Risk assessment for nuclear power plants against natural disasters

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Abstract: With the increasing tendency of natural hazards, the typhoon/hurricane/tropical cyclone induced surge, wave, precipitation and river flood as extreme external loads not only menace Nuclear Power Plants (NPP) in coastal areas, but also some inland territorial NPP. For all of planned, designed and constructed NPP the National Nuclear Safety Administration of China and International Atomic Energy Agency (IAEA) recommended safety regulations for NPP site evaluation installation and coastal defense infrastructures. These standards include Probable Maximum Hurricane /Typhoon (PMH/T), Probable Maximum Storm Surge (PMSS), Probable Maximum Flood (PMF) as well as Design Basis Flood (DBF). This paper discusses the joint probability analysis of meteorological, oceanographic and hydrological hazards based on our proposed Compound Extreme Value Distribution (CEVD), Multivariate Compound Extreme Value Distribution (MCEVD), Double Layer Nested Multi-Objective Probability Model (DLNMOPM) and compares with IAEA 2006-2011 recommended safety regulation design criteria for NPP coastal defense infrastructures in China. During the past 34 years since our CEVD firstly used to predict typhoon/hurricane extreme sea hazards in China, US Atlantic and Gulf of Mexico areas, 2005 hurricane Katrina, Rita and 2012 hurricane Sandy induced disasters proved 1982 CEVD and 2006 MCEVD predicted extreme hazards in New Orleans, Gulf of Mexico and Philadelphian areas, similarly, 2013 typhoon Fitow induced disaster in Shanghai area proved MCEVD and DLNMOPM 2004-2006 predicted results. Safety regulation for some NPP constructed coastal defense infrastructures located along East and South China Sea which recommended by China and IAEA are much lower than 500 years return period typhoon induced sea hazards predicted by our proposed models. Some inland NPP are not only menaced by extreme precipitation and flood, but also landslides and debris flows triggered by rainfall for NPP around territories.

Key-Words: - Risk assessment; Nuclear Power Plant; Compound Extreme Value Distribution

1 Introduction

In China, three NPP have been built along coasts in 1980, and more than 37 NPP along coast of South-East China Sea are in the stages of planning, design, or construction. According to the 2011-2020 safety planning of the China state council for nuclear power plants, it is necessary to do a comprehensive research on design standards for protective engineering and structural technology of the NPP based on the world's highest safety requirements.

China has a wide continental slope to decay tsunami energy. If M9 earthquake occurs at Manila trench or Rykyu trench, the wave produced by tsunami wave at south and southeast china coast would be no more than 5 - 6 m [1]. In 2006 five of the most severe typhoon disasters brought about 1600 deaths and disappearances, and affected 66.6 million people. The economic loss reached 80 billion

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RMB and influenced agriculture areas more than 2800 thousand hectares. Among these disasters, typhoon Saomai induced 3.76 m storm surges and 7 m waves, causing 240 deaths, sinking 952 ships and damaging 1594 others in Shacheng harbor. If the typhoon Saomai had landed 2 hours later, then the simultaneous occurrence of the typhoon surge and high spring tide with 7 m wave would have inundated most areas of the Zhejiang and Fujian provinces, where located several NPP. The results would be comparable with 2011 Japanese nuclear disaster.

With the global warming and sea level rising, the frequency and intensity of extreme external natural hazards would increase. All the coastal areas having NPP are menaced by possibility of future typhoon disasters. So calibration of typhoon disaster prevention criteria is necessary for existed and planning NPP. In China Nuclear Safety Regulations: “HAF101, HAD101/09~11” [2-5] and IAEA Engineering Safety Section: “Extreme External Events in the Design or Assessment of NPP’”, IAEA 2011 No. SSG-18 “Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations”[6-10] there appeared some vague definitions and they should be dissected and described with probability characteristics by using statistical analysis.

This paper discusses the joint probability analysis of simultaneous occurrence typhoon induced extreme external hazards and compared with safety regulation design criteria recommended by China and IAEA for some constructed NPP coastal defense infrastructures along China coasts.

2 Development Process of the CEVD, MCEVD and DLNMOPM

In 1972, Typhoon Rita attacked Dalian port in the North Bohai Bay of China, causing severe damage in this port. The authors found that, using traditional extrapolation (such as a Pearson type III model) was difficult to determine the design return period for the extreme wave height induced by a typhoon. According to the randomness of annual typhoon occurrence frequency along different sea areas, it can be considered as a discrete random variable and typhoon characteristics or typhoon-induced extreme sea events are continuous random variables. The CEVD can be derived by compounding a discrete distribution and the extreme distribution for typhoon induced extreme events in China coasts [13]. After then the CEVD was used to analyze long-term characteristics of hurricanes along the Gulf of Mexico and the Atlantic US coasts [14]. During the past few years, CEVD has been developed into MCEVD and applied to predict and prevent typhoon induced disasters for coastal areas, offshore structures, and estuarine cities [15,16,17,18,19]. Many applications of MCEVD in engineering design and risk analysis show the scientific and reasonable aspect of its predicted results in China and abroad [22, 23, 24, 25, 38, 39, 40, 41]. As mentioned in “Summary of flood frequency analysis in the United States” [26]: “The combination of the event-based and joint probability approaches promises to yield significantly improved descriptions of the probability laws of extraordinary floods”. MCEVD is the model which follows the development direction of the extraordinary floods prediction hoped for by Kirby and Moss. The CEVD [13,14] and MCEVD [11,15] four publications were cited as evidence of prevention criteria for hurricane disaster experimentation [27].

The CEVD, MCEVD and DLNMOPM can be derived by compounding a discrete distribution and the extreme distribution for typhoon induced extreme events in China The derivation of the MCEVD is as follows:

Let N be a random variable (representing the number of storms in a given year), with their corresponding probability

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$P\{N = k\} = p_k, \quad k = 1, 2, \cdots$;

and

$(\xi_{11},...,\xi_{n1}),(\xi_{12},...,\xi_{n2})......$

be an independent sequence of independent identically distributed random vectors (representing the observed extreme sea environments in the sense defined above within the successive storms) with common density $g(\cdot)$. Then we are interested in the distribution of

$(X_1,\ldots,X_n) = (\xi_{1i},\ldots,\xi_{ni})$

where ξ_{1i} is the maximum value of

$\xi_{1j}, 1 \le j \le N, N = 1,2,......$

This represents the maximum annual value of the principal variable, together with the simultaneously occurring values of the concomitant variables. There is a reasonable approximation in definition of $(X_1,\ldots,X_n)$, no concerning of N=0, because no extreme value of interest can occur outside the storm in case of N=0. The more detailed discussion of the model correction in case of $p(N=0)$ can be found in reference [12]

When multivariate continuous cumulative distribution is $G(x_1,\ldots,x_n)$, then we can derive the MCEVD as:

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

where $G_1(u_1)$ is the marginal distribution of $G(x_1,\ldots,x_n)$ $g(u_1,...u_n)$ is density function.

In which, λ means value of the annual typhoon frequency; Ω is joint probability domain; $f(\cdot), F(\cdot)$ are probability density function and cumulative function; $x_1, x_2, \ldots x_n$ are random variables such as typhoon characteristics : ΔP, Rmax, s, δ, θ and t. where ri, j is the correlation coefficient for i\j and i, j = 1, 2, 3.

When the trivariate nested logistic model [21] can be involved into formula (1), then Poisson Nested Logistic Trivariate Compound Extreme Value Distribution (PNLTVEVD) can be derived as a practically useful model of MCEVD[11,12]

The PNLTCED can be obtained from formula (1):

$$F_0(x_1,x_2,x_3) = e^{-\lambda}(1+\lambda\int_{-\infty}^{x_3}\int_{-\infty}^{x_2}\int_{-\infty}^{x_1} e^{\lambda \cdot F(u_1)} f(u_1,u_2,u_3) du_1 du_2 du_3 \quad (2)$$

In which, the cumulative distribution function of trivariate nested logistic model is expressed as:

$$F(x_1,x_2,x_3) = \exp\left[-\left\{\left[\left(1+\xi_1\frac{x_1-\mu_1}{\sigma_1}\right)^{\frac{-1}{\alpha\beta\xi_1}} + \left(1+\xi_2\frac{x_2-\mu_2}{\sigma_2}\right)^{\frac{-1}{\alpha\beta\xi_2}}\right]^{\beta} + \left(1+\xi_3\frac{x_3-\mu_3}{\sigma_3}\right)^{\frac{-1}{\alpha\xi_3}}\right\}^{\alpha}\right] \quad (3)$$

$$f(x_1,x_2,x_3) = \frac{\partial^3 F(x_1,x_2,x_3)}{\partial x_1 \partial x_2 \partial x_3} \quad (4)$$

in which ξ_j , μ_j , σ_j are the shape, location and scale parameters of marginal distributions $F(x_j)$ to x_j (j=1,2,3) , respectively. And dependent parameters α, β can be obtained through moment estimation

$$\hat{\alpha} = \frac{\sqrt{1-r_{13}}+\sqrt{1-r_{23}}}{2}$$
$$\hat{\beta} = \frac{\sqrt{1-r_{12}}}{\hat{\alpha}} \quad (5)$$

where $r_{i,j}$ is correlation coefficient ,i<j ; i,j=1,2,3.

Trivariate layer structure （α- outside, β -inside layer） shows that the correlation between x_1 and x_2 is stronger than those among x_1, x_3 and x_2, x_3.

The hurricane/typhoon characteristics such as wind speed and duration, surge, wave taken as valuables series x_1, x_2 and x_3.respectively. The correlation coefficient among them are r_{12}, r_{23}, r_{13}. Therefore PNLTVEVD can be used as theoretical solution for trivariate compound extreme value distribution[11,12].

3 2005 Hurricane Katrina and 2012 Hurricane Saydy disasters proved CEVD and MCEVD predicted results

3.1 Comparison between 1982 CEVD predicted results and NOAA proposed SPH and PMH

In 1979, American National Oceanic and Atmospheric Administration (NOAA) divided Gulf of Mexico and Atlantic coasts into 7 areas according to hurricane intensity, in which corresponding Standard Project Hurricane (SPH) and Probable Maximum Hurricane (PMH) were proposed as hurricane disaster prevention criteria[34]. Using CEVD[13,14], the predicted hurricane central pressures with return period of 50yr and 1000 yr were close to SPH and PMH, respectively, except that for the sea area nearby New Orleans (Zone A) and East Florida (Zone1) coasts, hurricane intensities predicted using CEVD were obviously severer than NOAA proposed values. SPH and PMH are only corresponding to CEVD predicted 30~40yr and 120yr return values, respectively.

Tab. 1 . Comparison between NOAA and PWCEVD predicted central pressure

Zone	NOAA In/hpa		CEVD In/hpa		Hurricane In/hpa
A	SPH PMH	27.8/941.0 26.3/890.5	50-yr 1000-yr	26.9/910.8 25.6/866.8	Katrina 26.6/902.0
1	SPH PMH	27.1/919.3 26.1/885.4	50-yr 1000-yr	26.7/904.0 24.6/832.9	Rita 26.4/894.9

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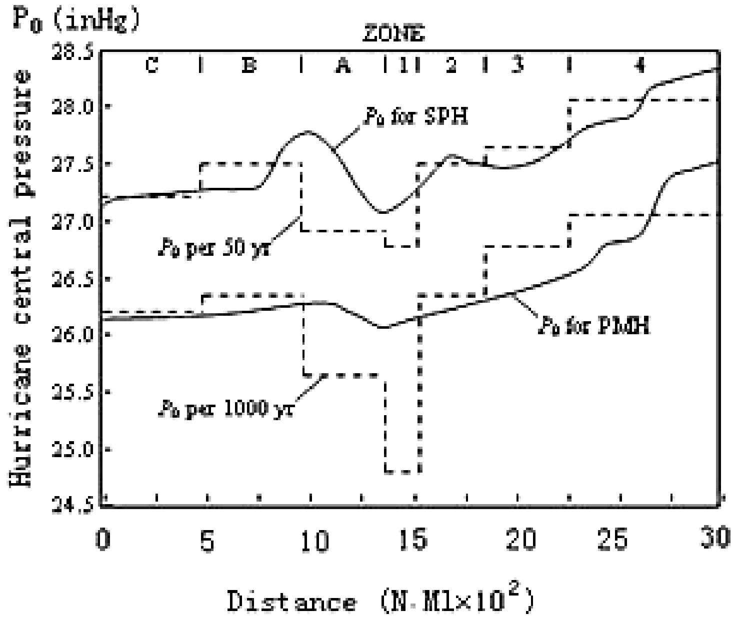

Fig. 1. Comparison of hurricane center pressures between CEVD predicted value and NOAA proposed design codes (see [14], Fig. 6).

In 2005, hurricane Katrina and Rita attacked coastal area of the USA, which caused deaths of about 1400 people and economical loss of $400 billion in the city of New Orleans and destroyed more than 110 platforms in the Gulf of Mexico. The disaster certified that using SPH as flood-protective standard was a main reason of the catastrophic results[22,23,24,25]. Fig. 1, and Tab. 1 indicate that CEVD predicted results are more reasonable than NOAA proposed safety regulations. The main reason of hurricane Katrina disaster is NOAA proposed unreasonable SPH and PMH.

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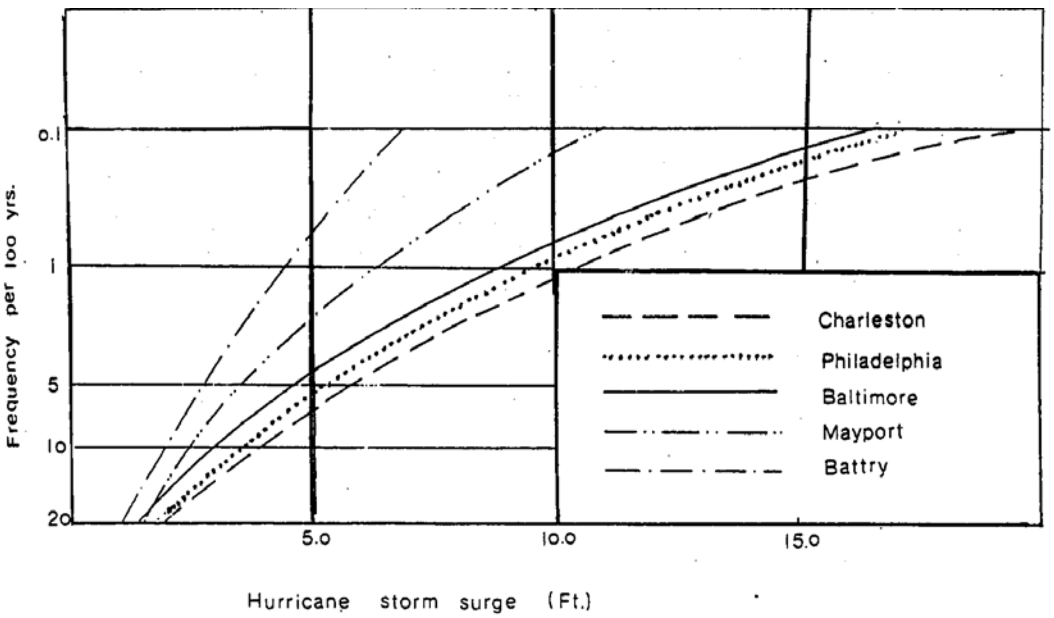

Fig. 2 CEVD predicted hurricane storm surge along Atlantic coast (see [14], Fig.8)

3.2 2012 Hurricane Sandy induced flooded area proved 1982 CEVD predicted storm surge

Hurricane Sandy is the second-costliest hurricane in US. Damage $75 billion and at least 285 people killed along the path of the storm. Sea level at New York and along the New Jersey coast has increased by nearly a foot over the last hundred years, which contributed to the storm surge. Based on the 1926 to 1960 observed data[28], 1982 CEVD predicted 100 years return period hurricane induced storm surge about 10 foot for Philadelphia areas which close to 2012 october 30, 08h:06 min. hurricane Sandy induced storm surge 10.62 ft, (as shown dot line in Fig. 2.), but NOAA predicted surge only 7.52 ft..

3.3 Hurricane Katrina and Hurricane Sandy proved MCEVD predicted results

After hurricane Katrina the 55 year (1950~2004) measured data of hurricane winds,hurricane effect duration (provided by NOAA and Unisys Company) and the simultaneous Mississippi water level (provided by USACE) are used for the long term joint probability prediction of Hurricane Katrina. Sometimes later than that when Fig.1 seven areas was proposed, Gulf of Mexico and Atlantic coasts were divided into 11 regions according to the regional planning of hurricane[34]

Tab. 2. Comparison 100yr wind speed (m/s) for New Orleans and New Jersey zones

Methods	MCEVD (2006) [17,20]	Coles (2003) [32]	Casson (2000) [33]	Georgion (1983) [34]
100yr wind for New Orleans	70.0	46.0	38.0	39.0
100yr wind for New Jersey	60.0	40.0	36.0	35.0

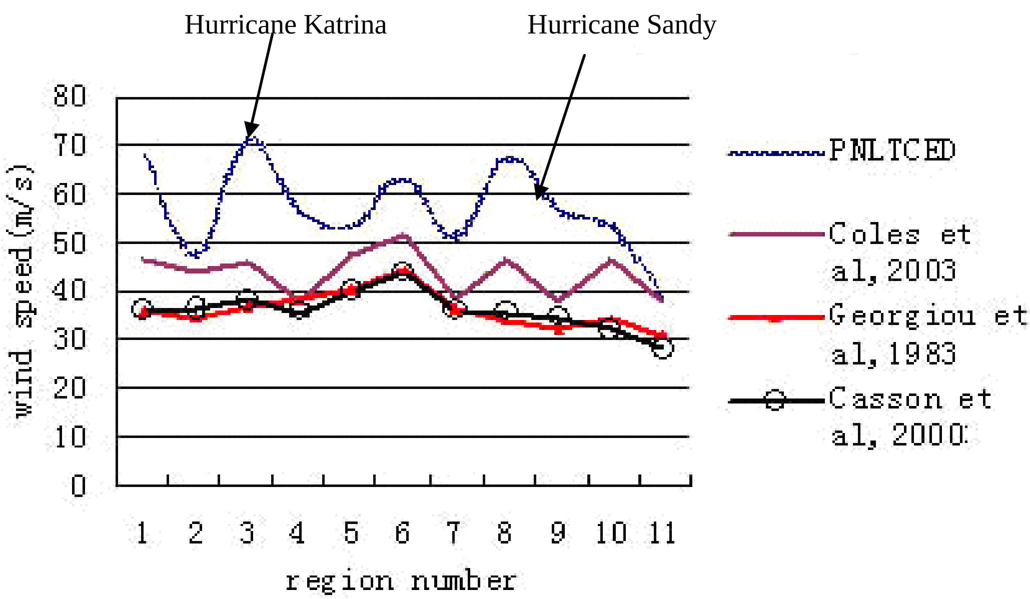

Fig. 3, Comparison of 100yr—hurricane wind speed using different methods([12],Fig. 6)

As shown in Tab. 2, Tab. 2 that MCEVD predicted 100 years return values not only proved by 2005 hurricane Katrina, but also by 2012 hurricane Sandy.

3.4 2013 Typhoon Fitow proved 2006 MCEVD predictedn disaster in Shonghai city

Shanghai city locates at the estuarine area of the Yangtze River in China. Historical observed data shows that the typhoon induced storm surges, rainstorm flood coupled with the astronomical spring tide had threaten the security of Shanghai City. Based on the long term typhoon characteristics around Shanghai area (Tab. 4) , the Double layer nested multi-objective

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probability model was used to predict combined effect of storm surge, rainstorm flood and spring tide on the Shanghai city[15,19,20].

2013 typhoon Fitow induced significant losses in China. As shown in Table 3, that 2013 typhoon Fitow induced over warning water level in Yangtze River 5.15m , but China design code recommended 500 years return period warning water level in this area 4.80m, only corresponding to MCEVD predicted 50 year return value of combined effect of typhoon induced rain-storm flood ,storm surge with simultaneous astronomic tide.

Tab.3, Comparison between disaster prevention design criteria for Shanghai city

Model	Return period(a)	Design Value(m)
MCEVD	100 50	5.89 5.10
China Design Code	1000	5.86
Shanghai Warning Water Level*	500	4.80
Typhoon Fitow observed water level		5.15

* Calculated by China Design Code

4 Risk analysis for L-NPP and Q-S NPP coastal defense along China Sea coast

MCEVD can be used for joint probability safety assessment for NPP coastal defense along china coast against typhoon attacks. When the dimension $n \le 3$, Eq.(1) can be solved by analytical method. For discussion on joint return period of storm surge, wave height with corresponding spring tide, the Poisson Nested Logistic Trivariate Compound Extreme value Distribution (PNLTCED) can be used for analytical solution. When $n > 3$, finding theory solution will become impractical , the Stochastic Simulation Method (SSM) should be used to solve MCEVD [20].Based on MCEVD (analytical solution and stochastic simulation), Double Layer Nested Multi-objective Probability Model (DLNMPM) can be established for long term probability prediction of typhoon characteristics and corresponding disaster factors..

For example, the characteristics of PMT and SPT in different sea areas is related to annual occurring frequency of typhoon (λ), maximum central pressure difference (ΔP), radius of maximum wind speed (Rmax), moving speed of typhoon center (s), minimum distance between typhoon center and target site (δ), typhoon moving angle (θ) and typhoon duration (t). It means that different PMT and SPT can be derived from different combinations of typhoon characteristics. For this reason, the characteristics of PMT and SPT inevitably involves selection of discrete distribution (λ) and multivariate continuous distribution of other typhoon characteristic factors (ΔP, Rmax, s, δ, θ, t), which can be described by Multivariate Compound Extreme Value Distribution (MCEVD). The calculation of PMT and SPT by numerical simulation method omitted the uncertainties of typhoon characteristics and may lead to different results, the PMSS obtained on basis of them may has some arbitrary and cause wrong decision making.

Nuclear power plant L is located at coast of South China Sea, where the combined extreme external events are dominated by waves. The statistical typhoon characteristics are listed in Tab.3.

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Table 3 Marginal distribution and parameters of typhoon characteristics of South China Sea

Variables	Distributions	Mean	Standard variance	Parameters
λ	Poisson	λ =6.19		
ΔP (hPa)	Gumbel	21.89	14.96	a=0.073, b=14.45
Rmax (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=294.6, b=333.8
θ (°)	Normal	15	37.36	μ=15, σ =37.36
t (h)	Gumbel	12.95	5.56	a=0.20, b=10.29

As the statistical checks of typhoon characteristics in Table 3 and Fig.5.1 to Fig.5.5 show that the different combinations of typhoon characteristics can be used to the first layer of DLNMPM by the Stochastic Simulation Method (SSM) [20].

For discussion on joint return period of wave height with storm surge and corresponding spring tide, the PNLTCED can be used for analytical solution [16,43,44]. Different combinations of typhoon characteristics in first layer of PNLCED (see Table 3) can induce different combinations of storm surge and waves. The distribution diagnostic checks of typhoon induced wave, surge and corresponding spring tide in Fig.4-a, 4-b and 4-c show that PNLTCED is applicable model.

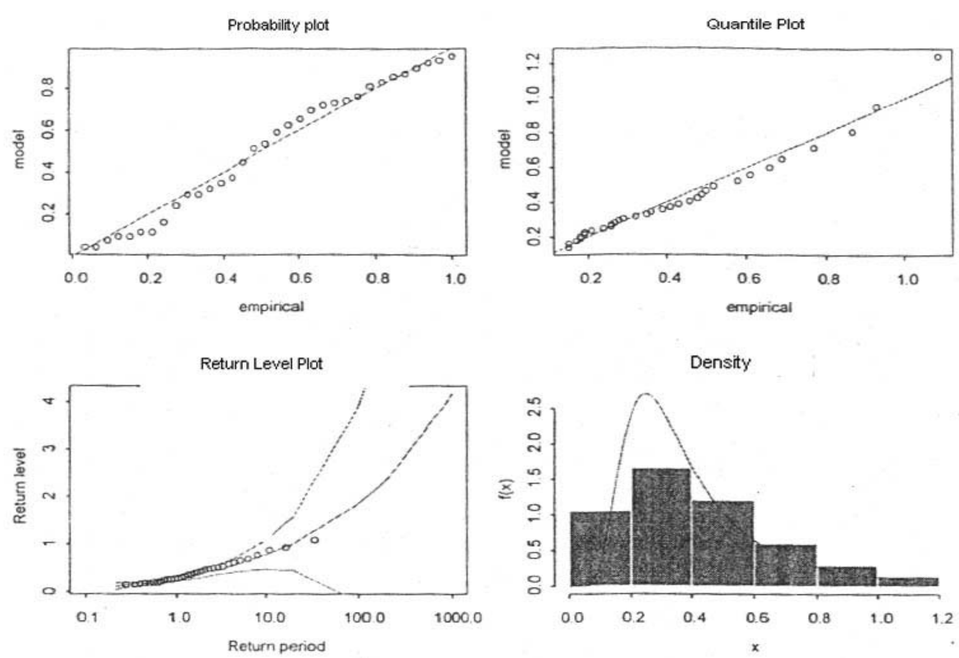

Fig.4-a Distribution diagnostic testing of storm surge

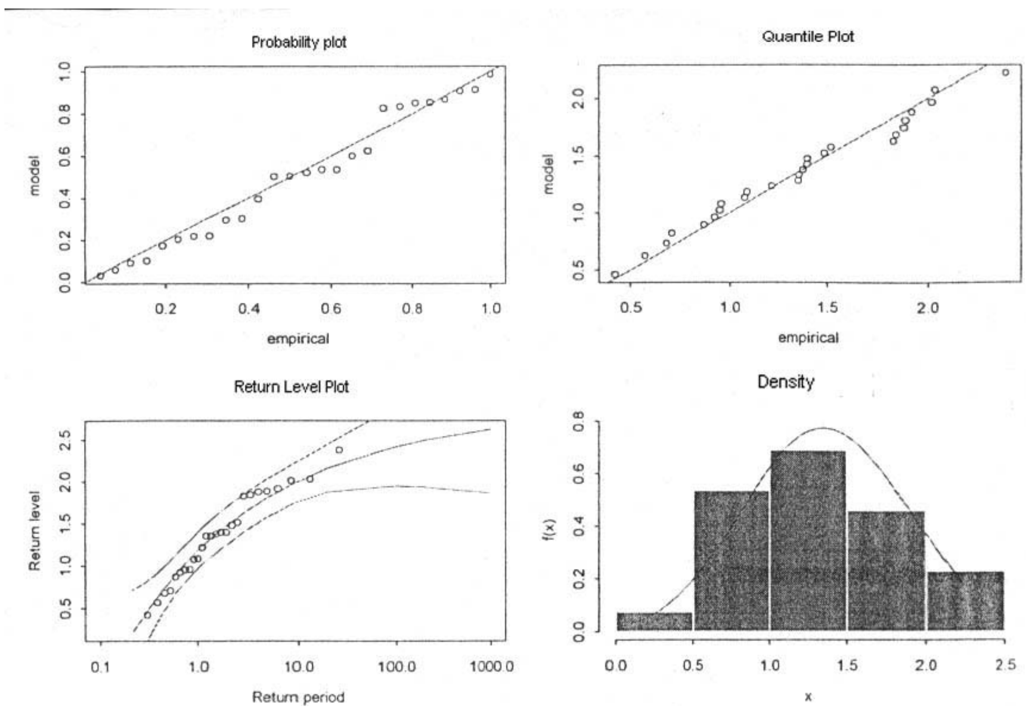

Fig.4-b Distribution diagnostic testing of spring tide

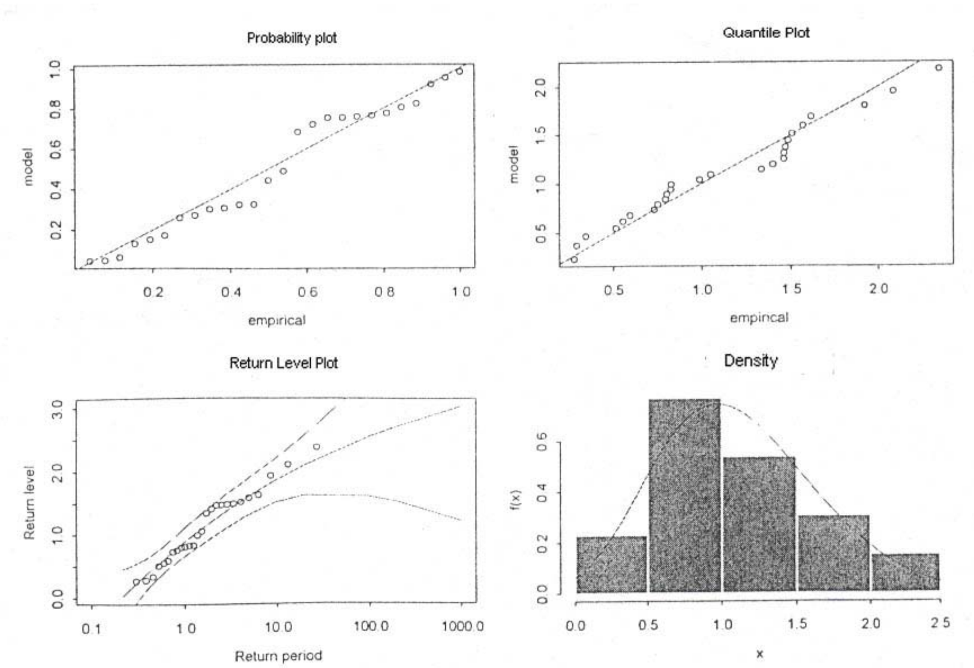

Fig.4-c Distribution diagnostic testing of wave height

Table 4. Present design criteria for coastal defense of L- NPP [36, 37]

Design water level	Design value (m)
DBF	6.35
PMSS	5.30
Extreme Wave Height	6.6
Design low water level	-1.93

The predicted results of storm surge, wave height and spring tide with different joint return periods and corresponding confidence intervals are shown in Table 5

Table5 Joint probability of typhoon induced storm surge, wave height and corresponding spring tide with confidence intervals

Return period (yr.) / variables	100	500	1000
Storm surge (m)	3.3	4.2	4.7
Spring tide (m)	2.4	2.8	3.2
Wave height (m)	6.9	7.9	8.7

It can be seen from Table 5, that 500 years return values of storm surge, spring tide with confidence intervals (4.2+2.8 =7.0m) and wave height (7.9m) should be severer than HAF0111 proposed DBF (6.35m) with 100 years return period wave height (6.6m)[36,37](see Table 4), rather than IAEA recommended 10000 years return values [2-8].

Figure 5 and Table 6 show the joint occurance of typhoon induced extreme sea hazards dominated by spring tide for coastal defense because the QS NPP located in estuarine area of the Yangtze River, where spring tide always is the severest sea hazards.

Table 6. Combined extreme external events with joint return period for QS NPP by PNLTCED

Joint Probability \ Extreme Event	Spring Tide (m)	Surge (m)	Wave (m)
100	4.2	3.0	2.5
500	5.0	3.5	3.0
1000	5.5	4.0	3.5
10000	6.5	4.8	4.0

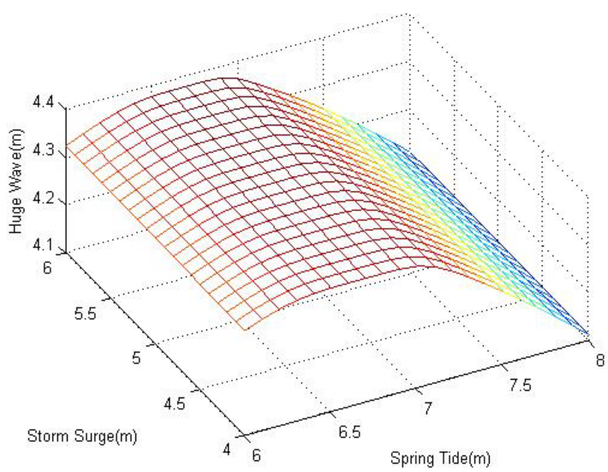

Figure 5. Joint probability distribution of spring tide ,storm surge and extreme wave with 1000 years joint return period for QS NPP.[16,44,45]

5 Flood disaster menaced inland NPP

5.1 Application of the PNLTCED to predict 3-day flood volume at Station Yichang

1975 typhoon Nina induced 1,631 mm of rainfall in 3 days. Banqiao dam and downstream 64 reservoir dams collapsed. The flooding resulted in more than 171,000 deaths affected 12,000,000 people by flood. The Banqiao dam was designed by P-Ⅲ distribution to withstand a 1,000-year flood. All of the authors found that, using traditional extrapolation (such as a Pearson type III model) was difficult to determine the design return period for the extreme events induced by natural disasters..The Yangtze River is the largest river in China, being 6,300 km long with a basin covering nearly 2 million km^2 or about one-fifth of the country's territory. It is the third longest river in the world. The spectacular TGP is located in the middle of the Xiling Gorge, in Yichang of Hubei province. The mean annual discharges exceeding 1,000 m^3/s are mainly through such tributary streams as the Jinsha, Min, Jialing and Wu rivers (Figure 6). More than half a billion people or 45 percent of China's total population live in the basin, which produce about 42 percent of the country's gross domestic product.

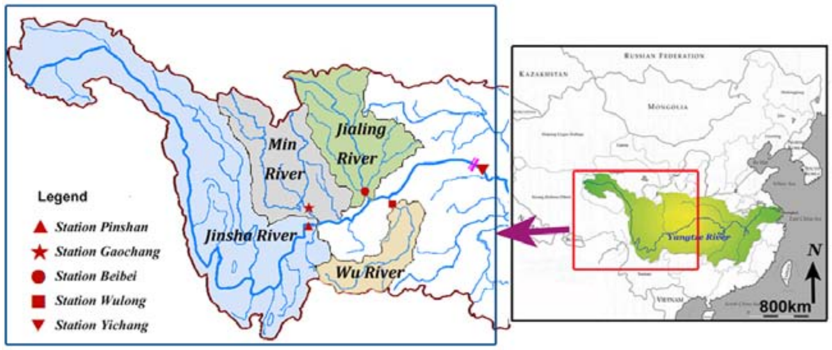

Figure 6. Illustration of the tributaries in the Yangtze River.

5.2 Risk assessment of design code for Three Gorge Dam

The 3-day flood volume of the Jinsha, Min, and Jialing rivers are taken as variables to carry out the joint probability analysis using the PNLTCED model. Twenty-six catastrophic flood volume data between 1965 and 1982 are chosen for the analysis.

The diagnostic checks show that all the data of the Jinsha River, Jialing River and Min River fit well to the generalized extreme value distribution, the frequency of flood fits Poisson distribution very well. The parameters are shown the distribution diagnostic testing of variables are acceptable. The better correlation between the Jinsha River and the Jialing River than between any other two rivers, so the Jinsha River (1) and Jialing River (2) should be taken as inside layer variables. Using the PNLTCED, one contour surface about the 3-day flood volume of the Jinsha, Jialing and Min rivers for each joint return period can be obtained. Fig.7 shows an example of the contour surface of 3-d flood volume calculated by PNLTCED with 100-year joint return period [41]..

Table 7. The combination of the tributaries flood with 100-year return period

Modes	*Jinsha River*		*Min River*		*Jialing River*		*Wu River*		*Fitting data of TGV 3-d flood volume*	
	T	*V*	*T*	*V*	*T*	*V*	*T*	*V*	*T*	*V*
Mode 1	2	43.3	25	51.2	65	92.8	2	26.8	100	260.4
Mode 2	68	70.7	26	51.4	2	52.8	2	26.8	100	245.9
TGV	*T*=100, *V*=208.0; *T*=500, *V*=235.6; *T*=1000, *V*=247.5;									

Note: *T* means return period (units: year); *V* means 3-day flood volume (units: 10^8 m^3).

The results show that when the return period of 3-day flood volume of the tributaries reached 60-70 years simultaneously, the 3-day flood volume for the TGP would be subjected to a severe test.

6 Conclusion

During the past 33 years since 1980 to 2013 three hurricane/ typhoon disasters proved new probability model –CEVD, MCEVD predicted results. With the increasing tendency of the natural hazards frequency and intensity, the first and second costliest hurricane disasters in United States history occurred only in seven years interval. Not only typhoon/ hurricane induced extreme sea hazards, but also flood, rainstorms menaced some important constructed engineering project designed by traditional China and IAEA recommended codes.

We hope that lesson from hurricane Katrina, Sandy and typhoon Fitow should be taken in to account for some NPP safety organizations in China and IAEA.

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