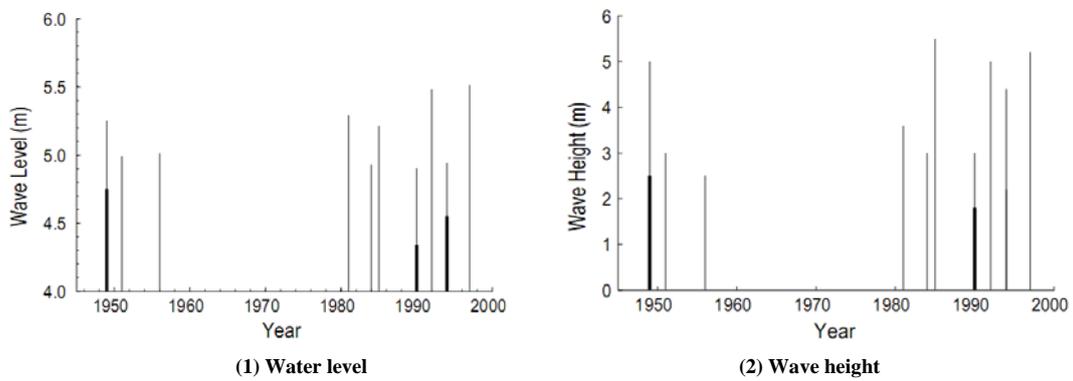
Figure 3. Observed extreme water level and wave height during each storm process
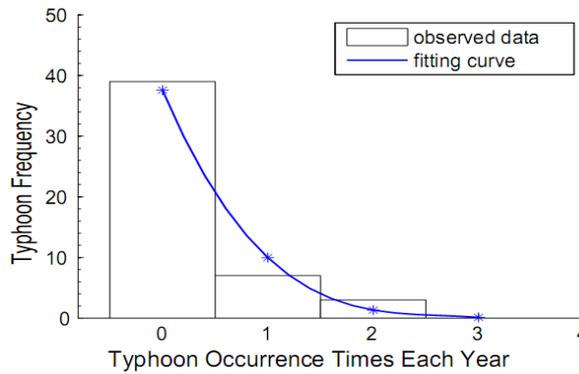
Figure 4. Poisson distribution of typhoon frequency

The Gumbel distribution fit of water level and wave height agrees with the Gumbel distribution at the 0.05 significance level by K-S test, see Figures 5~6.
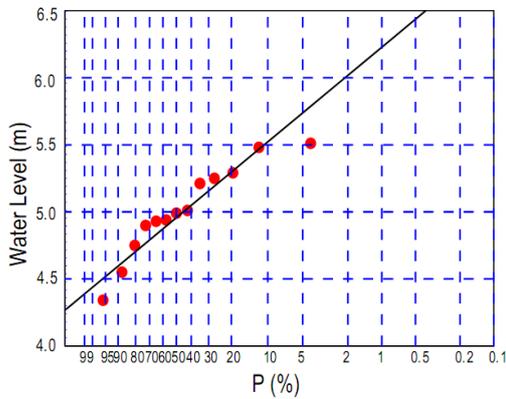
Figure 5. Gumbel distribution of water level
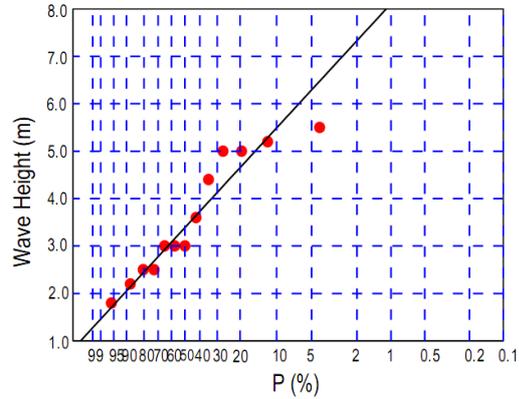
Figure 6. Gumbel distribution of wave height

Given the 50-year returned water level caused by storm surge in Qingdao 561cm, it can be seen from Figure 7 that the most probably occurred wave height is 3.5m. Figure 8 shows the joint probability contours of water level and wave height obtained from the PBGLD model. When the extreme water level arrives at the warning water level 525cm of Qingdao, the probability of simultaneous wave height 3.0m, 4.0m, 5.0m and 6.0m is respectively 4.5%, 2.9%, 1.7%, and 0.9%. Therefore, the conception of a warning water level can hardly reflect overall the recurrence feature of a storm surge disaster and it inevitably causes comprehensive deviation on the magnitude of disaster.
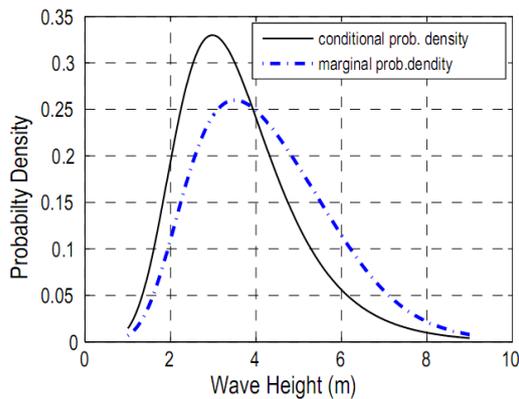
Figure 7. Conditional and marginal pd curve
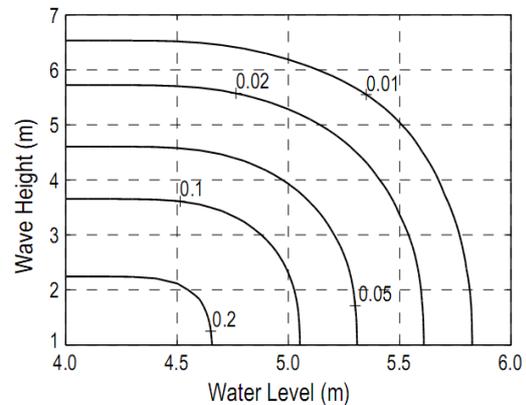
Figure 8. Joint probability contour

According to the joint return period of the extreme water level and corresponding wave height, a novel grade of disaster-induced typhoon surge intensity is presented in this study (see Table 2).

Table 2 Grade of typhoon surge intensity				
grade	1	2	3	4
disaster-induced intensity	mild	moderate	severe	especially severe
the return period of typhoon surge (a)	0~10	10~30	30~50	50~200

The joint return periods of typhoon surge disasters in Qingdao since 1949 have been calculated and listed in Table 3.

Table 3 Disaster-induced intensity of typhoon surge in Qingdao area					
Typhoon number	extreme water level (cm)	One-tenth wave height (m)	Return period (a)	Calculated surge intensity	Disaster rank
4906	475	5.0	31	severe	severe
4908	525	2.5	19	moderate	moderate
5116	499	3.0	12	moderate	moderate
5622	501	2.5	10	moderate	moderate
8114	529	3.6	31	severe	severe
8406	493	3.0	10	moderate	moderate
8509	521	5.5	77	especially severe	especially severe
9005	490	1.8	7	mild	mild
9015	434	3.0	7	mild	mild
9216	548	5.0	94	especially severe	especially severe
9414	494	2.2	9	mild	mild
9415	455	4.4	18	moderate	mild
9711	551	5.2	111	especially severe	especially severe

For comparison, the typhoon surge disaster grades in reference (Li 1998, Guo et al. 1998) are listed in Table 3. One can see that the above grade of typhoon surge intensity basically tallies with the statistical disaster conditions. Among them, although the calculated intensity of the typhoon No.9415 with error is medium grade (the return period is 18 years), the occurred disaster intensity agrees with the actual condition. The reason is related with the earlier happened typhoon No.9414. After this continuous storm surge, the people's consciousness of disaster mitigation extremely increased, and timely prediction reduced the disaster loss. It is pointed out that the nature intensity of typhoon surge No.9711, No.9216 and No. 8509 are the three severest of all.

In table 3, we can see that the typhoon disaster intensity is severe when higher extreme water level and huge wave height appear simultaneously (such as No.9711, No.9216 and No.8509), and the disaster intensity is mild when extreme water level is higher and concomitant wave height is relatively small (such as No.4908), in the process of typhoon surge. Furthermore, this verifies the hypothesis that serious typhoon surge disasters in Qingdao area are caused by the higher tidal level and concomitant huge wave heights toward shoreline.

CONCLUDING REMARKS

In this paper, a Poisson Bi-variable Gumbel Logistic Distribution is presented to predict typhoon surge intensity. The PBGLD model can make up the defects of the warning water level which cannot thoroughly describe the magnitude of storm surge, and take account of the joint distribution of bi-variable extreme environmental conditions as well as the typhoon occurrence frequency. On the basis of observed data of tidal level and simultaneously occurred wave height series that are sampled from typhoon processes in Qingdao coastal area since 1949, the return periods of typhoon surge are estimated. A new criterion is put forward to classify intensity grade of disaster-induced typhoon surge. Practical case indicates that new criterion is clear in probability concept, easy to operate, and fits to the calculation of typhoon surge intensity. Hence the procedure with the proposed statistical model will be a reference for the disaster mitigation in other coastal areas influenced by typhoon. Since data are limited, the calculation is only for reference, and the universal applicability of the PBGLD model needs more verification and perfection.

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