RISK ASSESSMENT OF INFRASTRUCTURES IN TYPHOON-RAINSTORMS PRONE REGIONS OF CHINA

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Abstract

With global warming and sea level rising, the frequency and intensity of typhoon-rainstorm induced disasters have been increasing. The infrastructures in typhoon-rainstorm prone area are menaced by natural hazards. This paper aimed to compare the risk level for infrastructures designed by China design code and by our proposed Multivariate Compound Extreme Value Distribution (MCEVD) model.

Risk assessment of some important infrastructures in typhoon-rainstorm prone areas are performed using MCEVD as follows: disaster prevention design water level for estuarine city Shanghai, failure probability for platform designed by China code shows that structure sliding and overturning estimation involved different Kinds uncertainties of environmental events and design flood volume for Three Gorges Dam (TGD).

The calculation results show that risk assessment based on MCEVD is a reasonable method for engineering planning, design, construction and management. The lessons from New Orleans catastrophe by hurricane Katrina shows: hurricane Katrina is natural hazards, when natural hazards combined with human hubris, disasters and catastrophes will follow sooner or latter. Some design code is not holy Bible.

1. Introduction

In China, typhoon-rainstorm disasters influence all the coastal provinces and many inland provinces. The infrastructures in these areas always menaced by strong winds, heavy rains, huge waves, storm surges, floods, landslides and debris-flow. Some typhoon-rainstorm disasters led to serious life and economic losses. In 1975, Typhoon Nina made 62 dams collapsed, 25, 000 deaths and economic loss 10 billion RMB. In 1994, Typhoon Fred led to 100,000 buildings and 521km seawalls collapsed, 1216 deaths, economic loss 12,440 million RMB. In 1997, No.11 Typhoon made 200,000 buildings and 1,000km seawalls collapsed, 344 deaths, economic loss 25 billion. In 2006, Typhoon Saomai and Bilis led to 1600 deaths and

80 billion economic losses. So it's necessary to develop a reasonable and scientific risk assessment method for infrastructures in typhoon-rainstorm prone regions on China.

In engineering field, the reliability based risk assessment is effective method. Usually the failure probability of structure is used as evaluation parameter for quantitative risk assessment (Henley and Kumamoto, 1981; Duckstein and Plate, 1987; Singpurwalla and Youngren,1993; Ellingwood and Mori, 1993; Hoeg, 1996; Finkelstein and Esaulova, 2001; Cox, L.A, 2002). In this method, random variables *X* is defined as the factors that affect structural performance, and *F=g(X)=R-S* is structure limit state function, in which *R* is resistances of structure, *S* is environment loads. When $g(X) > 0$,the structure is in safe state, while $g(X) < 0$,the structure is in unsafe state. Then, the failure probability can be defined as the probability of the occurrence of the unsafe event *F*:

$$p(F) = P[\mathrm{X} : \mathrm{g(X)} \le 0] = \int_{g(\mathrm{X})<0} \cdot \overset{n}{\cdots} \int f_{\mathrm{X}}(\mathrm{X}) d\mathrm{X} \tag{1}$$

Where $f_{\mathrm{X}}(\mathrm{X})$ is the joint probability density function of the basic random variables. The response behavior near the failure state is most important in the reliability analysis. The random design parameters, such as loadings, material parameters and geometry, are the set of basic random variables *X* which determine the probabilistic response of numerical model. The failure condition is defined by a deterministic limit state function

$$g(\mathrm{X}) = g(x_1, x_2, \cdots, x_n) \le 0 \tag{2}$$

There are two important problems in this method: firstly, the environment state of structures is so complex (especially in typhoon-rainstorms prone area) that it is difficult to find an absolutely accurate model to describe its features; secondly, for some intricate high dimensional models, it is impossible to get the analytical solutions.

To resolve above problem, Liu and Ma proposed Compound Extreme Value Distribution (CEVD) theory (Liu and Ma, 1980) and applied it to the long term probability analysis of hurricane characteristics along USA coasts (Liu, 1982). The predicted results showed that the hurricane central pressures of 50yr and 1000yr return period predicted by CEVD were close to SPH and PMH proposed by NOAA, respectively, except that for the sea area nearby New Orleans and East Florida coasts, hurricane intensities predicted using CEVD were obviously severer (See Fig.1). After then, CEVD was developed into Multivariate Compound Extreme Value Distribution (MCEVD), the corresponding stochastic simulation solution method----P-ISP was also proposed (Liu, et al., 2002, 2003, 2006a, 2006b, 2006c, 2008a, 2008b; Pang, 2007). MCEVD showed obvious advantages in joint probability analysis of extreme sea states induced by Hurricane Katrina2005. (Liu et al., 2006b, see Fig. 2).

In this paper, the reliable analysis method based on MCEVD and P-ISP is proposed and used in quantitative risk assessment of infrastructures in typhoon-rainstorm prone area of China.

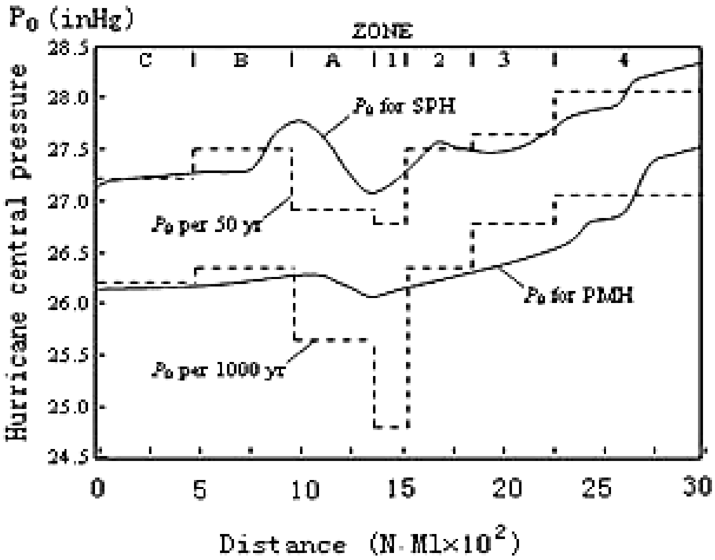

Fig. 1 Comparison between the results of CEVD and NOAA(Liu,1982)

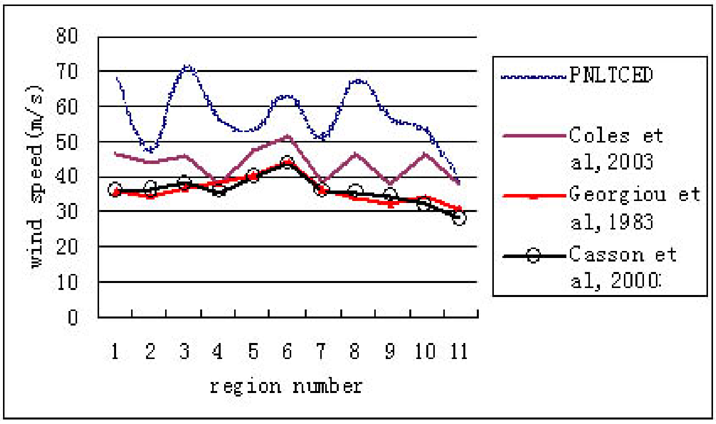

Fig.2 Comparison of 100yr—hurricane wind speeds by using different methods (Liu et al., 2006b)

2. Theory of Multivariate Compound Extreme Value Distribution (MCEVD)

For best practice papers, sections should include: Introduction, Thesis, Sources of information, Findings and Discussion.

Let ($\xi_1^*,\ldots,\xi_n^*$) and ($\xi,\ldots,\xi_n$) represent two continuous random rectors, with joint cumulative distributions being $Q(x_1,\ldots,x_n)$ and $G(x_1,\ldots,x_n)$, respectively, where $G(x_1,\ldots,x_n)$ has a joint probability density function $g(x_1,\ldots,x_n)$. Let the i-th independent observation values of random variables ξ_i be $(\xi_{1i},\ldots,\xi_{ni})$, (i=1,2,…), which are statistically independent and have the same probability distribution. Let N be a random independent variable of ξ_{1i}^* and ξ_{1i}, and be a non-negative integer, whose discrete probability distribution is $P(N=i)=p_i$, $\sum p_i = 1$ (i=1,2,…). Define the random vector($X_1,\ldots,X_n$) as

$$(X_1,\ldots,X_n)=\begin{cases}(\xi_{1i}{}^*,\ldots,\xi_{ni}{}^*) & N=0\\ (\xi_{1i},\ldots,\xi_{ni})\mid \xi_{1i}=\underset{1\le j\le N}{Max}\ \xi_{1j} & N=1,2,\ldots\end{cases}$$

Then the joint distribution function of ($X_1,\ldots,X_n$) can be represented by

$$F(x_1,\ldots,x_n)=p_0Q(x_1,\ldots x_n)+\sum_{i=1}^{\infty}p_i\cdot i\cdot\int_{-\infty}^{x_n}\ldots\int_{-\infty}^{x_1}G_1^{\ i-1}(u)g(u_1,\ldots,u_n)\,du_1\ldots du_n$$

where $G_1(u_1)$ is marginal distribution of $G(x_1,\ldots,x_n)$.

Proof : We have

$$F(x_1,\ldots,x_n)=p_0\cdot Q(x_1,\ldots,x_n)+\sum_{i=1}^{\infty}p_i\cdot P(X_1<x_1,\ldots,X_n<x_n\mid N=i)$$

where

$$\begin{aligned}&P(X_1<x_1,\ldots,X_n<x_n\mid N=i)\\ &=\sum_{k=1}^{i}P(\{X_1<x_1,\ldots,X_n<x_n\}\cap\{\underset{1\le j\le i}{Max}\,\xi_{1j}=\xi_{1k}\}\mid N=i\ )\\ &=i\cdot P(\xi_{11}<x_1,\ldots,\xi_{n1}<x_n,\xi_{11}>\xi_{1j},\ j=2,3,\cdots i\mid N=i\ )\\ &=iE\left\{E\left\{\prod_{K=1}^{n}I_{\{\xi_{1k}<x_k\}}(\omega)I_{\{\xi_{11}>\xi_{1j},\ j=2,3,\cdots i\}}(\omega)\right\}\mid(\xi_{11}=U_1,\ldots,\xi_{n1}=U_n)\right\}\\ &=iE\left\{\prod_{k=1}^{n}I_{\{U_k<x_k\}}(\omega)E\left\{I_{\{U_1>\xi_{1j},\ j=2,3,\cdots i\}}(\omega)\right\}\mid(\xi_{11}=U_1,\ldots,\xi_{n1}=U_n)\right\}\\ &=i\cdot\int_{-\infty}^{x_n}\ldots\int_{-\infty}^{x_1}G_1^{\ i-1}(u)g(u_1,\ldots,u_n)\,du_1\ldots du_n\end{aligned}$$

so

$$\begin{aligned}&F(x_1,\cdots x_n)=F_0(x_1,\ldots,x_n)-\varepsilon(x_1,\ldots,x_n)\\ &F_0(x_1,\ldots,x_n)=p_0+\sum_{i=1}^{\infty}p_i\cdot i\cdot\int_{-\infty}^{x_n}\ldots\int_{-\infty}^{x_1}G_1^{\ i-1}(u)g(u_1,\ldots,u_n)\,du_1\ldots du_n\\ &\varepsilon(x_1,\ldots,x_n)=p_0[1-Q(x_1,\ldots,x_n)]\end{aligned}$$

where($U_1,\ldots,U_n$)and($\xi_{11},\ldots,\xi_{n1}$)are statistically independent, their probability distribution function is $G(x_1,\ldots,x_n)$. I_A is the characteristic function of A.

Therefore, the theorem is proved.

We define $F_0(x_1,\ldots,x_n)$ as MCEVD which is compounded by discrete distribution $\begin{pmatrix} 0 & 1 & 2 & \cdots & k & \cdots \\ p_0 & p_1 & p_2 & \cdots & p_k & \cdots \end{pmatrix}$ and multivariate joint distribution $G(x_1,\ldots,x_n)$.

$$F_0(x_1,\ldots,x_n) = p_0 + \sum_{i=1}^{\infty} p_i \cdot i \cdot \int_{-\infty}^{x_n} \cdots \int_{-\infty}^{x_1} G_1^{\,i-1}(u) g(u_1,\ldots,u_n)\, du_1 \ldots du_n \tag{3}$$

It can be proved that by ignoring $\varepsilon(x_1,\ldots,x_n)$, $F(x_1,\ldots,x_n)$ can be approximated as $F_0(x_1,\ldots,x_n)$ (Liu, et al., 2006a).

Depending on different types of discrete distribution and multivariate joint probability distribution, formula (3) can be used to derive different types of MCEVD. As mentioned above the annual occurring rate of typhoon can be fitted with Poisson distribution, that is,

$$P_i = \frac{e^{-\lambda} \lambda^i}{i!}$$

Then formula (3) can be transformed into

$$F_0(x_1,\cdots,x_n) = e^{-\lambda} + \int_{-\infty}^{x_n} \cdots \int_{-\infty}^{x_1} \sum_{i=1}^{\infty} \frac{e^{-\lambda} \lambda^i}{i!} i G_1(u_1)^{i-1} g(u_1,\ldots,u_n) du_1 \ldots du_n \tag{4}$$

Let $m = i - 1$; then

$$F_0(x_1,\cdots,x_n) = e^{-\lambda} + \int_{-\infty}^{x_n} \cdots \int_{-\infty}^{x_1} \sum_{m=0}^{\infty} \frac{e^{-\lambda} \lambda^m}{m!} G_1(u_1)^m \lambda g(u_1,\ldots,u_n) du_1 \ldots du_n$$

$$= e^{-\lambda} (1 + \lambda \int_{-\infty}^{x_n} \cdots \int_{-\infty}^{x_1} e^{\lambda \cdot G_1(u_1)} g(u_1,\ldots,u_n) du_1 \ldots du_n) \tag{5}$$

Its corresponding probability density function is

$$f(x_1,\ldots,x_n) = \lambda e^{-\lambda[1-G_1(x_1)]} g(x_1,\ldots,x_n) \tag{6}$$

3. Importance Sampling Procedure based on MCEVD----P-ISP

The multivariate joint probability distribution such as Eq.(3) usually has a very complex mathematical form, the analytical solution is hardly possible, hence it leads to the need for Stochastic Simulation Method (SSM), or also known as Monte Carlo method.

For Eq. (3), we can generate N groups of $x_1, x_2, \cdots, x_n$, and record the number of groups that lead to limit state function≤0, if this number is M, the evaluation of Eq. (3) can be estimated by:

$$\hat{F}(x_1, x_2, \ldots x_n) = \lim_{N \to \infty} \frac{M}{N} \tag{7}$$

Usually, in the long term probability analysis of engineering and meteorology, the interested probability value is low, so the total number of simulations N can be extremely large to obtain sufficient number of samples in probability domain Ω, otherwise there will be a significant variance. To resolve this problem, Importance Sampling Procedure (ISP) need be used. The essential idea of ISP is sampling from the most important region which mainly contributes to the joint probability instead of the total definition domain (Bourgund and Bucher, 1986). Let $\boldsymbol{x}$ denotes a n-dimensional random vector, its corresponding joint probability density function is $f_X(\mathbf{x})$ Eq. (3) can be rewritten as:

$$F(\mathbf{x}) = \iint\limits_{g(\mathbf{x}) \le 0} \cdots \int I[g(\mathbf{x}) \le 0] \frac{f_X(\mathbf{x})}{h_X(\mathbf{x})} h_X(\mathbf{x}) d\mathbf{x} \tag{8}$$

in which, $\boldsymbol{x}$ is the n- dimensional random vector, $\boldsymbol{x} = x_1, x_2, \cdots, x_n$; $g(\mathbf{x}) \le 0$ is the joint probability domain decided by limit state function $g(\mathbf{x}) = 0$; $I[g(\mathbf{x}) \le 0] = \begin{cases} 1, g(\mathbf{x}) \le 0 \\ 0, g(\mathbf{x}) > 0 \end{cases}$ is the characteristic function; $h_X(\mathbf{x})$ is usually called weighting density function, from which the samples are generated in the simulation procedure.

Then the expected value of joint probability is expressed as:

$$\hat{F}(\mathbf{x}) = \frac{1}{N} \sum_{i=1}^{N} I[g(\mathbf{x}) \le 0] \frac{f_X(\mathbf{x}_i)}{h_X(\mathbf{x}_i)} \tag{9}$$

in which, N denotes the simulation times and $\mathbf{x}_i$ is the i-th simulation vector.

The sampling procedure of MCEVD (P-ISP) can be carried out as follows:

a. For a given λ, random number K which satisfies Poisson distribution is initially generated;

b. If K > 0, K groups of $x_1, x_2, \ldots x_n$ are then generated according to multivariate joint normal density function $h_X(\mathbf{x})$;

c. From K groups of $x_1, x_2, \ldots x_n$, select $(x_1, x_2, \ldots x_n) \big| x_1 = \underset{1 \le i \le K}{Max} x_{1i}$ as the annual maximum value of the met-oceanic factors induced by typhoon;

d. Repeat step a to c for N times, the N year samples satisfying MCEVD are generated.

4. The application of MCEVD to the risk assessment of infrastructures in typhoon-rainstorm prone areas in China

4.1 Risk assessment of prevention engineering in Shanghai city

Using P-ISP, the marginal distributions of different variables need to be defined. Poisson distribution is used to model the annual occurring rate of typhoon, while some continue distributions are used to describe the probability features of maximum central pressure difference (ΔP), radius of maximum wind speed (Rmax), duration from landfall to dissipation or leaving (t), moving speed of typhoon center (s), minimum distance between typhoon center and certain area (δ) and typhoon moving direction (θ). The marginal distribution parameters are listed in Table1.

The simulation can be performed when inputting the mean values, standard variances, marginal distribution parameters and correlation coefficient matrix of the variables. Table 2 lists a group result of ΔP, R_{max}, s, δ, θ, and t with 100-yr joint return period and their individual return period according to the marginal distributions.

Table 1 Distributions and distribution parameters used for simulation

Variables	Distributions	Mean	Standard variance	Parameters
λ	Poisson			λ=1.76
ΔP (hPa)	Gumbel	21.89	14.96	a=0.073, b=14.45
R_{max}(km)	Lognormal	45.79	25.22	μ=3.71, σ=0.5
s (m/s)	Gumbel	30.19	15.95	a=0.07, b=22.4
δ (km)	Uniform	44.37	169.63	a=-294.57, b=333.84
θ (°)	Normal	15	37.36	μ=15, σ=37.36
t (h)	Gumbel	12.95	5.56	a=0.20, b=10.29

Table 2. Comparison using different methods

	ΔP (hPa)	R_{max} (km)	s (m/s)	δ (km)	θ (°)	T (h)	Joint return period
P-ISP	72	74	30	-150	15	6	100
ISP	72	74	30	-150	15	6	177

It can be seen, the combination of 100-yr typhoon features calculated by using P-ISP (MCEVD) correspond to about 177-yr results using ISP. At present, design water level of Shangha calculated by using univariate frequency extrapolation method of annual maximum data is 5.86m, its return period is 1000-yr. But using data series of Harmonic Analyzed Tide (HAT), typhoon-induced storm surges (h_s) (Wusong hydrological station) and the simultaneous data of flood peak run-off from the Yangtze River (h_f) (Daton hydrological station), 100-yr combination can be predicted using P-ISP. Results are as follows: HAT=4.33 m, h_f = 0.46 m, h_s = 1.30 m. It means that, using our proposed method, the design water level with 100-yr return period is 6.09m. This result shows the failure risk of prevention structure in Shanghai should be noticed by government.

4.2 Risk assessment of platform

For the risk assessment of jacket platform in South China Sea with depth of 145m, the extreme load combination of typhoon induced wind, wave and current on platform were calculated. According to API suggestion, 100-yr wave height (15.6m) with the associated wind speed (52.7m/s) and current (1.96m/s) are used to structural failure analysis, the result of failure probability is $Pf = 0.102\times10^{-5}$. If the uncertainty of 100-yr design wave height in South china sea is considered (Cov=0.15), the design wave height will be raised to 17.9m, and corresponding failure probability will be $Pf = 0.195\times10^{-3}$.

According to ALARP (As Low As Reasonable Practice) principle (Schofield, 1998; Melchers, 2001), it is acceptable failure probability without considering uncertainty of design wave height, but unacceptable considering uncertainty of design wave height (see Fig.3).

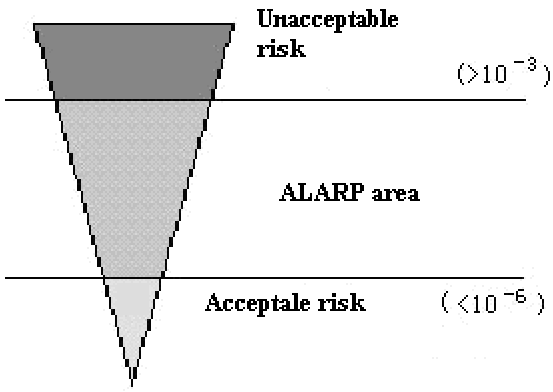

Fig.3 ALARP Principle

4.4 Risk assessment of design flood for Three Gorges Project

The design flood into reservoir for Three Gorges Project (TGP) mainly depends on the flood volume from Jinsha river (station 1), Min River (station 2), Jialing River (station 3), Wu River (station 4) and the trunk Yangtze river in Yichang station (5) as the last stage control station into TGP. (see Fig.4). Considering the ratio of the tributary's drainage area to the total area of the trunk and flood propagation time from tributary's stations to station (5), the 3-day flood volume to TGP reservoir can be obtained as a sum of four tributary's 3-day flood volume. The calculated results are consistent with the observed flood data in station (5). Therefore, the P-ISP method can be used to simulate the four-variables joint probability of 3-day flood volume in TGP. The simulated design 3-day flood volume in TGP with four combinations of tributary's rivers are shown in Table 3.

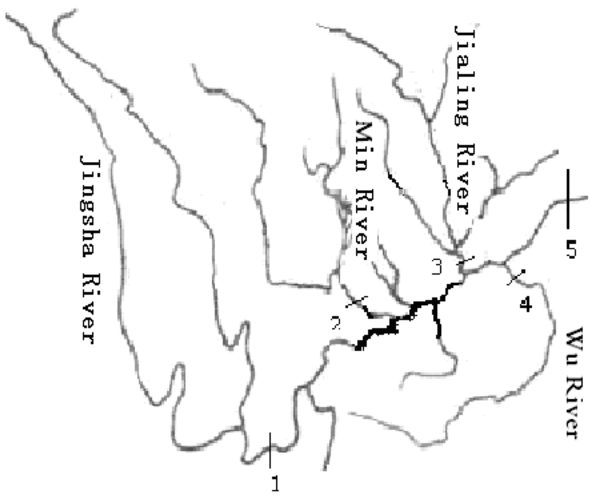

Fig. 4. Illustration of the tributaries of the Yangtze river

Table 4.Simulated 100-yr return period 3-day flood volumes by using different tributary river combinations

Tributary river \ Combination		1	2	3	4
Jinsha River	T(return period)	2	2	2	76
	V(volume10^9m)	43.80	43.30	42.40	75.20
Min River	T	75	5	2	4
	V	57.49	38.20	33.25	37.62
Jialing River	T	2	60	2	2
	V	52.80	104.8	52.80	52.80
Wu River	T	2	2	80	4
	V	26.40	26.80	55.36	26.8
Simulated results forThree Gorges	Joint return period	100	100	100	100
	V	211.1	249.2	215.0	225.4
Design volume for Three Gorges	T	100			
	V	208.0			

It can be seen in Table 3, when the flood return period of Jialing River is 60 yrs and the corresponding flood return period of other 3 branches are 2~5 yrs respectively, the 3-day flood volume of Yichang station with 100-yr joint return period will exceed present 100-yr design flood about 20%, let alone combinations of simultaneous occurrence more severe flood in other two or three tributaries. It is a number shouldn't be ignored.

5. Conclusions

The mainly advantages of MCEVD consist in two aspects: firstly, the annual occurring rate of typhoon is taken into account, it realizes the development from yearly maximum method into process maximum method and reduces the errors induced by sampling uncertainties; secondly, it is the improvement from univariate distribution model to multivariate model. P-ISP is a valid method to solve the joint probability problem of non-Gaussian, correlated multi-dimensional variables, especially efficient in long term probability analysis of complex typhoon induced sea environments. The improved reliability analysis based on MCEVD and P-ISP is reasonable and effective risk assessment method for infrastructures in typhoon-rainstorm prone regions which can offer the scientific references in engineering planning, design, construction and management.

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