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The conditional risk probability-based seawall height design method

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ABSTRACT: *The determination of the required seawall height is usually based on the combination of wind speed (or wave height) and still water level according to a specified return period, e.g., 50-year return period wind speed and 50-year return period still water level. In reality, the two variables are be partially correlated. This may be lead to over-design (costs) of seawall structures. The above-mentioned return period for the design of a seawall depends on economy, society and natural environment in the region. This means a specified risk level of overtopping or damage of a seawall structure is usually allowed. The aim of this paper is to present a conditional risk probability-based seawall height design method which incorporates the correlation of the two variables. For purposes of demonstration, the wind speeds and water levels collected from Jiangsu of China are analyzed. The results show this method can improve seawall height design accuracy.*

***KEY WORDS*:** Seawall height; Water level; Wind speed; Combination; Risk probability.

INTRODUCTION

A seawall is a form of coastal defense. The purpose of a seawall is to reduce coastal flooding mainly caused by waves combined with high water levels in low-lying coastal areas, and the water level may be a combination of mean sea level, tides and surges generated by storm events (Wolf, 2009). Especially if storm events occurred at high tide during a spring tide, this could produce much more severe consequences like damaging or destroying defences, coastal structures and property and causing coastal erosion (Maspataud et al., 2013). In some areas such as deltas and estuaries, river flow may also contribute to coastal flooding. Mitigating the effects of coastal flooding requires accurate predictions of the destructive hydrodynamic forces for engineering design of coastal infrastructure (Chen et al., 2007).

In design of a seawall, a key step is the determination of the required seawall height which usually based on the combination of extreme wave heights and extreme still water levels. In locations where no enough wave observations are available, the wind speeds are usually used for calculating wind wave heights. Up to now, there is not a universal design standard for seawall heights. The design condition consisting of the two variables depends on economy, society and natural environment in the region. In Jiangsu province of China, the design standard recommended is the 50-year return period water levels combined with wind speeds between 24.5 *m/s* and 28.4 *m/s* (wind power class 10). However, in the Pudong district of Shanghai of China, with a stronger economy and higher population density, the 200-year return period water level combined with wind speed between 32.6 *m/s* and 37.0 *m/s* (wind power class 12) is adopted. In fact, water levels and wind speeds are usually partially dependent

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(Hawkes et al., 2002), and high water levels are not always occurring together with high wind speeds. These traditional design methods without incorporating the dependence between variables are deterministic and empirical for the combination of water levels and wind speeds. This usually has the potential effect of a seawall being designed to the incorrect level leading to costs (over-designed) or damages (under-designed).

So, when dealing with multiple design variables, the main question is 'How should one incorporate the dependence between variables?'. Actually, some topics about joint probability of variables are of great interest and have been receive significantly increased attention over the past few years. For example, larger positive surges often occur during low tides and the larger negative surges are more frequent at the rising tide. Thus, they can be related due to a coupling effect. Rodríguez et al. (1999) focused on the existence of a possible statistical dependence among these variables for their probability of joint occurrences by analysing simultaneous sea-level and wave-height data recorded at A Coruña from 1992 to 1996. In order to estimate the probability of flooding, Hawkes (2008) analyzed the likelihood of occurring simultaneously of large waves combined with a high sea level or high river flow combined with a high sea level by an approach involving Monte Carlo simulation. Most of the hydrological and hydraulic studies refer to the notion of a return period to quantify design variables. Vandenberghe et al. (2012) gived an overview of the method for defining joint return periods through the use of copulas (Salvadori and Michele, 2004). Compared with some statistical methods, Woodworth et al. (2007) investigated the dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation with the use of a depth-averaged tide+surge numerical model.

In China, a joint probability-based design concept has been presented and little researchs have been carried out in recent years, but it is still less. Based on a bivariate equivalent maximum entropy distribution, joint design parameters were estimated for the concomitant wave height and wind speed at a site in the Bohai Sea (Dong et al., 2012). Yang and Zhang (2013) investigated the joint probability distribution of wind speeds and significant wave heights from wave simulation of 20 years (1989-2008) in Bohai Bay based on the Gumbel-Hougaard copula function. Lian et al. (2013) investigated the joint distribution and combined risk probability of rainfall and tidal level using the Gumbel-Hougaard copula function. Liu and Chen (2009) applied the copula theory to construct the joint distribution of interzone rainstorm and the flood level of the outer river. Xie et al. (2012) applied Gumbel-Hougard copula to construct the joint probability distribution model of rainstorm and water level in outside river in river network area. Xu et al. (2014) investigated the joint probability of extreme precipitation and storm tide using copula-based models in Fuzhou City.

As stated above, joint probability refers to the probability that two variables occur at the same time, and makes sense to optimize the combination of still water levels and wind speeds in seawall height designs. However, from a view point of economy, the design of seawall height to reduce the damages infinitely small is impractical and uneconomic. A specified risk level of overtopping and damage is usually allowed, e.g., the seawall height was designed by a 50 years return period. This means there is a 2% exceedance probability of damage and overtopping in excess of this design standard. For determining the optimal combination of design water levels and design wind speeds, this paper will present a conditional risk probability-based seawall height design method with a specified risk level allowed. For purposes of demonstration, the wind speeds and water levels collected from Jiangsu of China were analyzed.

CONDITIONAL RISK PROBABILITY-BASED METHOD

When a reasonable risk probability of failure of seawall is allowed based on local economic and social conditions, conditional risk probability for a seawall design is of greater interest. To find the best possible combination of water levels and wind speeds in seawall height designs, the objective of this section is to study the conditional risk probability-based seawall height design method.

Risk threshold probability and value

In China, seawall design usually has the return periods of 20, 50, 100 or 200 year. In Jiangsu, a 50 years return period is adopted, and this means there is a 2% risk probability of overtopping allowed by the design standard. The Risk Threshold Probability (RTP) can be given as

$$\text{ms } RTP(T) = \frac{1}{T} \times 100\% \tag{1}$$

where T is equal to return period, and its value is determined by a specified design standard.

When assessing the risk threshold value caused by extreme still water levels (denoted by MZ) or extreme mean wind speeds (denoted by MW) respectively, failure of seawall occurs whenever natural water level or wind speed exceeds the risk threshold value mz_T or mw_T. The risk threshold value of extreme still water levels is given by the following equation:

$$1 - F(mz_T) = RTP(T)$$

$$\text{with} \quad F(mz_T) = P(MZ \le mz_T) \tag{2}$$

where mz_T = risk threshold value of extreme still water levels; P=non-exceedance probability; $F(mz_T)$ = the marginal cumulative distributions of variable MZ.

Similarly, the risk threshold value of extreme wind speeds is given by the following equation:

$$1 - F(mw_T) = RTP(T)$$

$$\text{with} \quad F(mw_T) = P(MW \le mw_T) \tag{3}$$

where mw_T = risk threshold value of extreme wind speeds; P = non-exceedance probability; $F(mw_T)$ = the marginal cumulative distributions of variable MW.

Conditional risk probability

In seawall height designs, since high water levels are not always occurring together with high wind speeds, it is uneconomic if design values of water level and mean wind speed are equal to the specified risk threshold values discussed above simultaneously. Accordingly, it may be more suitable that the water level with the return period T matches the mean wind speed with a lower return period (denoted by W), or the mean wind speed with the return period T matches the water level with a lower return period (denoted by Z). This yields

Condition I (Water level with the return period T**)** : Let mz_T be threshold value of design water level which is seen as a major risk factor. The conditional risk probability of MZ and W, given $MZ \le mz_T$, is

$$\begin{aligned} CRP(mz_T, w) &= P(W > w \mid MZ \le mz_T) = \frac{P(MZ \le mz_T, W > w)}{P(MZ \le mz_T)} \\ &= \frac{F(mz_T) - F(mz_T, w)}{F(mz_T)} = \frac{1 - RTP(T) - F(mz_T, w)}{1 - RTP(T)} \end{aligned}$$

$$\text{with} \quad F(mz_T, w) = P(MZ \le mz_T, W \le w) \tag{4}$$

where $CRP(mz_T, w)$ = conditional risk probability; w=values of variable W; $F(mz_T, w)$ = joint cumulative distribution function of variable MZ and W.

Condition II (Mean wind speed with the return period T**)** : Let mw_T be threshold value of design mean wind speed which is seen as a major risk factor. The conditional risk probability of MW and Z, given $MW \le mw_T$, is

$$CRP(mw_T, z) = P(Z > z \mid MW \le mw_T) = \frac{P(MW \le mw_T, Z > z)}{P(MW \le mw_T)}$$
$$= \frac{F(mw_T) - F(mw_T, z)}{F(mw_T)} = \frac{1 - RTP(T) - F(mw_T, z)}{1 - RTP(T)}$$
$$\text{with } F(mw_T, z) = P(MW \le mw_T, Z \le z) \tag{5}$$

where $CRP(mw_T, z)$ = conditional risk probability; z=values of variable Z; $F(mw_T, z)$ = joint cumulative distribution function of variable MW and Z.

Critical values of design water level and wind speed

If the conditional risk probability discussed above meets minimum risk requirement determined by an allowed risk probability, the combination of design water level and design wind speed is regarded as optimal. For exemple, when the $RTP(T)$=2%, the CRP may be larger than 2% and this will lead to under-design (damages) of seawall structure. Conversely, the CRP may be smaller than 2% and this will lead to over-design (costs) of seawall structure. This yields

$$\begin{cases} CRP(mz_T, w_{CT}) = RTP(T) \\ CRP(mw_T, z_{CT}) = RTP(T) \end{cases} \tag{6}$$

where w_{CT} and z_{CT} are the critical values of variable W and Z. (mz_T, w_{CT}) and (mw_T, z_{CT}) are regarded as two different optimal combinations of design water level and design wind speed. By comparing the design seawall height calculated according to (mz_T, w_{CT}) with that according to (mw_T, z_{CT}), the larger value among them should be adopted.

APPLICATION AND RESULTS

Study area and field data

Jiangsu province, with its capital in Nanjing, situated on the eastern China coast, has an area of 102,600 km^2 and a population of 69,670,000. Jiangsu has a coastline of over 1,000 *km* along the Yellow Sea, and the Yangtze River passes through the southern part of it. In coastal area of Jiangsu, storm surges and waves caused by typhoon are the main hazard inducers, and from 2000 to 2010, these hazards had taken 33 lives and caused property losses of CNY5.96 billion.

Fig. 1 Locations of in-situ tide stations.

The still water levels (vertical datum: Feihuanghe) and short time-interval (10 *min*) mean wind speeds from 1972 to 2011 are used in this paper, including the annual maximum still water level (denoted by *MZ*) and its corresponding maximum short time-interval (10 *min*) mean wind speed (denoted by *W*) on the same day, the annual maximum short time-interval (10 *min*) mean wind speed (denoted by *MW*) and its corresponding maximum still water level (denoted by *Z*) on the same day. They are from four in-situ stations (shown in Fig. 1), namely Lianyungang, Sheyang Estuary, Xiaoyang Port and Tiansheng Port that located at northern, middle and southern of Jiangsu coastline, respectively.

These data had been provided by the Jiangsu Water Conservancy Project Construction Bureau. Fig. 2 shows an example of observations at Tiansheng Port. It can be seen that high still water levels are not always occurring together with high wind speeds. The small likelihood of both conditions occurring simultaneously means there is plenty of room for designers to optimize the combination of both variables. Especially, the empirical determination of the required seawall height based on the joint event of 50-year return period still water level and specified wind speed (wind power class 10) is no longer satisfactory in Jiangsu. Besides, according to some design guidelines of Fujian, Guangdong, Zhejiang of China, the joint event of 50-year return period still water level and 50-year return period wind speed should be adopted. This obviously will lead to over-design (costs) of seawall structures. Therefore when one is designing a seawall, one should look at the likelihood of both conditions occurring simultaneously.

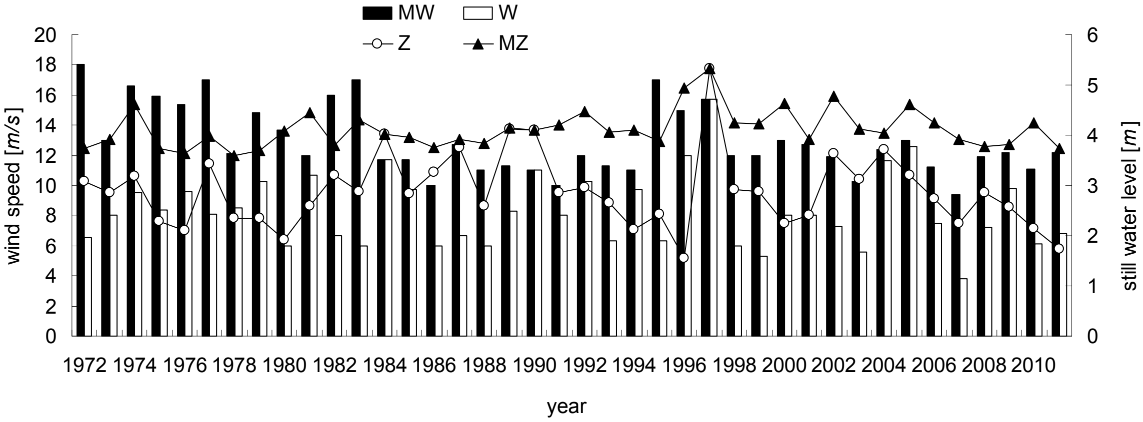

Fig. 2 Example of observations of mean wind speed and still water level (station: Tiansheng Port).

Marginal cumulative distributions and extreme value analysis

The Pearson Type III (P-III) distribution widely used in hydrological field of China (Lian et al., 2012) is adopted to fit the marginal distributions of still water levels (*MZ*, *Z*) and mean wind speeds (*MW*, *W*).

$$\begin{cases} F(mz) = P(MZ \le mz) \\ F(z) = P(Z \le z) \\ F(mw) = P(MW \le mw) \\ F(w) = P(W \le w) \end{cases} \tag{7}$$

where *mz*, *z*, *mw*, *w*=values of variable *MZ*, *Z*, *MW*, *W*, respectively; *P*=non-exceedance probability; $F(mz)$, $F(z)$, $F(mw)$, $F(w)$ = the marginal cumulative distributions of variable *MZ*, *Z*, *MW*, *W*, respectively.

The analysis of extreme still water levels and extreme wind speeds uses the annual maxima water levels (*MZ*) and wind speeds (*MW*). Table 1 shows the marginal cumulative distributions of *MZ* and *W*. Table 2 shows the marginal cumulative distributions of *MW* and *Z*. In the meantime, the return periods of extreme still water levels and extreme mean wind speeds at the four stations can be seen from Table 1 to 2.

Table 1 Marginal cumulative distributions of *MZ* and *W*.
(A: Lianyungang; B: Sheyang Estuary; C: Xiaoyang Port; D: Tiansheng Port)

MZ							W				
T [*years*]	F (mz) [%]	Value [*m*]					F (w) [%]	Value [*m/s*]			
		A	B	C	D			A	B	C	D
200	99.5	4.31	4.06	7.52	5.71		99.5	22.19	22.52	24.59	24.06
100	99.0	4.17	3.92	7.25	5.46		99.0	20.41	20.79	22.87	21.71
50	98.0	4.03	3.77	6.98	5.21		98.0	18.58	19.04	21.09	19.34
20	95.0	3.83	3.56	6.60	4.87		95.0	16.04	16.68	18.63	16.17
10	90.0	3.67	3.38	6.29	4.60		90.0	14.01	14.85	16.65	13.73
5	80.0	3.49	3.18	5.94	4.32		80.0	11.80	12.94	14.48	11.23
2	50.0	3.20	2.84	5.39	3.91		50.0	8.33	10.20	11.05	7.74
1.33	25.0	3.00	2.61	5.04	3.69		25.0	6.20	8.76	8.92	6.01
1.11	10.0	2.86	2.43	4.79	3.55		10.0	4.74	7.94	7.43	5.10
1.05	5.0	2.79	2.34	4.66	3.50		5.0	4.05	7.62	6.71	4.78
1.02	2.0	2.72	2.24	4.54	3.45		2.0	3.41	7.38	6.05	4.55

Table 2 Marginal cumulative distributions of *MW* and *Z*.
(A: Lianyungang; B: Sheyang Estuary; C: Xiaoyang Port; D: Tiansheng Port)

MW							Z				
T [*years*]	F(mw) [%]	Value [*m/s*]					F(z) [%]	Value [*m*]			
		A	B	C	D			A	B	C	D
200	99.5	27.58	27.25	27.73	32.27		99.5	4.04	3.74	6.76	5.36
100	99.0	25.96	25.78	26.33	29.83		99.0	3.86	3.54	6.45	5.04
50	98.0	24.29	24.27	24.88	27.36		98.0	3.68	3.33	6.13	4.70
20	95.0	21.99	22.19	22.89	24.00		95.0	3.42	3.03	5.67	4.24
10	90.0	20.14	20.52	21.29	21.37		90.0	3.20	2.80	5.29	3.85
5	80.0	18.13	18.72	19.57	18.60		80.0	2.94	2.53	4.85	3.43
2	50.0	14.97	15.91	16.89	14.52		50.0	2.49	2.10	4.10	2.73
1.33	25.0	13.04	14.22	15.29	12.27		25.0	2.17	1.81	3.58	2.27
1.11	10.0	11.71	13.08	14.20	10.92		10.0	1.91	1.61	3.17	1.94
1.05	5.0	11.08	12.54	13.69	10.36		5.0	1.76	1.50	2.95	1.77
1.02	2.0	10.50	12.06	13.24	9.90		2.0	1.61	1.40	2.72	1.60

Joint cumulative distributions analysis

Over the past few years, there has been a growing interest in applying copulas to hydrologic frequency analysis and deriving multivariate distributions (Zhang and Singh, 2007). The copula method has the advantage in that it does not assume marginal distributions to be normal or independent. Therefore, the objective of this study is to derive joint cumulative distribution function $F(mz,w)$ and $F(mw,z)$, using bivariate copulas.

A few well-known copulas can be considered as potential candidates for the joint cumulative distribution: Gumbel-Hougaard, Clayton, Frank, and etc. However, in China, some new results (Yang and Zhang, 2013; Lian et al., 2013; Kong et al., 2015) on the joint distribution with two hydrological variables showed that the Gumbel-Hougaard copula was the ideal model. Using the Gumbel-Hougaard copula, the theoretical joint distribution $F(mz,w)$ and $F(mw,z)$ can be expressed as

$$\begin{cases} F(mz,w) = P(MZ \le z, W \le w) = \exp\left\{-\left[\left(-\ln F(mz)\right)^{\theta} + \left(-\ln F(w)\right)^{\theta}\right]^{\theta}\right\} \\ \\ F(mw,z) = P(MW \le w, Z \le z) = \exp\left\{-\left[\left(-\ln F(mw)\right)^{\theta} + \left(-\ln F(z)\right)^{\theta}\right]^{\theta}\right\} \end{cases} \tag{8}$$

where θ=parameter of the copula function. Parameter θ can be estimated by the correlation test of empirical and theoretical joint distribution (Genest et al., 1995). The correlation test results of both show there are good coefficients of 0.9758~0.9951, and the Gumbel-Hougaard copula is an ideal model for this two variables. The optimal θ values at each station are given in Table 3.

Table 3 Optimal values of parameter θ.

Condition	θ			
	Lianyungang	Sheyang Estuary	Xiaoyang Port	Tiansheng Port
Condition I: *MZ* and *W*	1.26	1.30	1.59	1.16
Condition II: *MW* and *Z*	0.92	1.27	0.98	1.03

CRP at each station

Detailed data on CRP at each station are shown in Table 4 to 11. Using these tabular data, we can find the proper critical values and get the best combinations of water level and wind speed at each station in design of a seawall.

Table 4 CRP(mz_T,w): Lianyungang.

RTP (T) [%]	T [*year*]	mz_T [*m*]	w [*m/s*]	CRP(mz_T,w) [%]
0.5	200	4.31	20.14	1.62
			21.99	0.74
			24.29	0.25
			25.96	0.11
1	100	4.17	20.14	1.49
			21.99	0.65
			24.29	0.21
			25.96	0.09
2	50	4.03	18.13	2.24
			20.14	0.77
			21.99	0.30
			24.29	0.10

Table 5 CRP(mw_T,z): Lianyungang.

RTP (T) [*%*]	T [*year*]	mw_T [*m/s*]	z [*m*]	CRP(mw_T,z) [*%*]
0.5	200	27.58	3.67	2.20
			3.83	1.23
			4.03	0.58
			4.17	0.33
1	100	25.96	3.67	2.24
			3.83	1.26
			4.03	0.59
			4.17	0.34
2	50	24.29	3.49	4.44
			3.67	2.30
			3.83	1.30
			4.03	0.61

Table 6 CRP(mz_T,w): Sheyang Estuary.

TP (T) [*%*]	T [*year*]	mz_T [*m*]	W [*m/s*]	CRP(mz_T,w) [*%*]
0.5	200	4.06	20.52	1.63
			22.19	0.76
			24.27	0.27
			25.78	0.13
1	100	3.92	20.52	1.47
			22.19	0.66
			24.27	0.23
			25.78	0.11
2	50	3.77	18.72	3.21
			20.52	1.27
			22.19	0.54
			24.27	0.19

Table 7 CRP(mw_T,z): Sheyang Estuary.

RTP(T) [*%*]	T [*year*]	mw_T [*m/s*]	z [*m*]	CRP(mw_T,z) [*%*]
0.5	200	27.25	3.38	1.53
			3.56	0.77
			3.77	0.33
			3.92	0.18
1	100	25.78	3.38	1.41
			3.56	0.68
			3.77	0.28
			3.92	0.15
2	50	24.27	3.18	2.82
			3.38	1.24
			3.56	0.58
			3.77	0.23

Table 8 CRP(mz_T,w): Xiaoyang Port.

RTP(T) [*%*]	T [*year*]	mw_T [*m/s*]	z [*m*]	CRP(mw_T,z) [*%*]
0.5	200	7.52	21.29	3.01
			22.89	1.40
			24.88	0.54
			26.33	0.23
1	100	7.25	21.29	2.73
			22.89	1.19
			24.88	0.42
			26.33	0.17
2	50	6.98	18.38	4.74
			21.29	2.34
			22.89	0.93
			24.88	0.30

Table 9 CRP(mw_T,z): Xiaoyang Port.

RTP(T) [*%*]	T [*year*]	mw_T [*m/s*]	z [*m*]	CRP(mw_T,z) [*%*]
0.5	200	27.73	6.29	1.56
			6.60	0.80
			6.98	0.33
			7.25	0.18
1	100	26.33	6.29	1.59
			6.60	0.82
			6.98	0.34
			7.25	0.19
2	50	24.88	5.94	3.42
			6.29	1.63
			6.60	0.84
			6.98	0.35

Table 10 CRP(mz_T,w): Tiansheng Port.

RTP(T) [*%*]	T [*year*]	mz_T [*m*]	w [*m/s*]	CRP(mz_T,w) [*%*]
0.5	200	5.71	21.37	1.59
			24.00	0.71
			27.36	0.23
			29.83	0.10
1	100	5.46	21.37	1.52
			24.00	0.67
			27.36	0.21
			29.83	0.10
2	50	5.21	18.60	3.58
			21.37	1.44
			24.00	0.62
			27.36	0.20

Table 11 CRP(mw_T,z): Tiansheng Port.

RTP(T) [%]	T [*year*]	mw_T [*m/s*]	z [*m*]	CRP(mw_T,z) [%]
0.5	200	32.27	4.60	2.66
			4.87	1.51
			5.21	0.74
			5.46	0.42
1	100	29.83	4.60	2.67
			4.87	1.52
			5.21	0.74
			5.46	0.42
2	50	27.36	4.32	4.52
			4.60	2.68
			4.87	1.53
			5.21	0.75

Optimize combination of design water level and wind speed

Table 12 and Table 13 show the optimal combinations of design water levels and design wind speeds by Formula 6 and Table 4 to 11 at each station. By comparing two different design seawall heights calculated according to (mz_T, w_{CT}) and (mw_T, z_{CT}), the larger value among them should be adopted. For comparison, the traditional combination rule of a 50-year return period water level and 10 class wind speed (24.5~28.4 *m/s*) is adopted in Jiangsu. The difference (denoted by D_I and D_{II}) between the two methods can be expressed in percentage. This yields

$$\begin{cases} D_I = \dfrac{H - H_I}{H} \times 100\% \\ D_{II} = \dfrac{H - H_{II}}{H} \times 100\% \end{cases} \tag{9}$$

where H = design seawall height according to traditional method; H_I, H_{II} = design seawall height according to (mz_T, w_{CT}) and (mw_T, z_{CT}). Table 14 shows the comparison results at each station. It can be seen that: (1) At same station, this phenomenon ($D_I < D_{II}$) means seawall height calculated according to (mz_T, w_{CT}) is more larger than that according to (mw_T, z_{CT}); (2) the design seawall height according to the traditional method adopted in Jiangsu is 2.07% ~5.96% higher than that according to the presented method; (3) The traditional method will produce an overestimate of design seawall height from a view of the likelihood of both variables occurring simultaneously.

Table 12 Optimal combination: (mz_T, w_{CT}).

Station	Water level		Mean wind speed	
	mz_T [*m*]	T [*year*]	w_{CT} [*m/s*]	T [*year*]
Lianyungang	4.03	50	18.45	5.8
	4.17	100	21.22	15.8
	4.31	200	23.12	34.7
Sheyang Estuary	3.77	50	19.84	8.1
	3.92	100	21.49	15.8
	4.06	200	23.29	35.9
Xiaoyang Port	6.98	50	21.68	12.4
	7.25	100	23.38	27.4
	7.52	200	25.07	56.5
Tiansheng Port	5.21	50	20.65	8.7
	5.46	100	22.98	16.1
	5.71	200	25.47	33.1

Table 13 Optimal combination: (mw_T, z_{CT}).

Station	Mean wind speed		Water level	
	mw_T [*m/s*]	T [*year*]	z_{CT} [*m*]	T [*year*]
Lianyungang	24.29	50	3.72	13
	25.96	100	3.91	31.6
	27.58	200	4.07	66
Sheyang Estuary	24.27	50	3.28	7.6
	25.78	100	3.48	15.6
	27.25	200	3.69	38.4
Xiaoyang Port	24.88	50	6.22	9
	26.33	100	6.53	17.7
	27.73	200	6.84	39.1
Tiansheng Port	27.36	50	4.76	15.9
	29.83	100	5.1	40
	32.27	200	5.4	87.5

Table 14 The comparison results at each station.

Station	D_I [*%*]	D_{II} [*%*]
Lianyungang	5.96	10.74
Sheyang Estuary	5.03	16.98
Xiaoyang Port	2.07	14.85
Tiansheng Port	3.38	10.14

CONCLUSIONS

A seawall is an important form of coastal defence constructed on the inland part of a coast to reduce storm tide disasters and to defend the coast around a town or harbour from erosion. Generally, the design standard of a seawall is defined as the disasters protecting ability and may be expressed by the return period of design occurrence of storm tide disasters. The choice of the recommended return period in a region is usually made balancing the total costs of the seawall structure and the good benefit of coastal defence, and so the specified return period for the design of a seawall depends on economy, society and natural environment. This means a specified risk level of overtopping or damage of a seawall structure is usually allowed. The determination of the required seawall height is usually based on the combination of wind speed (or wave height) and water level according to the above-mentioned return period. To fully know the combined effect of both variables which influence the engineering design is a major advantage in incorporating the dependence between the two variables in design of a seawall. With a specified risk level allowed, the aim of this work is to define a methodology to identify the optimal combination between these two values for the design of seawalls based on conditional risk probability.

The work is split into three main parts: (a) the research background; (b) the establishment of the conditional risk probability-based seawall height design method; (c) the optimal combinations of design water levels and design wind speeds at four in-situ stations from Jiangsu of China are analyzed. The facts that are deduced from this study can be summarized as follows:

- The observed data from Jiangsu of China shows high still water levels are not always occurring together with high wind speeds.
- When there is a small likelihood of high water levels and high wind speed occurring simultaneously, it makes sense to optimize the combination of design water level and design wind speed in design of a seawall.

- The joint cumulative distribution and conditional risk probability of water level and wind speed are estimated using the bivariate copula function. The correlation test of this paper shows the Gumbel-Hougaard copula is an ideal model for this two variables.
- From a view point of economy, a specified risk level (or return period) of overtopping and damage of seawall structure is usually allowed in the design of seawall. Therefore, conditional risk probability has much more meanings than the joint probability in the aspect of determining a seawall height.
- Any one station has a pair of optimal combinations: (mz_T, w_{CT}) and (mw_T, z_{CT}). By comparing two different design seawall heights calculated according to (mz_T, w_{CT}) and (mw_T, z_{CT}), the larger value of design seawall heights should be adopted. In jiangsu, seawall height calculated according to (mz_T, w_{CT}) is more larger than that according to (mw_T, z_{CT}).
- The method presented by this paper incorporates bivariate joint probabilistic and conditional probability of design technologies in order to yield a proper seawall design event. Compared with the traditional design methods adopted in Jiangsu, this method can improve seawall height design accuracy.
- In Jiangsu, the design seawall height according to the traditional method is 2.07% ~5.96% higher than that according to the presented method. This usually has the potential effect of a seawall being designed to the incorrect level leading to costs (over-designed).

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