Prediction of Typhoon Triggered Sea Hazards in China

Liu Defu Jiang Hao Wang Fengqing
Ocean University of China, No.5 Yushan Road, Qingdao, 266003, China
Wang Yongfa
China Merchants International Terminal Co., Ltd No. 567 Tongjiang Road, Qingdao, 266520, China
Yuan Lingling
National Center of Ocean Standard and Metrology, Jiyuan West Road,Tianjin 300112, China45 Hoes Lane

***Abstract*-With global warming and sea level rising, the frequency and intensity of typhoon triggered sea hazards such as storm surge, wave, wind and current, especially the combined effects of such extreme events have been increasing and led to significant losses of life and properties. The traditional method cannot determine the design return level for extraordinary sea hazards. This paper introduces the new model Compound Extreme Value Distribution (CEVD) and its applications for prediction of univariate extreme sea hazards, and the Multivariate Compound Extreme Value Distribution (MCEVD) model to predict the joint return level of simultaneous occurrence of multivariate typhoon triggered sea hazards. Based on the MCEVD, a Double Layer Nested Multiobjective Probability Model (DLNMPM) is proposed for sea hazards zoning and prevention criteria.**

***Key words*- Sea Hazards, CEVD, MCEVD, sea hazards zoning, prevention criteria**

I. INTRODUCTION

During the past century the typhoon brought the great losses of lives and property in China. The historical records showed: in 1922, typhoon brought 34500 deaths; in 1956, typhoon brought 20000 deaths; in 1975 the landed typhoon induced Banqiao dam of reservoir collapsed and led to downstream 62 dams collapse, brought 230000 deaths and 12000000 people hit by typhoon induced flood; 1980: 414 deaths, 3133 ships sunk; 1992: 12256 dams and sea well collapsed, 5258 ships sunk, 200 deaths 。1994: 1216 deaths; 1997: 330 deaths. For the offshore structures: in 1979, a jack-up platform sunk and 72 deaths; in 1983, a semisubmersible Jeva Sea sunk in South China Sea and 81 deaths.

In the past years, typhoon disasters are especially serious in China. All the typhoons in 2006 brought 1266 deaths and seventy six billions (RMB) economic losses directly. The first typhoon Chauchu also damaged some deep water platforms.

The typhoon Saomai induced 3.76 m surge and 7m wave, caused 240 death, 952 ships sunk and 1594 others damaged (except foreign ships and ships from other provinces) at Shacheng Port. If the typhoon land 2 hours later, then simultaneously occurrence of typhoon surge and spring tide should flood most area of Zhejiang and Fujian provinces. The results would be several times severe than the New Orleans disaster caused by Katrina. Such catastrophe is possible!

This work was supported by the National Natural Science Foundation of China. (Grant No. 50679076)

The traditional environment loads design criteria for coastal structures is extrapolation of observed annual maxima data by Pearson type three model, which is recommended by Chinese design codes，see [1]. But some extraordinary sea hazards, for example, 1956 No.12 Typhoon induced maximum sea level observed in Ganpu hydrological stations reached 9.68m, but predicted 10000 years return period sea level by traditional method based 50 years observed data is only 8.2m. For the offshore structure design, the API recommended “100-yr return period wave height with associated wind and associated current" as the combined extreme environmental loads for fixed platform, but the meaning of “associated” is some what ambiguous. see [2].

Hurricane Katrina in 2005 induced the most catastrophic failure in engineering system in the history of America. 2000 people died and 400 billions dollars economic losses are the result of this disaster in New Orleans [3,4].. Hurricane Katrina and Rita destroyed 111 platforms and damaged 52 platforms [5]. Mentioned above typhoon induced disasters in China and hurricane Katrina in USA taught one important lesson: when natural hazards are combined with human hubris (blind trust) and government organizational performance failure, disasters and catastrophes will come sooner or later [4]. This lesson shows the necessity of improvement the traditional prediction model.

II. FUNDAMENTAL THEORY OF CEVD AND MCEVD

Proposed in this paper the Double-layer nested Multi-objective probability Model of typhoon disaster zoning and prevention criteria is based on the MCEVD. The derivation of the MCEVD is as follows:

Let N be a random variable (the number of storms in a given year), with their corresponding probability $P\{N=k\}=p_k$, $k=1,2,\cdots$; and let $(\xi_{11},\ldots,\xi_{n1})$, $(\xi_{12},\ldots,\xi_{n2})$...... be an independent sequence of independent identically distributed random vectors (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 $\xi_{1j}, 1\le j\le N, N=1,2,\ldots\ldots$

It 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 $(X_1,\ldots,X_n)$, the case of N=0 should be neglected, because no extreme value of interest can occur outside the storm when N=0 (Liu and Ma, 1980)..

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

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

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

As mentioned above, the frequency of typhoon (hurricane, winter storm) occurrence can be fitted to Poisson distribution $P_i=\dfrac{e^{-\lambda}\lambda^i}{i!}$.

Then the MCEVD can be derived as:

$$P(\lambda;x_1,x_2,\ldots x_n)=e^{-\lambda}\left(1+\iint_{\Omega}\cdots\int e^{\lambda F(x)}f(x_1,x_2,\ldots x_n)dx_1dx_2\cdots dx_n\right) \tag{2}$$

In which, λ is mean 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 storm surge, wave, wind, current or typhoon characteristics. In the case of univariate problem, equation (1) can be simplified to CEVD as in [6]:

$$P(\lambda,x)=\sum_{i=1}^{\infty}p_i\cdot i\cdot\int_{-\infty}^{x}G_i^{i-1}(u)g(u)du=\sum_{i=0}^{\infty}p_iG_x^i(u).$$

The validity of CEVD and MCEVD can be seen from comparison between predicted results by CEVD and NOAA proposed SPH, PMH along Gulf of Mexico and Atlantic coasts in Figure.1 [7] and comparison between MCEVD and others in Figure.2 [8， 9， 10， 11， 12].

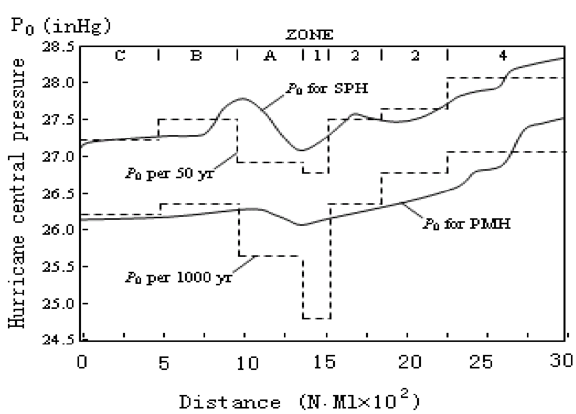

Figure. 1 Comparison between the results of CEVD and NOAA , from [2, Figure.6]

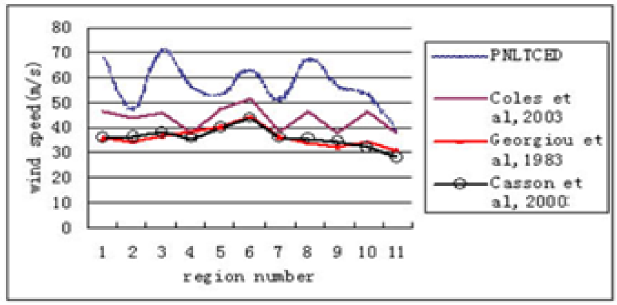

Figure. 2 Comparison between MCEVD and other researchers [11, 12]

III. APPLICATION CEVD AND MCEVD FOR COASTAL AND OFFSHORE ENGINEERING DESIGN

1. Determination of return period for extraordinary sea level of Hangzhou Bay by CEVD and MCEVD.

Many Chinese design criteria are based on limited observed annual maximum data extrapolation by P-□ type model. This method only takes the strongest typhoon triggered event from each year as annual maximum data, which waste many valuable information. And if there are not enough data, the error of the design value may be larger. Therefore, when calculating the extreme sea level of given return period, process data sampling is more reasonable than annual maximum data sampling.

China experiences many landed typhoons in each year. Particularly, southeast coasts of China, which meets nearly three ~ five typhoons every year, is typhoon disaster-stricken area. Therefore, it is important to calculate the extraordinary sea level based on the reasonable method. Based on CEVD and MCEVD, we calculate the extraordinary sea level of given return period in Hangzhou Bay, which is a typical sea area of southeast coasts in China. Data was collected at the Ganpu hydrological station from 1972 to 2005.

First, based on CEVD, we calculate the typhoon induced extraordinary sea level of given return period. Mean value of the annual typhoon frequency λ is 2.8. Ganpu hydrological station's extraordinary sea level curve fitting can be seen in Figure. 3.

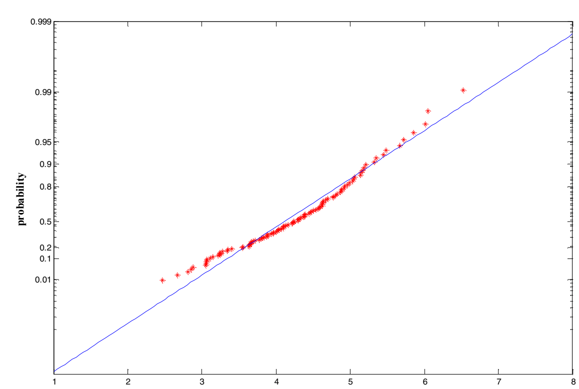

Figure. 3 Curve fitting of CEVD of Ganpu hydrological station

By hypothesis test, we can find that the extraordinary sea level fits Gumbel distribution. And then we calculate return period of extraordinary sea level by Pearson type three and CEVD - Poisson-Gumbel model, see [6]. The result can be seen in TABLE. I.

TABLE I
COMPARISON OF RESULT BY DIFFERENT MODELS

Ganpu hydrological station		
Return Period (a)	P-III (m)	CEVD (m)
500	7.56	8.51
100	6.85	7.46
50	6.53	6.98
20	6.09	6.34
10	5.75	5.84

Extraordinary sea level can be combined of spring tide and surge. Based on MCEVD method, joint occurrence of typhoon induced spring tide and surge can be calculated. The spring tide and surge data fitting can be seen in Figure. 4 and Figure. 5.

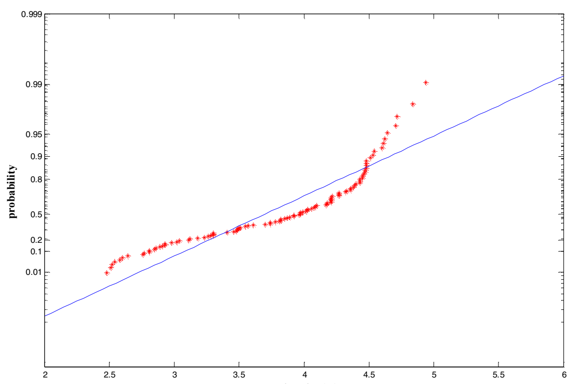

Figure. 4 Curve fitting of spring tide of Ganpu hydrological station

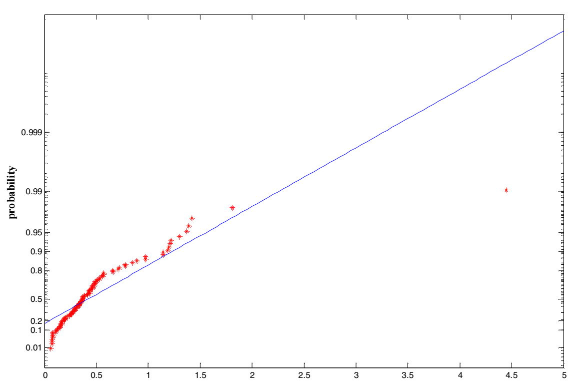

Figure. 5 Curve fitting of surge of Ganpu hydrological station

The spring tide and surge of Ganpu hydrological station can pass the hypothesis test. The cumulative distribution function (cdf) and probability density function (pdf) figures of Ganpu hydrological station can be seen in Figure. 6 and Figure. 7.

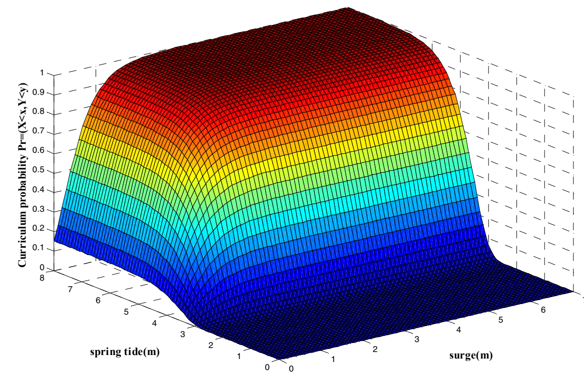

Figure. 6 Cdf figure of Ganpu hydrological station

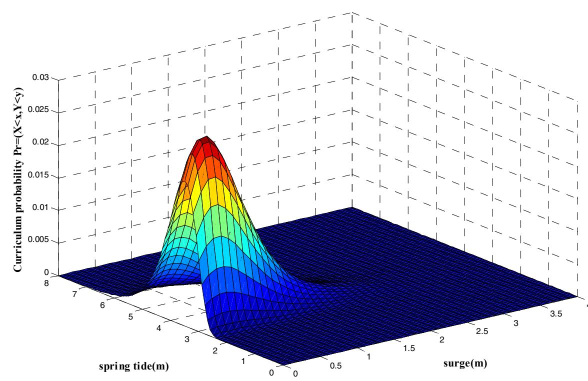

Figure. 7 Pdf figure of Ganpu hydrological station

Then we calculate the extraordinary typhoon induced spring tide and surge of different return period of Ganpu hydrological station. And the sum of them can be used as extraordinary sea level. The result can be seen in TABLE II.

TABLE II
EXTRAORDINARY SEA LEVEL OF DIFFERENT RETURN PERIOD OF GANPU HYDROLOGICAL STATION

Joint return period		combination 1 (m)	combination 2(m)	combination 3(m)
50 a	Spring tide	5.6	5.7	5.5
	Surge	2.0	1.9	2.1
	sea level	7.6	7.6	7.6
100 a	Spring tide	5.7	5.8	5.8
	Surge	2.5	2.4	2.3
	sea level	8.2	8.2	8.1

500 a	Spring tide	6.6	6.6	6.7
	Surge	4	3.9	3.7
	sea level	10.6	10.5	10.4
1000 a	Spring tide	6.9	6.9	6.9
	Surge	4.3	4.1	4.2
	sea level	11.2	11.0	11.1

CEVD and MCEVD are both based on typhoon process sampling, which will take full use of data. This method is better than that based on annual maxima data sampling, and can show more discipline of things than latter.

2. Prediction of disaster prevention design water level of Yangtzi River for Shanghai city by MCEVD

Shanghai City is located at the estuarine area of the Yangtze River in China. Historically observed data shows that the surges induced by typhoons and the flood peak run-off from Yangtze River coupled with the astronomical spring tide have caused significant losses of lives and properties to Shanghai City. Combined effect of storm surge, upper river flood and spring tide on the coastal structures is the prime factor for disaster prevention [13]..

Based on the traditional univariate annual maxima extrapolation method, the 1000yr return period disaster prevention design water lever for Shanghai City is 5.86 m. But No.4 typhoon in 1981 had caused the water level as high as 5.74 m [14]. Obviously, the univariate extrapolation design water level neglects the contribution of the random combination of typhoon frequency, storm surge, flood and astronomical spring tide. PNLTCED can be used to predict design water level more accurately.

Daton Hydrological Station is located at the upper river of Yangtze River, 642 km from Wuson Oceanologic Station near Shanghai City. The observed water levels of flood at Daton station are not influenced by typhoon surge from sea side. Data of water level collected at the Wuson Station from 1970 to 1990, and the data of flood at the Daton Station are used in this study.

Observed water level at Wuson station during typhoon season (h_w) can be divided into three components:

1) The hourly harmonic analyzed tide (h_a) obtained from 63 harmonic constants model during 1912~1987. Because there are different uncertainties included in harmonic analysis (such as uncertainty induced by the choice of different numbers of harmonic constants, uncertainty in different duration of observations, uncertainty in analyzed harmonic constants from different period of observations, et. al), so that for the following multivariate joint probability study the astronomical spring tide would be considered as random variables.

2) The flood peak run-off from Yangtze River (h_f) can be obtained by linear regression equation $h_f = 7.67\times10^{-6} Q_D - 0.19^*$, where Q_D is observed flood peak volume (m^3/s) at station Daton in 24 hours before the typhoon occurring Shanghai sea area.

3) The typhoon induced storm surge (h_s) can be obtained by $h_s = h_w - h_f - h_a$.

It can be seen from the discussion that the annual typhoon occurring frequency varying from year to year is fitting to the Poisson distribution (see TABLE III). The typhoon induced storm surge, simultaneous rise of water level by flood run-off from Yangtze River and astronomical Spring tide are continuous variables. Therefore, the PNLTCED can be used to predict disaster design water level for Shanghai city.

TABLE III
TYPHOON FREQUENCY IN SHANGHAI (1912-1987)

The number of tropical storm in one year								Total years/Total number	frequency
0	1	2	3	4	5	6	7		
Year of occurrence									
0	4	3	3	6	2	2	1	72/21	$\lambda = 3.43$

The total 72 groups of simultaneous h_f, h_s and h_a are used to study trivariate joint probability. Diagnostic check shows that h_a, h_f and h_s fit to generalized extreme value distribution (See Figure. 8. a,b,c).

Location, scale and shape parameters and corresponding standard deviation of marginal distributions estimated by maximum likelihood method are shown in TABLE IV.

The correlation coefficients between h_a and h_f; h_a and h_s; h_f, h_s and dependent Parameters $\hat{\alpha}$, $\hat{\beta}$ are shown in TABLE V.

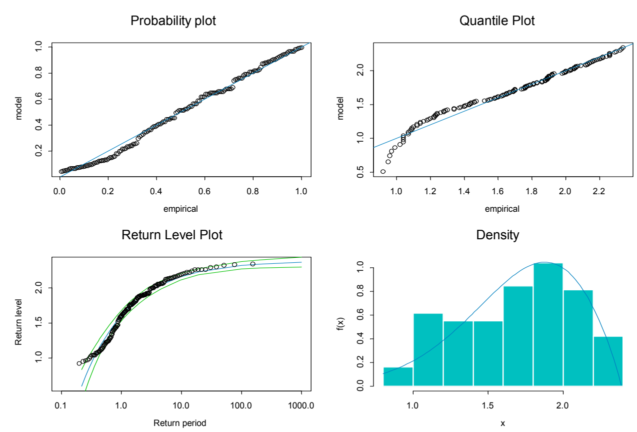

Figure. 8.a. Diagnostic check of spring tide

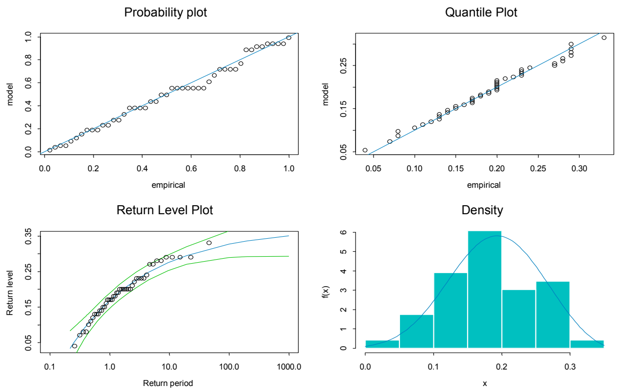

Figure. 8.b. Diagnostic check of flood

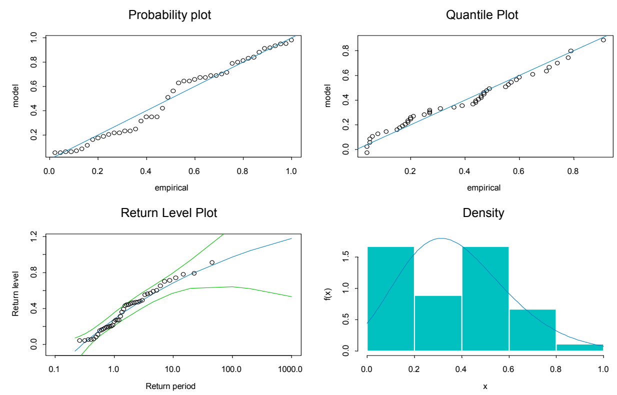

Figure. 8.c. Diagnostic check of storm surge

TABLE IV
PARAMETERS OF MARGINAL DISTRIBUTION

Parameter of marginal distribution	h_a (m)	h_f (m)	h_s (m)
Location parameterμ	1.98	0.17	Location parameterμ
Standard deviation of μ	0.02	0.01	Standard deviation of μ
Scale parameterσ	0.14	0.02	Scale parameterσ
Standard deviation ofσ	0.02	0.01	Standard deviation ofσ
Shape parameterξ	-0.18	0.42	Shape parameterξ
Standard deviation ofξ	0.15	0.17	Standard deviation ofξ

TABLE V
CORRELATION COEFFICIENTS AND DEPENDENT PARAMETERS

h_a vs h_f ($r_{1,2}$)	h_a vs h_s ($r_{1,3}$)	h_f vs h_s ($r_{2,3}$)	$\hat{\alpha}$	$\hat{\beta}$
0.29	0.075	0.10	0.95	0.84

TABLE V shows that the correlation between h_a and h_f is comparatively stronger than the others. Therefore, ha and hf can be treated as inside layer variables, while hs as outside layer variable.

In this example, the design water level with 100-yr joint return period is obtained by using the data sampling dominated by the extreme storm surge with concomitant flood and tide. (See TABLE VI)

TABLE VI
ESTIMATED DISASTER PREVENTION DESIGN WATER LEVEL FOR SHANGHAI CITY

Joint return period (years)	Flood surge (m)	Storm surge (m)	Spring-tide (m)	Design water level (m)
100	0.43	1.32	4.14*	5.89*

*at Wuson datum plane.

TABLE VI shows that the 100-yr joint return period design water level predicted by PNLTCED is close to that of the 1000-yr return period water level predicted by the traditional univariate extrapolation method for Shanghai .

3. Combined extreme environmental loads criteria for platform based on MCEVD

The application of the joint probability method to template platform, jack-up platform and riser are shown below.

The template platform we studied in this paper lies in the South China Sea where the water depth is 145m. The base overturning moments as combined platform responses were calculated from Typhoon induced wave, current, and wind during the period 1953-1986 [15].

The simulation results are shown in TABLE VII. And API recommended three definitions about the combined extreme environmental loads as following:

*1)*100-yr return period wave height with "associated" wind and "associated" current;

*2)*Any "reasonable" combination of wind speed, wave height and current speed that results in the 100-yr return period combined platform load;

*3)*100-yr return period wave height combined with the 100-yr return period wind speed and the 100-yr return period current speed.

TABLE VII
COMPARISON OF DIFFERENT METHODS FOR FIXED PLATFORM IN SOUTH CHINA SEA

Method	Wave Height (m)	Current Velocity (m/s)	Wind Speed (m/s)	Joint return period (year)
API definition 1	15.6	1.96	52.7	180
API definition 2	14.3	2.31	54.7	150
API definition 3	15.6	2.77	55.9	600
100-yr return period joint probability method	14.2	2.18	53.7	100

From the TABLE VII, it can be obviously seen that the combinations of environmental factors obtained by different methods can occur simultaneously at different return periods. The joint probability method considers the correlation among the factors and takes the simultaneous wave, wind and current as design criteria, so it can give the real "100-yr sea state".

The jack-up platform model is from "Bohai IV" which has three triangular truss legs. Under the extreme sea state, jack-up platform stands on the sea bottom with its legs inserting into the seabed. As the template platform, the overturning moment is the judge condition to determine the single solution. Here joint probability method is applied to jack-up platform and 31 storms hind-casting data of Yellow sea are used. The results are shown in TABLE VIII.

TABLE VIII
DESIGN CRITERIA OF DIFFERENT METHODS FOR JACK-UP PLATFORM IN YELLOW SEA

State	Method	Wind (m/s)	Wave (m)	Current (m/s)	Overturning Moment (N.m, 10^8)
Dominated by wave	Joint probability method	29.0	4.42	0.50	1.3500
Dominated by current	Joint probability method	24.6	3.70	1.0	1.0220
Dominated by wind	Joint probability method	32.5	3.50	0.52	1.6459

Like the first example, it also can be found that the design criteria from joint probability method and traditional method have great differences. In addition, the response corresponding to the combination dominated by wind is much lager than wave or current dominated condition for jack-up platform. Because the windward area increases since there are a part of legs stick to the main body of jack-up platform. The wind dominated condition is most severe in this situation.

4. Typhoon triggered sea hazards zoning

Typhoon triggered sea hazards zoning based on a new type of double layer nested multi-objective probability model, in which the joint probability predictions of different typhoon characteristics are taken as the first layer and typhoon induced disaster factors (such as strong wind, storm surge, huge wave, heavy rain, flood, and so on) are taken as the second layer. The new model will be used to establish typhoon disaster zoning and the prevention criteria system.[12].

Typhoon triggered sea hazards prediction, emergency, zoning and risk assessment system can be established as follows (see TABLE IX).

IV. CONCLUSIONS

The hurricane Katrina and typhoon Nina disaster taught one important lesson: unreasonable disaster protection criteria with human, government performance failure might turn natural hazards into terrible catastrophic. Proposed in this paper double layer nested multi-objective probability model focus on optimization of natural hazards, protection, reduction, mitigation system and human, government performance and established the typhoon disaster zone and prevention criteria along China coasts.

The theoretical base of DLNMOPM is MCEVD. As mentioned in the " Summary of flood-frequency Analysis in the United States": The combination of the event-based and joint-probability approaches promises to yield significantly improved descriptions of the probability laws of extraordinary floods" [16]. MCEVD is first applicable model for this promise to predict typhoon/hurricane induced extraordinary events.

REFERENCES

[1] Code for Sea Port Hydrology, Sector Standard of The People's Republic of China, JTJ 213-98, 1999

[2] Army Corps of Engineers.(2005). History of Lake Pontchartrain and Vincinity Hurricane Protection Project. *U.S.Government Accountability Office* (GAO-06-244T). pp1~4

[3] API RP 2A-LRFD. "Planning, Designing and Constructing for Fixed Offshore Platforms - Load and Resistance Factor Design". ISO13819-2:1995(E)pp127

[4] Robert Bea. (2007) "Reliability assessment & management lessons from hurricane Katrina," Proc. Offsh. Mech.& Arc. Eng. San Diego, OMAE2007-29650

[5] Wisch David J. and Ward E.G.,(2007) " Offshore Standards - The Impact of Hurricanes Ivan/Katrina/Rita"Proc. Offsh Mech & Arc.Eng., San Diego, OMAE2007-29764

[6] Liu T.F. and Ma, F.S.(1980)."Prediction of Extreme Wave Heights and Wind Velocities," *Journal of the Waterway Port Coastal and Ocean division*, ASCE,106, No.WW4, pp469~479.

[7] Liu.T.F.(1982)."Long term Distribution of Hurricane Characteristics," *Proc. Offshore Tech Con,* Houston, TX, OTC 4325, pp 305~313

[8] Stuart Coles and Emil Simiu (2003). "Estimating Uncertainty in the Extreme Value Analysis of data Generated by a Hurricane Simulation Model," *J of Engineering Mech* ASCE, ISSN 0733-9399, pp 1288-1294.

[9] Georgiou, P.N., Davenport, A.G. and Vickery, P.J.(1983). "Design wind speeds in regions dominated by tropical cyclones," *J. Wind Engng Industrl Aerodyn.*,13, pp139-152.

[10] Edward Casson, and Stuart, Coles (2000). "Simulation and Extremal analysis of hurricane events," *Appl.Statist.*,49, Part 2, pp 227-245.

[11] Liu Defu, Pang Liang, Fu Gang, et al. (2006). "Joint Probability Analysis of Hurricane Katrina 2005" . *Proc Intern Offshore & Polar Eng Conf.* San Francisco, USA.

[12] Liu Defu, Pang Liang , Xie Botao & Wu Yuankang (2008) "Typhoon disaster zoning and prevention criteria - A double layer nested multi-objective probability model and its application" ,Science in China ,Series E - Technological Sciences,:V.51,No.7..

[13] Liu Defu, Shi Hongda, Pang Liang.(2006) Disaster Prevention Design Criteria for the Estuarine Cities: New Orleans and Shanghai—the Lesson from Hurricane Katrina[J]. *Acta Oceanologica Sinica* Vol.25, No.4 pp 124-130

[14] Liu Defu, Song Y and et al,(2002). "Combined Environmental Design Loads Criteria for Marine Structures," *Proc. Offshore Tech Conf*, Houston, TX, OTC 14191.pp1749-1755

[15] Liu Defu (Liu T.F), Ma Li, Jing Kun. (2004). Risk analysis of the disaster prevention design criteria for an estuarine city – Shanghai. *Proc. Offsh. Mech.& Arc. Eng.* Canada, OMAE2004-51505

[16] Kirby WH, Moss ME (1987) "Summary of flood-frequency analysis in the United States," *Journal of Hydrology*, 96； 5-14

TABLE IX
TYPHOON INDUCED SEA HAZARDS PREDICTION, EARLY-WARNING, DISASTER ZONING AND RISK ASSESSMENT

<table>
<tr><td rowspan="2">Typhoon characteristics and joint return period</td><td>Frequency (λ)</td><td>Intensity (□P)</td><td>Max. Wind Speed (U)</td><td>Radius of typhoon (Rmax)</td><td>Moving Speed (v)</td></tr>
<tr><td colspan="5">Joint return period</td></tr>
<tr><td>Factors of typhoon induced disaster</td><td>Wind (U)</td><td>Wave (H)</td><td>Surge (S)</td><td colspan="2">Rainstorm (R)</td></tr>
<tr><td>Combined with severe conditions</td><td>Spring tide (A)</td><td>Current (C)</td><td>Rainstorm induced inundation (F)</td><td colspan="2">Rainstorm induced landslide and debris (D)</td></tr>
<tr><td>Influenced infrastructures</td><td>Coastal prevention engineering</td><td>Offshore engineering (platform, pipe, riser)</td><td>Civil engineering and farmland</td><td>Evacuation of disaster-hit area</td><td>Coastal infrastructures</td></tr>
<tr><td>Combination of factors
（main factor rank first）</td><td>H, S</td><td>H, U, C, S</td><td>R, S, F</td><td>R, S, U, F, D</td><td>U, R</td></tr>
<tr><td rowspan="2">Prediction, early-warning and disaster level</td><td>joint return period</td><td>＜50a</td><td>＞50a</td><td>100a</td><td>＞100a</td></tr>
<tr><td>Early-warring level</td><td>Engineering prevention criteria (Blue)</td><td>Light disaster (Yellow)</td><td>Severe disaster (orange)</td><td>Catastrophe (Red)</td></tr>
<tr><td>Disaster Zoning</td><td colspan="5">According to the prevention objects and aims of each province, making typhoon induced sea hazards zoning and risk assessment</td></tr>
</table>