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Probability Prediction of Typhoon/Hurricane induced Hazards: Theory and Applications

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Abstract

Since 1972 Rita typhoon attacked on Dalian Port and induced severe catastrophe, we were studied on statistical prediction model of typhoon induced wave height and wind speed. With an increasing tendency of the natural hazards frequency and intensity, risk assessment of some design codes for coastal defense infrastructures should be of paramount importance influencing the economic development and a lot of lifes in China. Comparison between existing extreme statistical model like Gumbel, Weibull, P-III distribution or Probable Maximum Typhoon/Hurricane (PMT/PMH), Design Basis Flood (DBF) with our 1975-1980 proposed (CEVD) model showed that all the planned, designed and constructed coastal infrastructures accepted the traditional safety regulations are menaced by possibility of future typhoon/hurricane disasters and cannot satisfy the safety requirements with the increasing tendency of the extreme natural hazards. Our first publication in US J. of Waterway Port Coastal & Ocean Eng. ASCE, 1980, ww4) proposed a new model “Compound Extreme Value Distribution” used for China Sea, after then the model was used in “Long term Distribution of Hurricane Characteristics” for Gulf of Mexico & Atlantic coasts, U.S. (OTC.1982). 2005 hurricane Katrina, Rita and 2012 hurricane Sandy induced disasters proved 1982 CEVD and CEVD has been developed into Multivariate Compound Extreme Value Distribution (MCEVD). 2006 MCEVD predicted extreme hazards in New Orleans, Gulf of Mexico and Philadelphia areas. 2013 typhoon Fitow induced disaster in China also proved MCEVD 2006 predicted results.

Theory of Multivariate Compound Extreme Value Distribution

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), it 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. Typhoon characteristics or typhoon-induced extreme sea events are continuous random variables. The Compound Extreme Value Distribution (CEVD) can be derived by compounding a discrete distribution and the extreme distribution for typhoon induced extreme events along China's coasts [14]. Then the CEVD is used to analyze long-term characteristics of hurricanes along the Gulf of Mexico and the Atlantic US coasts [15，16，17]. During the past years, CEVD has been developed into MCEVD and applied to predict and prevent typhoon induced disasters for coastal areas, offshore, hydrological engineering, estuarine cities and nuclear power plants 75 English publications. In this paper only 26 important publications referenced [14-40]. Both CEVD and MCEVD have the following advantages: instead of traditional annual maximum data sampling, the typhoon process maximum data sampling is used and the typhoon frequency is used in the models.

During the past years, CEVD and MCEVD have been applied to more than 50 coastal, offshore, and hydraulic projects in China and abroad. The theory of CEVD is also referenced by some foreign experts and used for extreme sea hazards study in North Sea and around Korean coast [16， 24]. In view of the ‘‘Summary of flood frequency analysis in the United States" concluded that "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 that follows the development direction of the extraordinary floods prediction, as desired by Kirby and Moss [7]. It stands to reason that MCEVD is a good model for typhoon (or hurricane) disaster prediction. Our proposed methods in [14,17,19,23,28,30] are used as design criteria of wind-structure interaction experimentation for mitigating hurricane-induced U. S. coastal disasters

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

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

and

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

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

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

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 [11,12].

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

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

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

This can be proved as follows:

$$\begin{aligned}
F(x,y,z) &= P(X < x, Y < y, Z < z) \\
&= P(\bigcup_{i=0}^{\infty} \{X < x, Y < y, Z < z\} \bigcap \{n = i\}) \\
&= \sum_{i=0}^{\infty} P(X < x, Y < y, Z < z \mid n = i) \cdot P(n = i) \\
&= \sum_{i=0}^{\infty} p_i P(X < x, Y < y, Z < z \mid n = i) \\
&= p_0 \cdot Q(x,y,z) + \sum_{i=1}^{\infty} p_i \cdot P(X < x, Y < y, Z < z \mid n = i)
\end{aligned}$$

in which

$$\begin{aligned}
&P(X < x, Y < y, Z < z \mid n = i) \\
&= P(\bigcup_{k=1}^{i} \{X < x, Y < y, Z < z\} \bigcap \{\underset{1 \le j \le i}{Max}\, \xi_j = \xi_k\} \mid n = i)
\end{aligned}$$

$$= \sum_{k=1}^{i} P(\{X < x, Y < y, Z < z\} \bigcap \{\underset{1 \le j \le i}{Max}\, \xi_j = \xi_k\} \mid n = i)$$

Let $\xi_k = \xi_1$,

then

$$P(X < x, Y < y, Z < z \mid n = i) \quad = iP(\{X < x, Y < y, Z < z\} \bigcap \{\underset{1 \le j \le i}{Max} \xi_j = \xi_k\} \mid n = i)$$

$$= i \cdot P(\xi_1 < x, \eta_1 < y, \varsigma_1 < z, \xi_1 > \xi_j, \ j = 2,3,\cdots i \mid n = i)$$

$$= iE\left\{I_{\{\xi_1 < x\}}(\omega) I_{\{\eta_1 < y\}}(\omega) I_{\{\varsigma_1 < z\}}(\omega) I_{\{\xi_1 > \xi_j, \ j=2,3,\cdots i\}}(\omega) \middle| n = i\right\}$$

$$= iE\left\{\begin{array}{l} E\left\{I_{\{\xi_1 < x\}}(\omega) I_{\{\eta_1 < y\}}(\omega) I_{\{\varsigma_1 < z\}}(\omega) I_{\{\xi_1 > \xi_j, \ j=2,3,\cdots i\}}(\omega)\right\} \\ \mid (\xi_1 = U, \eta_1 = V, \varsigma_1 = W) \end{array}\right\}$$

where (U, V, W) and ($\xi_1, \eta_1, \varsigma_1$) are statistically independent, their probability distribution function is $G(x, y, z)$.

$$P(X < x, Y < y, Z < z \mid n = i)$$
$$= iE\left\{\begin{array}{l} I_{\{U < x\}}(\omega) I_{\{V < y\}}(\omega) I_{\{W < z\}}(\omega) E\left\{I_{\{U > \xi_j, \ j=2,3,\cdots i\}}(\omega)\right\} \\ \mid (\xi_1 = U, \eta_1 = V, \varsigma_1 = W) \end{array}\right\}$$

$$= iE\left\{I_{\{U < x\}}(\omega) I_{\{V < y\}}(\omega) I_{\{W < z\}}(\omega) G_1^{\ i-1}(u)\right\}$$

$$= i \cdot \int_{-\infty}^{z} \int_{-\infty}^{y} \int_{-\infty}^{x} G_1^{\ i-1}(u) \cdot dG(u, v, w)$$

$$= i \cdot \int_{-\infty}^{z} \int_{-\infty}^{y} \int_{-\infty}^{x} G_x^{\ i-1}(u) g(u, v, w) \ dudvdw$$

where

$$I_A = \begin{cases} 1, x \in A \\ 0, x \notin A \end{cases}$$

is the characteristic function of A

$$F(x, y, z) = p_0 Q(x, y, z) + \sum_{i=1}^{\infty} p_i \cdot i \cdot \int_{-\infty}^{z} \int_{-\infty}^{y} \int_{-\infty}^{x} G_1^{\ i-1}(u) g(u, v, w) \ dudvdw$$

$$= p_0 Q(x,y,z) + \sum_{i=1}^{\infty} p_i \cdot i \cdot \int_{-\infty}^{z}\int_{-\infty}^{y}\int_{-\infty}^{x} G_1^{i-1}(u) g(u,v,w)\, dudvdw + p_0 - p_0 \tag{2}$$

When the case of n=0 is ignored, Eq.(2) can be approximated as formula (3)

$$F(x,y,z) = p_0 + \sum_{i=1}^{\infty} p_i \cdot i \cdot \int_{-\infty}^{z}\int_{-\infty}^{y}\int_{-\infty}^{x} G_1^{i-1}(u) g(u,v,w)\, dudvdw \tag{3}$$

Therefore, formula (1) is proved.

Poisson-Gumbel Compound Extreme Value Distribution (P-G CEVD) and its applications

When $G(x_1,\ldots,x_n)$ is probability distribution function of unit-variant random variable x, then formula (1) can be simplified to

$$F(x) = \sum_{i=0}^{\infty} p_i [G(x)]^i \tag{4}$$

When typhoon occurrence frequency can be fitted to Poisson distribution, typhoon induced wave or wind fitted to Gumbel distribution, as formula (5)

$$G(x) = e^{-e^{-x}} = \exp\{-\exp[-\alpha(x-\mu)]\} \tag{5}$$

where α and μ as parameters of Gumbel distribution.

Then Poisson-Gumbel Compound Extreme Value Distribution (P-G CEVD) can be derived as[18，19，20]:

$$F(x,y) = \sum_{i=0}^{\infty} p_i [G(x)]^i = \sum_{i=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{i!}[G(x)]^i = e^{-\lambda[1-G(x)]} = 1 - P \tag{6}$$

American Journal of Engineering, Science and Technology (AJEST) Volume 11, 2021

Typhoon induced extreme wave (wind speed) with return period T (1/p) can be calculated by formula (7):

$$H_P = \mu + X_P / \alpha \qquad (7)$$

where

$$X_P = -\ln\{-\ln(1+\frac{\ln(1-P)}{\lambda})\}$$

$\lambda = \frac{n}{N}$ is the yearly mean value of typhoon frequency

N is total number of year

n is total typhoon number

$$\left.\begin{aligned} \alpha &= \sigma_n / S \\ \mu &= \overline{H} - y_n / \alpha \end{aligned}\right\}$$

$\overline{H}, S$: mean value and standard deviation of typhoon induced wave,

σ_n, y_n can be calculated by typhoon number.

Comparison between P-G CEVD, Gumbel and P-IIIdistributions

1953–2006 observed typhoon induced wave data in East China sea are used to statistical check for Gumbel P-III and P-G CEVD. The Kolmogorov-Smilrov test based on the 20 years moving average data sampling used for calculation maximum deviation between empirical and theoretical distributions as formula (8):

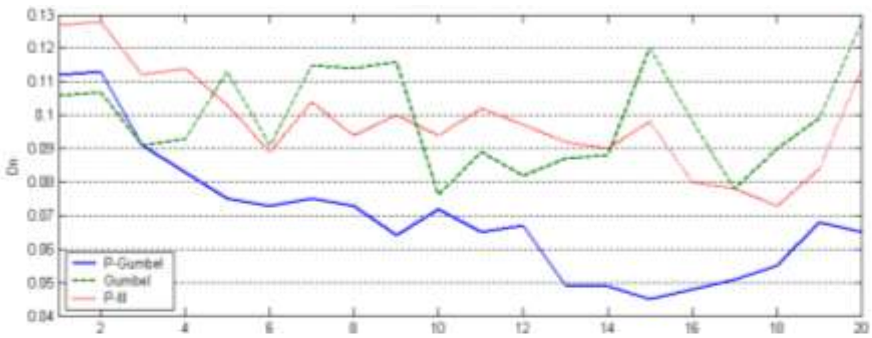
$$D_n = \sup_{-\infty<x<\infty} \left|F_n(x) - F_0(x)\right| \qquad (8)$$

Where $F_n(x)$ ix empirical distribution, $F_0(x)$ is theoretical distribution, Standard deviation as

$$d = \sqrt{\frac{\sum_{i=1}^{n}(pl - pj)^2}{n-1}} \tag{9}$$

Where; p and pj are theoretical and empirical value

The estimated Dn and d for Gumbel, P-III and P-G CEVD models are shown in Figure 1, 2.

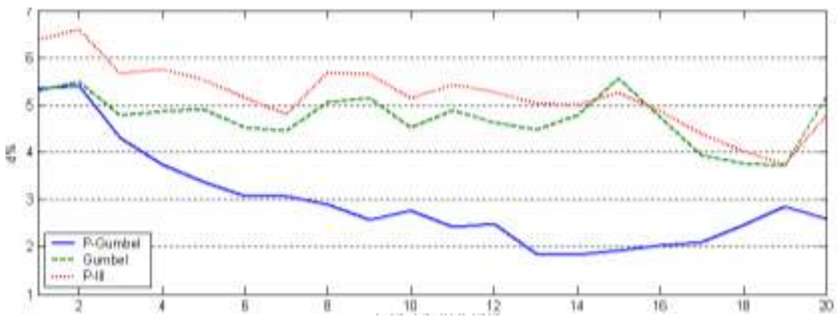


20 yrs moving average data sampling from 50 yrs observed wave data

Figure 1. Comparison of calculated Dn between three models.

Figure 1, 2 and Table 1 show that P-G CEVD is a more reasonable model for extreme wave prediction than traditional models.

The P-G CEVD used to design wave prediction for more than 40 coastal structures of China and accepted in 2008 “China Code for Sea Port Hydrology “ as a recommended model for design wave prediction.



20 yrs moving average data sampling from 50 yrs observed wave data

Figure 2. Comparison of calculated d between three models.

Table 1. Relative differences of predicted return value Δh between three models

Model	100 a	50 a	20 a
	Δh	Δh	Δh
Gumbel	26%	25%	23%
P－III	26%	25%	22%
P-Gumbel	18%	17%	16%

Poisson- Weibull Compound Extreme Value Distribution (P-W CEVD) and Its Application along U. S. Coasts

Long term hurricane data show that frequencies of hurricane occurrence along the U.S. Atlantic East coast and Gulf of Mexico coast agree with the Poisson distribution (Figure 5), Seven regions along Gulf of Mexico and Atlantic east coasts for hurricane frequencies occurrence frequencies, and the hurricane central pressure, wind velocities, wave heights and storm surges agree with the Weibull distribution, a Poisson- Weibull Compound Extreme Value Distribution (P-W CEVD) is presented to predict hurricane central pressure, wind velocities, wave heights and surges [18，19，21，22] : 7 regions along Gulf of Mexico and Atlantic east coasts for hurricane frequencies occurrence frequencies。

Weibull distribution as formula (10):

$$G(x)=1-\exp\left\{-\left(\frac{x}{b}\right)^{r}\right\} \tag{10}$$

P-W CEVD can be derived as:

$$X_p=\left(-\ln\left\{-\frac{1}{\lambda}\ln(1-p)\right\}\right)^{\frac{1}{r}}-b \tag{11}$$

Where b, r are parameters of Weibull distribution

$$\lambda = \frac{n}{N}$$

is the yearly mean value of hurricane frequency

Poisson-Nested Logistic Tri-variety Compound Extreme Value Distribution (PNLTCEVD)

As mentioned above, frequency of hurricane occurrence can be fitted to Poisson distribution (Figure 3), as

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

And substitute nested–logistic tri-variety distribution for the continuous distribution into formula (3), the PNLTCED can be obtained Nested–logistic tri-variety distribution is expressed as

$$G(x_1, x_2, x_3) = \exp\left[-\left\{\left[\left(1+\xi_1\frac{x_1-\mu_1}{\sigma_1}\right)^{-1/(\alpha\beta\xi_1)} + \left(1+\xi_2\frac{x_2-\mu_1}{\sigma_2}\right)^{-1/(\alpha\beta\xi_2)}\right]^{\beta} + \left(1+\xi_3\frac{x_3-\mu_3}{\sigma_3}\right)^{-1/(\alpha\xi_3)}\right\}^{\alpha}\right] \quad (12)$$

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

$$\hat{\alpha} = \frac{\sqrt{1-r_{13}} + \sqrt{1-r_{23}}}{2}$$

$$\hat{\beta} = \frac{\sqrt{1-r_{12}}}{\hat{\alpha}}$$

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

Let

$$s_j = \left(1 + \xi_j \frac{x_j - \mu_j}{\sigma_j} \right)^{-1/\xi_j} \text{ j=1, 2, 3}$$

then formula (12) can be written as

$$G(x_1, x_2, x_3) = \exp\left\{-\left[(s_1^{1/(\alpha\beta)} + s_2^{1/(\alpha\beta)})^{\beta} + s_3^{1/\alpha}\right]^{\alpha}\right\} \tag{13}$$

and the corresponding probability density function is

$$\begin{aligned} g(x_1, x_2, x_3) &= \frac{\partial^3 G}{\partial x_1 \partial x_2 \partial x_3} \\ &= \frac{1}{\sigma_1 \sigma_2 \sigma_3} e^{-u} u^{1-2/\alpha} v^{1/\alpha - 2/\alpha\beta} s_1^{1/(\alpha\beta)-\xi_1} s_2^{1/(\alpha\beta)-\xi_2} s_3^{1/\alpha - \xi_3} Q \end{aligned} \tag{14}$$

in which

$$v = (s_1^{1/(\alpha\beta)} + s_2^{1/(\alpha\beta)})^{\alpha\beta}$$

$$u = \left[(s_1^{1/(\alpha\beta)} + s_2^{1/(\alpha\beta)})^{\beta} + s_3^{1/\alpha}\right] = (v^{1/\alpha} + s_3^{1/\alpha})^{\alpha}$$

$$Q = \left(\frac{v}{u}\right)^{1/\alpha} Q_3(u; \alpha) + \frac{1-\beta}{\alpha\beta} Q_2(u; \alpha)$$

$$Q_2(u; \alpha) = u + \frac{1}{\alpha} - 1$$

$$Q_3(u; \alpha) = u^2 + 3\left(\frac{1}{\alpha} - 1\right)u + \left(\frac{1}{\alpha} - 1\right)\left(\frac{2}{\alpha} - 1\right)$$

Tri-variant 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.

As shown above, PNLTCED can be obtained through the estimation of parameters of the marginal distributions and their dependent parameters.

The New Model Has some Advantages

Considering the hurricane occurring frequency and combination of trivariate environmental factors induced by hurricane.

Considering the dissymmetry of two dependent parameters, it has the simple structure, and easy to be applied in engineering applications.

Solution of MCEVD by Stochastic Simulation Method – P-ISP

The coastal engineering occupies valuable coastline resource that is non-renewable, and the investment of coastal engineering is always great. Thus, the failure of coastal structures would cause enormous economic loss and possible environmental pollution, so the reliability analysis of coastal engineering in extreme sea state should be taken into account. Freudenthal was the first person who proposed the structural reliability theory in the world. In recent years, reliability analysis has gotten more and more applications. The Monte Carlo method (MC method), the first-order reliability (FORM) and the design point method (JC method) are the three methods that have been widely used to estimate the failure probability of structure. Compared with FORM, JC method and MC method, MCEVD based P-ISP method is regarded as a relative accurate method for reliability analysis of structure.

The multivariate joint probability distribution usually has a very complex mathematical form, solution of high dimensional MCEVD leads to the need of stochastic simulation method.

Based on some characteristics and hypotheses of the realistic data, simulation method is the approach of representing some procedures with the computer, for example, Monte-Carlo method. However, inevitably great computational efforts are needed to make and the large variances exist when the analyzed joint probabilities are small by use of Monte-Carlo method. Hence, different sampling methods have been developed to reduce the number of simulations and to decrease variance, among which the Importance Sampling Procedure (ISP) is an efficient method [36,37].

The basic idea of ISP method consists of concentrating the distribution of the sampling points in the region of great importance, i.e., the part, which mainly contributes to the joint probability instead of spreading them out evenly in the whole range of definition of the involved parameters. Particularly, the multi-normal distribution centering on the design point is defined as the important sampling distribution. ISP thus requires an optimization procedure to find the design point. The joint probability can then be evaluated by weighted sampling procedure. A most significant advantage of ISP method is that it can also be used in the original space, regardless of the type of the basic random variables. The transformation of the basic variables into a vector of independent standard normal variables, which may be difficult for correlated variables, is avoid. The weighted sampling is not affected by any non-Gaussian distribution because the actual joint probability is calculated by use of original distribution.

For formula (1), 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 formula (1) can be

estimated by:

$$F(x_1,\, x_2, \ldots\, x_n) = \lim_{N \to \infty} \frac{M}{N} \tag{15}$$

Let x denotes a n-dimensional random vector, its corresponding joint probability density function is $f_X(\mathbf{x})$ formula (1) can be rewritten as:

$$F(\mathbf{x}) = \iint_{g(\mathbf{x}) \le 0} \cdots \int I[g(\mathbf{x}) \le 0] \frac{f_X(\mathbf{x})}{h_X(\mathbf{x})} h_X(\mathbf{x}) d\mathbf{x} \tag{16}$$

in which, x is the n- dimensional random vector, 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:

$$\hat{F}(\mathbf{x}) = \frac{1}{N} \sum_{i=1}^{N} I[g(\mathbf{x}) \le 0] \frac{f_X(\mathbf{x}_i)}{h_X(\mathbf{x}_i)} \tag{17}$$

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

As shown above, the main advantage of ISP is in that, samples are generated according to density function $h_X(\mathbf{x})$ rather the original density function $f_X(\mathbf{x})$. The efficiency of ISP is obviously higher than basic Monte-Carlo simulation.

The variance of $\hat{F}(\mathbf{x})$ is derived as follows:

$$Var(\widehat{F}(\mathbf{x})) = \frac{1}{N}\left[E\left(I[g(\mathbf{x}) \le 0]\cdot\frac{f_X(\mathbf{x})}{h_X(\mathbf{x})}\right)^2 - F(\mathbf{x})^2\right] \quad (18)$$

It can be seen that if the forms of $h_X(\mathbf{x})$ and $f_X(\mathbf{x})$ are similar, the variance will below.

The sampling procedure of MCEVD 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 $h_X(\mathbf{x})$. The design point $\mathbf{x}^*$ which derived by using second-moment method can be taken as sampling center;

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 meteo-oceanic factors induced by typhoon;

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

It should be noticed that, $x_1, x_2, \ldots x_n$ are correlated variables with different kinds of non-Gaussian or Gaussian distributions. This method can be used to predict long-term joint probability of typhoon characteristics and other multivariate typhoon induced environments with different kinds of marginal distributions and different correlation coefficients between variables.

These features affect disaster intensity and consequence directly. So the analysis of typhoon characteristic combinations and the corresponding disaster consequences in different areas should be the important part of typhoon disaster zoning. The typhoon characteristics are usually described by using 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) and typhoon moving angle (θ). But one of the chief advantages lies in taking the annual typhoon frequency (λ) into account as a discrete random variable in the MCEVD model. What's more, considering the secondary typhoon disaster, for instance typhoon Nina 1975 in China induced the dam collapse of Banqiao reservoir that led to the tragic loss of life in numbers and Typhoon Bilis2006 made terrible loss of life in the land provinces. So that in this study the typhoon duration from landfall to dissipation (t) is also considered in the prediction model. For the analysis procedure of multivariate joint probability which combined by a kind of discrete distribution (λ) and six kinds of continuous distributions(ΔP, Rmax, s, δ, θ, t), stochastic simulation technique based on theory of

MCEVD is a valid way to solve such a six-dimensional non-Gaussian problem.

It should be noticed that, the solution of the multi-dimensional joint probability problem is a contour surface with some probability value. In the application process, aiming at different objectives, for instance,(⊿P) reflects typhoon intensity, (Rmax) reflects area influenced by typhoon,(s) reflects intensity of typhoon induced surges and waves, (t) reflects inland areas affected intensity and should be selected as the dominated factor respectively to calculate the unique solution of joint probability for different disaster consequences. This procedure is taken as the first layer of the double-layer nested multi-objective probability model, which is offered as the basis for typhoon disaster zoning.

In the simulation procedure P-ISP, it is needed to input mean value of typhoon frequency (λ), marginal distribution of the six kinds of typhoon characteristics (P-ISP is suitable for Normal,

Uniform, Exponential, Rayleigh, Gumbel, Weibull, Log-normal, Gamma and Frechet distribution）， mean value and standard deviation of each variable group, matrix correlation coefficients among the variables and the limit state equation, then the joint probability of different typhoon characteristics with some typhoon occurrence frequency can be calculated as the output. Comparing with basic Monte Carlo Method, P-ISP performs more quickly and accurately, so it has been successfully applied to the joint probability analysis of typhoon induced extreme sea environmental loads such as wind, wave, storm surge, current, et al., for different kinds of offshore structures; risk assessment of coastal and hydraulic structures [16， 27， 31， 33].

Hurricane Katrina and Rita of 2005 and Hurricane Sandy of 2012 as a validation

(1) Comparison between 1982 PWCEVD predicted results and NOAA-proposed SPH and PMH

In 1979, the U.S. National Oceanic and Atmospheric Administration (NOAA) divided the 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[5-7]。 Using CEVD [14-19], the predicted hurricane central pressures with return period of 50yr and 1000 years 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 more severe than NOAA proposed values. In these regions, SPH and PMH only correspond to CEVD predicted 30~40yr and 120yr return values, respectively.

In 2005, Hurricanes Katrina and Rita attacked coastal areas of the USA, causing the deaths of about 1833 people and an economic loss of $400 billion in the city of New Orleans and destroyed more than 110 oil platforms in the Gulf of Mexico. The disaster implied that using SPH as the flood-protective standard was a main reason for the catastrophic outcome [1，. Fig. 3 and Tab. 2 indicate that CEVD predicted results are more reasonable than the safety regulations proposed by NOAA. The main reason of hurricane Katrina and Rita disasters is NOAA proposed unreasonable SPH and PMH. [5-7]

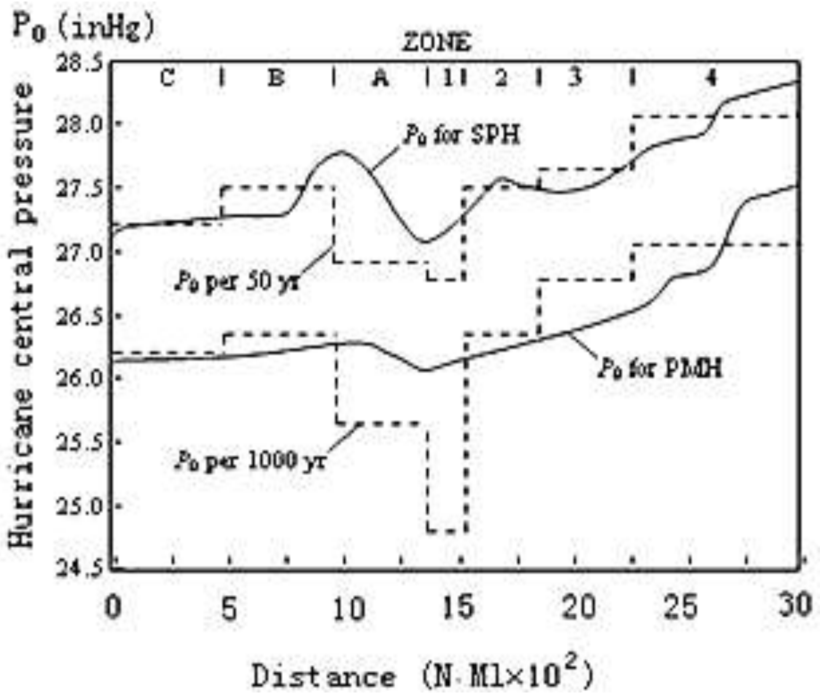


Fig. 3. Comparison of hurricane center pressures between CEVD predicted values and NOAA proposed design codes ([15], Fig. 6)

Table. 2 . 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

(2) 2012 Hurricane Sandy induced flooded area as a validation of the 1982 CEVD predicted storm surge

Hurricane Sandy is the second-costliest hurricane in US. Damage $75billion and at least 233 people killed **Error! Reference source not found.**. In 1982, based on the 1926 to 1960 observed data, we used CEVD to predict the storm surge which was induced by the 100 year return period hurricane for the Philadelphia area. We chose this site based on the following reasons :

a. We have 1926 to 1960 observed data in this area.

b. Philadelphia was indeed affected by Sandy's storm surge and that the area is vulnerable to hurricane-induced storm surges.

The result was about 10 foot and was close to the storm surge of 10.62 ft that was observed on October 30, 2012 at 08h:06; the Hurricane Sandy induced water level is shown by the dotted line in Fig. 4. But the surge predicted by NOAA was only 7.52 ft.

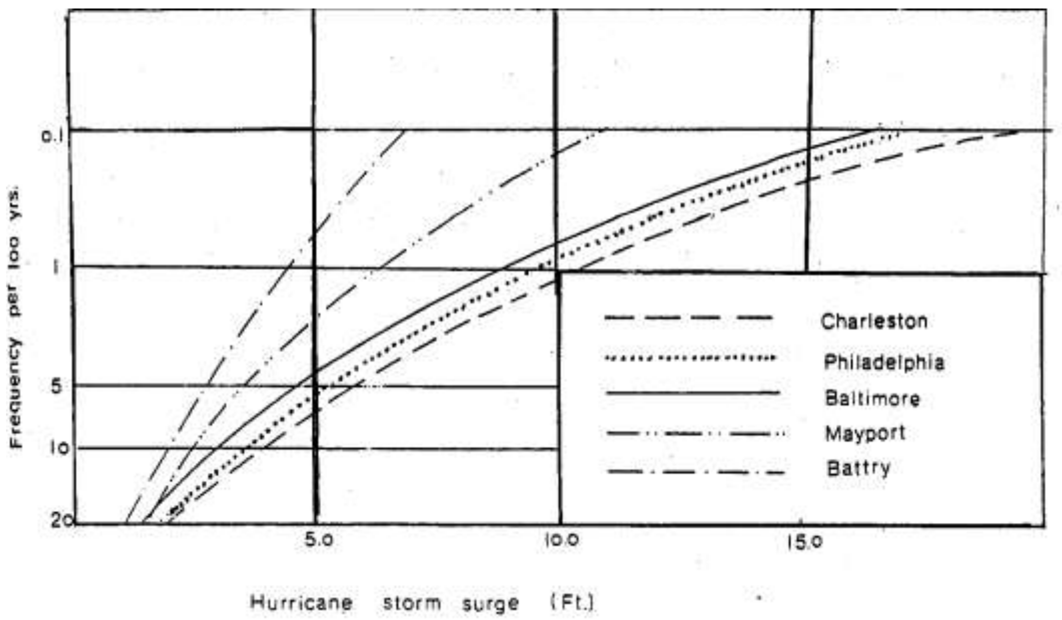


Fig. 4 CEVD predicted hurricane storm surge from Hurricane Sandy for locations along Atlantic coast (see[14], Fig.8)

（3）Hurricane Katrina and Hurricane Sandy as a validation of MCEVD predicted results

Here the 55 year (1950-2004) measured data of hurricane winds, hurricane effect duration (provided by NOAA and Unisys) and the simultaneous Mississippi water level (hurricane process data, provided by USACE) are used for the long term joint probability prediction of Hurricane Katrina. Sometime after the establishment of the seven zones (as shown in Fig.3) was proposed, the Gulf of Mexico and Atlantic coasts were divided into 11 regions according to regional planning for hurricane hazard [15].

Following the requirements of the MCEVD calculation procedure, a statistical check shows that the frequency of hurricane in this area fits to a Poisson distribution (Fig.5). The diagnostic checks show that all of the data of the wind speed (Ws), water level (Wl) and hurricane duration (Wd) fit to the generalized extreme value distribution (Fig.6a,b,c). Using MCEVD, a single contour surface for wind speed, hurricane inference duration and water level for each joint return period can be obtained, as shown for the 100 year joint return period in Fig.7. Thus there should be different combinations of duration and wind speed that can result in with same joint return period of surge.

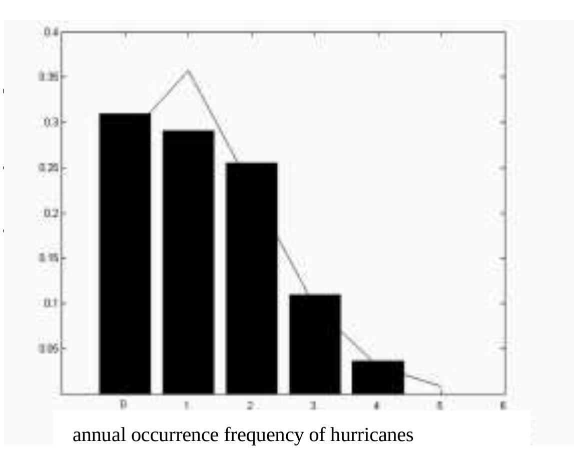


Fig. 5 Curve fitting of hurricane frequency for the Gulf of Mexico and Atlantic coast

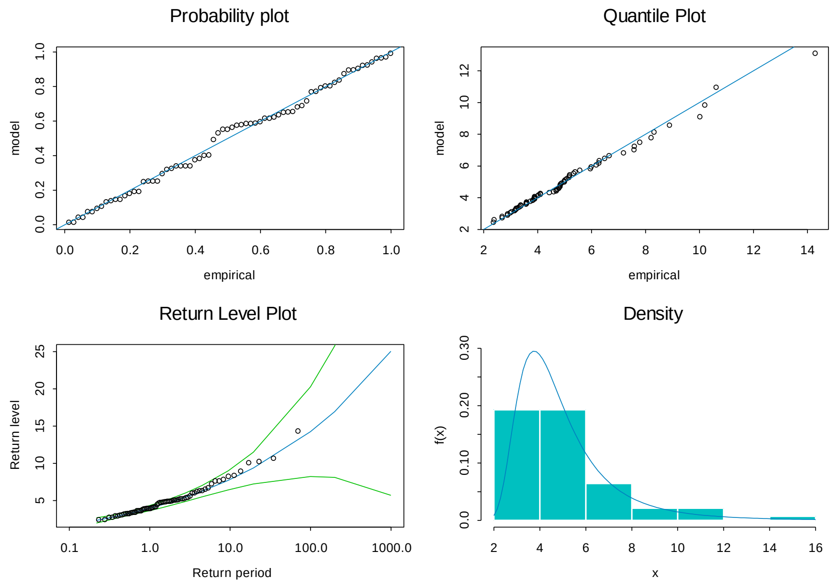


Fig. 6a Distribution diagnostic testing of water level for the Gulf of Mexico and Atlantic coast

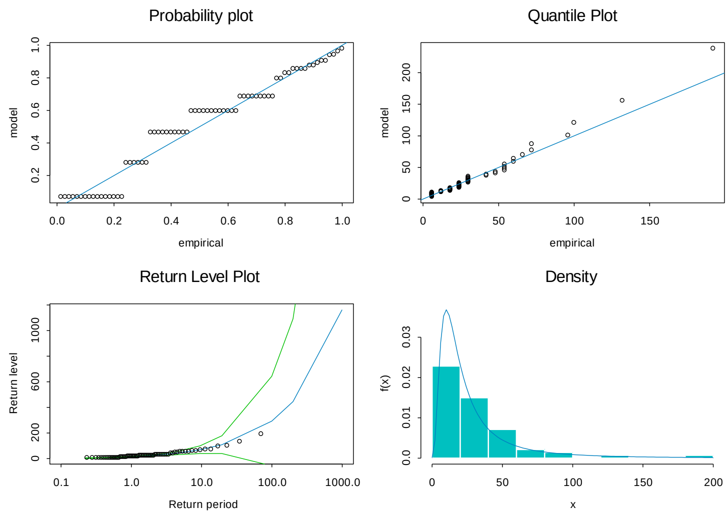


Fig. 6b Distribution diagnostic testing of hurricane duration for the Gulf of Mexico and Atlantic coast

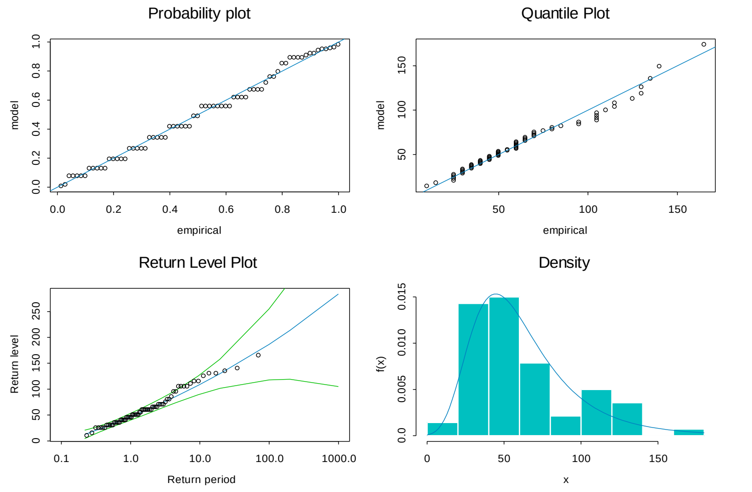


Fig.6c Distribution diagnostic testing of wind speed for the Gulf of Mexico and Atlantic coast

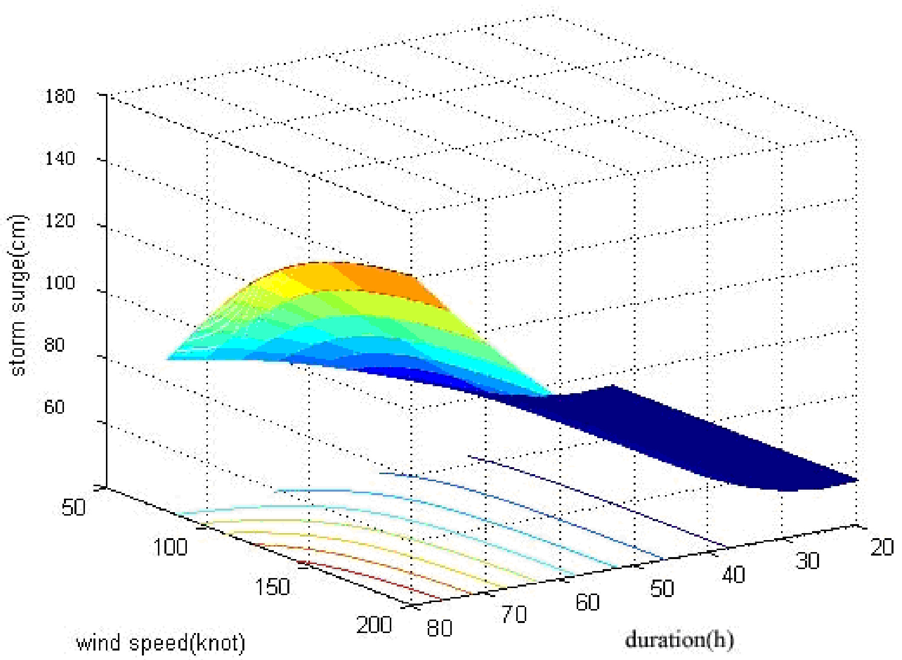


Fig. 7 Contour surface of storm surge with return period of 100 years for the Gulf of Mexico and Atlantic coast

Table. 3 The calculated results with different joint return period for New Orleans

	1000yr	100yr	50yr	10yr
Ws (m/s)	89.4	70.6	64.2	44.1

Wl (m)	7.6	4.11	3.35	2.04
Wd (h)	149	107	96	60

Hurricane Katrina Hurricane Sandy

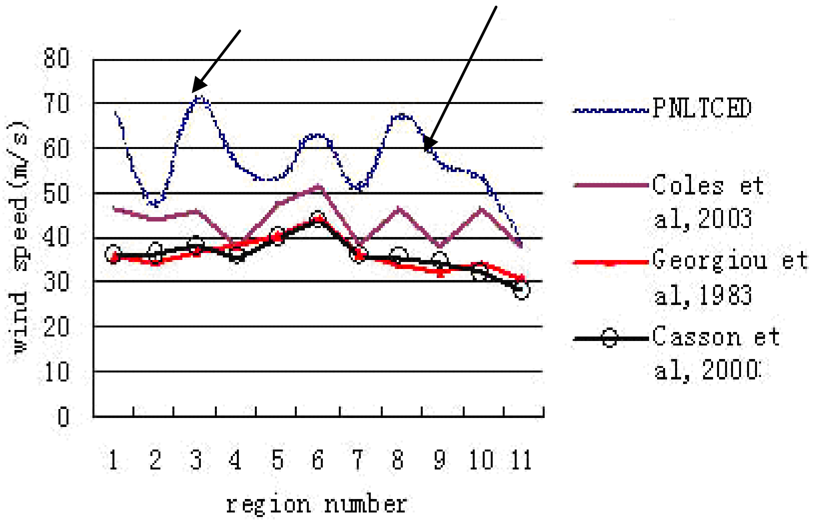


Fig. 8 Comparison of 100yr—hurricane wind speed using different methods over different regions。 see Casson[4], Coles[5],Georgiou[6]

Tab. 4. Comparison of 100yr wind speed (m/s) for New Orleans (2005)and New Jersey zones (2012)

Methods	MCEVD (2006)	Coles et al. (2003)	Casson et al (2000)	Georgion et al (1983)
100yr return value for zone 3 (New Orleans)	70.0	46.0	38.0	39.0
100yr return value for zone 9 (New Jersey)	60.0	40.0	36.0	35.0

American Journal of Engineering, Science and Technology (AJEST) Volume 11, 2021

As shown in Tab. 3, Tab. 4 and Fig. 8, the MCEVD predicted 100 years return values not only validated by 2005 hurricane Katrina, but also by 2012 hurricane Sandy.

4. Corrections to SPH/PMH and API Recommendations Proposed by NOAA based on observed wave damage to fixed platforms by 2005 Hurricanes Katrina and Rita

In 2005, Hurricanes Katrina and Rita destroyed more than 110 platforms in the Gulf of Mexico (Fig.9,a). There were many platforms with reported wave in deck (WID) damage, attributed to the crest of the large hurricane wave hitting the platform decks and causing major damage. The catastrophic failures and damage of platforms in GOM region show the deficiencies of API recommendations [1,2].

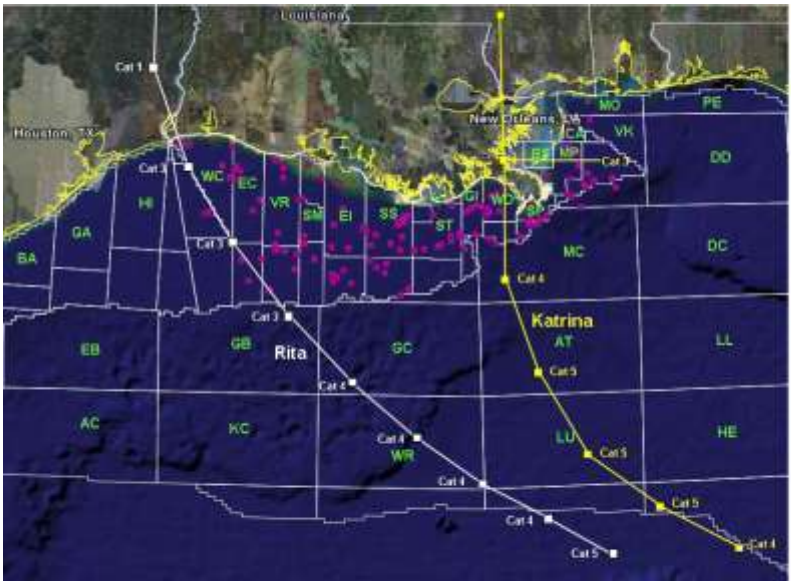


Fig.9.a. Hurricane Katrina and Rita destroyed and damaged 116 platforms.

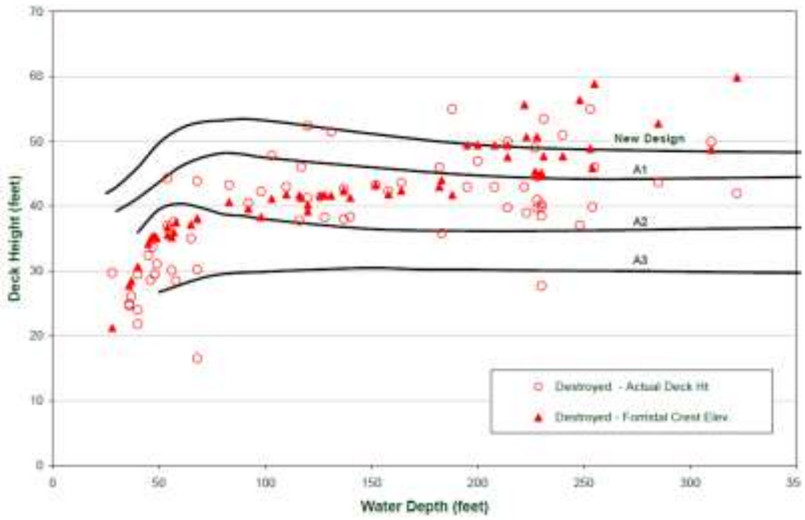


Fig.9.b. Platform deck height compared to predicted wave crest height,

API RP2A (2002) categorizes platforms according to the consequence of failure, designated as A-1 for high consequence, A-2 for medium consequence and A-3 as low consequence**Error! Reference source not found.**. The report by Forristall shows a comparison of the deck elevation for the destroyed platforms (there were 76 cases where the deck elevation was available) at the location. The circles in Figure 9,b show the deck heights of individual platforms and the triangles show the wave crest heights predicted by Forristall. The curves A-1, A-2, and A-3 designate the deck heights recommended by API RP2A. For example, at a water depth of about 325 ft, the destroyed platform's deck height is about 42 ft and the wave crest height is about 60 ft. Thus the wave crests height was almost 18 ft higher than platform deck clearance. It is then no surprise that the platform was destroyed [1].

After hurricane Katrina and Rita, API issued Bulletin 2INT-DG, which provides procedures for using the hurricane conditions contained in BULL 2INT-MET for the associated type of platforms. API Bulletin 2DG updates specific recommendations for cellar deck elevation as the 'new design' that accounts for a typical 5 meters air gap above the 100-year wave crest and also an additional allowance of 15% of the crest elevation to account for local wave effects [2].

Further, some of the primary causes of damage were wave, wind and current forces greater than 100 yr conditions, and foundations that were unable to support the fixed platform for the additional load level experienced from the increased metocean conditions beyond the industry accepted standard for survival

The SPH was the initial model used to determine how strong the hurricane protection system should be in order to protect the New Orleans, Louisiana area from flooding due to hurricanes. The U.S. Army Corps of Engineers began developing the model with the United

States Weather Bureau (USWB). Subsequently, the USWB defined a probable maximum hurricane (PMH) as one that may be expected from the most severe combination of critical meteorological conditions that are "reasonably possible" for the region.

The original project designs of SPH were developed against the assumption that hurricane that might strike the coastal Louisiana region once in 200-300 years. However, the standard was developed before the Saffir-Simpson hurricane scale came into use, and the features of the storm fit poorly with the scale. The model projected a storm roughly equivalent to a fast-moving Category 3 hurricane; other features more closely resemble a much more severe Category 4. In fact, hurricane Katrina was a category-5 hurricane before making landfall in Louisiana. In fact, Hurricane Katrina was a category-5 hurricane before making landfall in Louisiana, and storm surge heights correlate better with pre-landfall wind speeds than wind speeds at landfall [32,35]..

In the design of a fixed platform, the topside structure should normally have adequate clearance above the design wave crest. Any topside structure of piping not having adequate clearance would be affected by waves and current. The loss of the air gap and deck inundation has a large impact in reliability due to the following factors:

a. Large increase in hydrodynamic loading;
b. Large increase in the uncertainty associated with hydrodynamic loading;
c. Potential increase in dynamic sensitivity.

In order to provide adequate clearance to resist these large forces and overturning moments by wave, API [1] gives some recommendations as follows:

a. Omni-directional guideline wave heights with a nominal return period of 100 years, together with the applicable wave theories and wave steepness, should be used to compute wave crest elevations above storm water level, including guideline storm tide.
b. A safety margin, or air gap, of at least 5 feet should be added to the crest elevation to allow for platform settlement, water depth uncertainty, and for the possibility of extreme waves in order to determine the minimum acceptable elevation of the bottom beam of the lowest deck to avoid waves striking the deck.

The predictions of the lowest deck height of the platforms by different designers may differ greatly for there is no clear definition of the 'applicable wave theories' in the API recommendations. In addition, API just offers the reference standards of guideline storm tide in American sea regions by graphical interpretation; it cannot provide any reference value for platform design in other countries influenced by typhoons or hurricanes.

The definition of water level and deck height is shown in Figure 10. The height of significant wave (Hs) is the average height of the highest one third of the waves in the record and the crest height is the vertical distance from the top of the wave crest to the still-water.

LAT is the lowest astronomical tide. Still water level is the average water surface elevation at any instant, excluding local variation due to waves and wave set-up, but including the effects of tides, storm surges and long period seiches. For other uncertain factors such as subsidence of the platform and sea bed, the present author gives 1.5m recommended height in this study [2]..

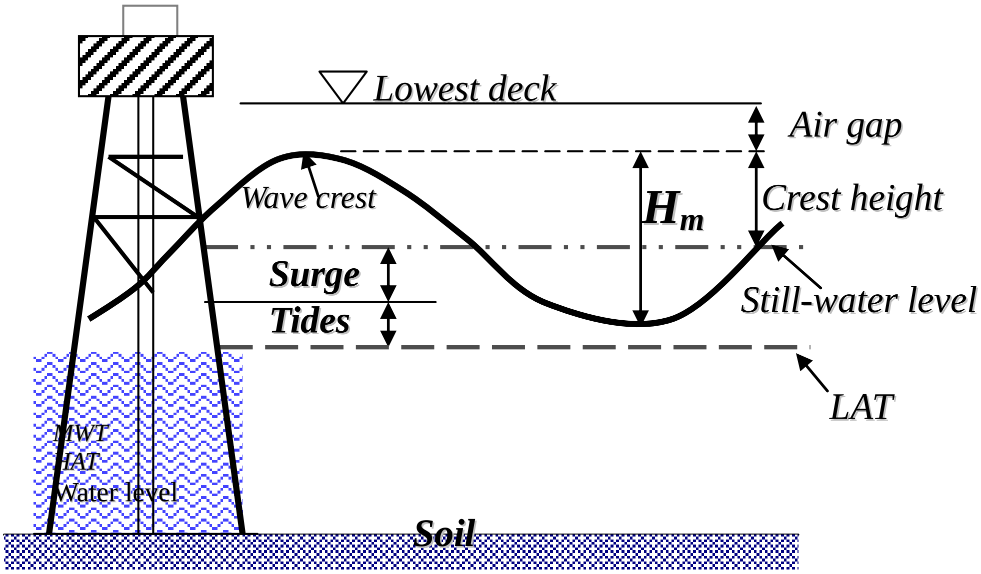


Fig. 10, The definition of water levels and the lowest deck height

LAT –Lowest Astronomical Tide

Therefore, Hs, storm surge and tide are taken as variables in PNLTCED for calculation of the required deck height in this section.

Using PNLTCED, a single contour surface for wave, surge and tide for a specified joint return period can be obtained. Because tide has its well-predicted law of motion, its periodical change is varied by other factors such as geographical influences. The astronomical tide height was taken as 2.45m (19 yr return period) in the present paper, and then we obtain the combination of Hs, surge and tide with 100-year return period (Fig.10).

Different standards give different relations between the crest height, Hs and the maximum wave height (Hm). The ratio of crest height/Hm=0.6 was adopted in the present paper [1].. In the API standard, the relationship of Hs and Hm is Hm/ Hs=1.7 to 1.9. According to the rules and regulations for the construction and classification of mobile offshore drilling rigs in China, Hm=min{2$H_{1/3}$, Hb }, where Hb is the critical wave height of breaking waves. In the South China Sea water depth is 25.0 m, the sea bottom gradient is 1/300 [39]..

Tab. 5. H_s and concomitant surge samples of South China Sea (1979-1987)

Typhoon No.	H_s (m)	Surge (m)	Typhoon No.	H_s (m)	Surge (m)	Typhoon No.	H_s (m)	Surge (m)
197909*	4.6	0.46	198211	4.5	0.87	198508	3.2	0.24
197910	3.3	1.09	198219	3.4	0.29	198519	3.6	0.28
197915	3	0.21	198305	2.6	0.27	198607	2.1	0.35
197919	3.4	0.61	198310	3.3	0.58	198615	5.3	0.49
198001	2.1	0.18	198402	1.3	0.5	198617	2.5	0.39
198002	2.3	0.48	198403	1.6	0.15	198700	1.2	0.18
198003	5	0.26	198406	2	0.66	198701	1.5	0.26
198004	4.3	0.41	198407	2.5	0.19	198704	4.7	0.36
198101	4.5	0.93	198409	3.7	0.77	198705	2.2	0.17
198102	4.5	0.15	198504	2	0.19	198707	3.9	0.43
198209	2.2	0.52	198506	3.4	0.32	198711	2.8	0.69
*: No. 9 typhoon in 1979.								

A traditional addition method which defined the maximum level as the sum of MHWS (Mean High Water level Spring tide), 100-year storm surge and 100-year crest height, was used to compare with the prediction by MCEVD. The comparison and calculated results were shown in Tab. 6. (1 and 2 in Tab.6 are two combinations with 100-year return period.) [39].**Error! Reference source not found.**.

Note that the tidal datum of deck elevation in this paper is different from the definition in

API [1]. API adopted the Mean Lower Low Water (MLLW) which was only used in United States. In order to extend its applicability and operability, LAT was used in the present paper [23] and the most severe combination of the surges, tides and crests can be obtained by MCEVD.

This example shows results for 33 typhoons in the East China Sea and selects the significant wave height (Hs), concomitant surge and corresponding tide of each process as samples (Tab. 6).

Tab. 6. Comparison of traditional method and MCEVD method

<table>
<tr><td rowspan="2">Traditional addition method</td><td colspan="2">H_s (m)</td><td>Crest height with 100 return period years (m)</td><td>Surge with 100 return period years (m)</td><td>Tide & Air gap(m)</td><td>Deck elevation above LAT(m)</td></tr>
<tr><td colspan="2">5.56</td><td>6.78</td><td>1.23</td><td rowspan="5">2.45+1.5</td><td>11.96</td></tr>
<tr><td rowspan="4">MCEVD method</td><td colspan="4">Joint probability of 100-yera return period</td><td rowspan="2"></td></tr>
<tr><td colspan="2">H_s (m)</td><td>Crest height（m）</td><td>Surge (m)</td></tr>
<tr><td>1.</td><td>5.95</td><td>7.26</td><td>1.98</td><td>13.19</td></tr>
<tr><td>2.</td><td>5.62</td><td>6.86</td><td>2.10</td><td>12.91</td></tr>
</table>

5. 2013 Typhoon Fitow validation of 2006 MCEVD predicted disaster in Shanghai city

Shanghai city is located in the estuarine area of the Yangtze River in China. Historical observed data shows that the typhoon-induced storm surges and rainstorm flood, coupled with the astronomical spring tide, had threatened the security of Shanghai. Based on the long term(1970-2005) typhoon characteristics around Shanghai area (Tab. 7) , the double layer nested multi-objective probability model [29,32] was used to predict combined effect of storm surge, rainstorm flood and spring tide on the Shanghai city

In 2013, typhoon Fitow induced significant losses in China. As shown in Tab.8, the water level induced by 2013 Typhoon Fitow in Yangtze River was 5.15m , but the recommended 500 years return period warning water level calculated by the China design code was 4.80m in this area, which only corresponds to the 50 year return value predicted by MCEVD.

Tab. 7, Marginal distribution of typhoon characteristics for Shanghai

Typhoon	Distribution type	Mean	Standard	Distribution parameters

Characters		value	deviation	
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

Tab. 8, 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

6. Risk assessment for Nuclear Power Plant (NPP) against sea hazards

6.1 Joint Probability Safety Assessment for NPP Coastal Defences infrastructure Against Typhoon Disaster in the South China Sea

MCEVD can be used for joint probability safety assessment for NPP coastal defence along

China coast against typhoon attacks [38,39]. Nuclear power plant L is located at coast of South China Sea, where the combined extreme external events are dominated by waves. Based on the China and IAEA safety regulations, the L-NPP calculated design water level is shown in Tab. 9:

Tab. 9. Present design criteria for coastal defense of L- NPP Error! Reference source not found.

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 by MCEVD are shown in Tab. 10.

Tab. 10, Joint probability of typhoon induced storm surge, wave height and corresponding spring tide with Confidence intervals for L-NPP

Return period (yr.)	100	500	1000
Storm surge (m)	2.79+0.51	3.49+0.71	3.85+0.80
Spring tide (m)	2.14+0.30	2.19+0.35	2.75+0.46
Wave height (m)	6.6+0.3	7.3+0.6	7.9+0.8

It can be seen from Tab. 10, that the MCEVD-predicted 500 year return values of storm surge, spring tide (4.2+2.8=6.9m) and wave height (7.9m) should be more severe than DBF (6.35m) with 100 year return period wave height (6.6m), rather than the IAEA recommended 10000 years return values ..

6.2 Joint Probability Safety Assessment for QS-NPP Defense Infrastructure in Qiantang River Estuarine Area, East China Sea

American Journal of Engineering, Science and Technology (AJEST) Volume 11, 2021

The combination of typhoon-induced storm surge with the strongest spring tide in Qiantang river estuarine always leads to disasters. The observed maximum surge and spring tide is more than 9m. The QS NPP is located in the south coast of the estuarine Qiantang River and faces to the East China Sea, where always occurs the most severe spring tide in China.

The height of the constructed breakwater is 9.76m. So the joint probability safety assessment of combined extreme external events for coastal defense infrastructure dominated by spring tide should be taken into account.

As the severest extreme external events for QS NPP are the combined effect of spring tide and surge, a two dimensional joint probability model can be used to calculate the corresponding joint probability density function and cumulative distribution function (Fig.11,a and Fig.11,b). The joint probability distribution of spring tide, storm surge and corresponding extreme wave with 1000 year joint return period can be seen in Fig.12.

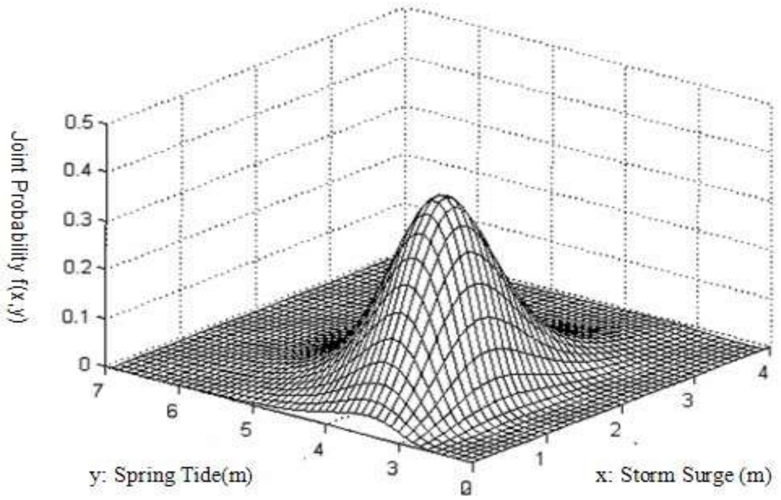


Fig.11.a. Probability density distribution of spring tide and storm surge for the QS NPP

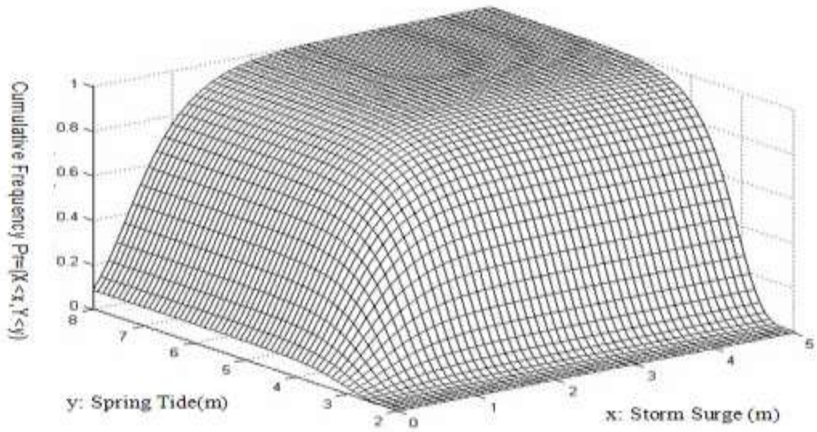


Fig.11.b. The same as Fig. 11a for the cumulative probability distribution of spring tide and storm surge.

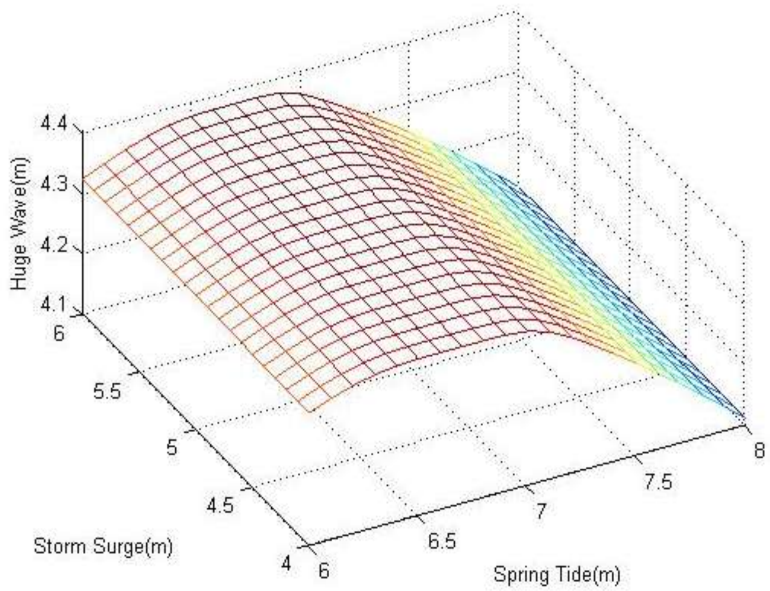


Fig.12. Joint probability distribution of spring tide, storm surge and extreme wave with 1000 year joint return period for the QS NPP.

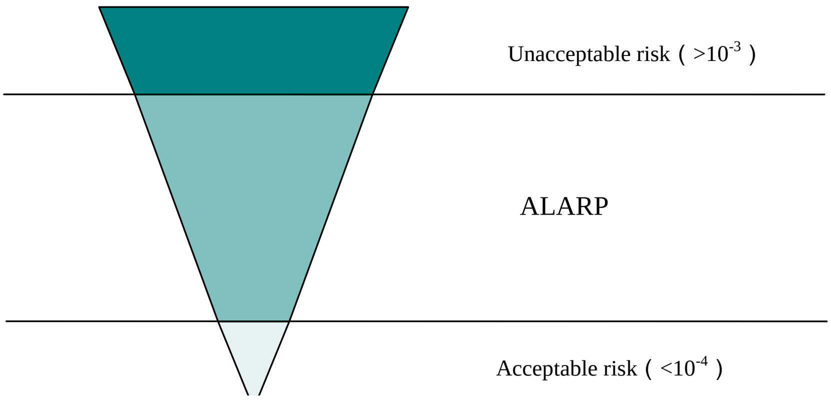


Fig.13. Schematic diagram illustrating the "As Low As Reasonable Practice (ALARP)" concept, by Det Norsk Veritas,

Risk assessment for NPP coastal defense is based on the ALARP principle (Fig.13). Joint probability risk assessment for the above mentioned two constructed nuclear power plants shows that the coastal defense infrastructure of both NPP cannot satisfy the 10^{-3} combined extreme external events risk according to the ALARP principle [38,39]. This means that the risk to constructed infrastructure is unacceptable.

Tab.11. Combined extreme external events with joint return period for QS NPP by PNLTCED

Extreme Event / Joint Probability	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

The joint probability safety assessment for NPP coastal defense infrastructure against extreme external hazards shows that the China and IAEA recommended safety regulations appear to have some vague definitions and different kinds of uncertainties. Both of the two constructed NPPs are located along the South China Sea and the East China Sea where the dominant external events are wave and spring tide, and the China and IAEA recommended safety regulation are much lower than 1000 year return period typhoon induced sea hazards predicted by DLNMPM.

CONCLUSIONS

Design codes calibration of offshore, coastal and hydraulic infrastructures show that some traditional methods and models can’t support enough safety for very important infrastructures in global climate change conditions. The disasters induced by the 1975 typhoon Nina and 2005 hurricane Katrina give an important lesson: When natural hazards combined with human hubris, the natural hazards become act-astrological disaster sooner or latter.

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