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Joint distribution of wind speed and direction in the context of field measurement

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Abstract. The joint distribution of wind speed and wind direction at a bridge site is vital to the estimation of the basic wind speed, and hence to the wind-induced vibration analysis of long-span bridges. Instead of the conventional way relying on the weather stations, this study proposed an alternate approach to obtain the original records of wind speed and the corresponding directions based on field measurement supported by the Structural Health Monitoring System (SHMS). Specifically, SHMS of Sutong Cable-stayed Bridge (SCB) is utilized to study the basic wind speed with directional information. Four anemometers are installed in the SHMS of SCB: upstream and downstream of the main deck center, top of the north and south tower respectively. Using the recorded wind data from SHMS, the joint distribution of wind speed and direction is investigated based on statistical methods, and then the basic wind speeds in 10-year and 100-year recurrence intervals at these four key positions are calculated. Analytical results verify the reliability of the recorded wind data from SHMS, and indicate that the joint probability model for the extreme wind speed at SCB site fits well with the Weibull model. It is shown that the calculated basic wind speed is reduced by considering the influence of wind direction. Compared to the design basic wind speed in the Specification of China, basic wind speed considering the influence of direction or not is much smaller, indicating a high safety coefficient in the design of SCB. The results obtained in this study can provide not only references for further wind-resistance research of SCB, but also improve the understanding of the safety coefficient for wind-resistance design of other engineering structures in the similar area.

Keywords: joint distribution; wind speed; wind direction; Sutong Cable-stayed Bridge (SCB); field measurement; Structural Health Monitoring System (SHMS); basic wind speed

1. Introduction

Wind load generally plays a dominant role in the design of flexible long span bridges. With the rapid increase of the bridge span, the bridge structure becomes even more sensitive to wind actions. The reliable design of these structures in hostile environment can be assured through better understanding of the environment load effects and enhanced response prediction capabilities (Davenport 1977, Kareem 1999, Fujino 2002). Advances have been made in the prediction of the

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dynamic and aerodynamic characteristics of the wind-bridge interaction system over the last several decades, which also put forward demand for more accurate estimates of the basic wind speed. In the conventional wind resistant design, the influence of wind direction is usually not considered in the analysis of basic wind speed (Herb *et al.* 2007, Zhang *et al.* 2014). This is mostly due to the assumption of evenly distributed wind velocity at different directions and the difficulty of collecting complete wind environment data at the bridge site. However, typically wind velocity at a specific location is a function of the wind direction. Hence, it is more appropriate to describe the natural wind by both speed and direction. Furthermore, as for long span bridges, it is well known that the structural aerodynamic properties are sensitive to both the wind speed and direction. Therefore, it is necessary to study the joint probability distribution of wind speed and wind direction at the bridge site. In such a case, the influence of wind direction on the basic wind speed can be investigated.

Several statistical analysis methods concerning the effects of joint action of wind speed and direction have been proposed over the last several decades, e.g., stationary random process method (e.g., Davenport 1977, Wen 1983), maximum wind coefficient method (e.g., Simiu and Filliben 1981), and joint probability distribution method (e.g., Gomes and Vickery 1974, Cook 1982). Among these, the joint probability distribution method is widely used due to its high efficacy in analyzing the joint action of wind speed and direction. Simiu et al. (1985) presented a method for calculating structural failure probabilities by using directional wind speed data as obtained from weather station records, the failure probabilities subjected to wind forces were then computed with the wind direction considered. Coles and Walshaw (1994), using multivariate extreme value method, established the joint probability distribution model of wind speed and direction, which accounts for the correlation among wind speeds across directions. Ge and Xiang (2002) proposed a simplified statistical analysis method of basic wind speed based on the joint probability distribution model with directional independent coefficients. Once the wind speed data are obtained, the randomness of the wind load or wind load effect could be combined to provide a more reliable design wind load or load effect for the structure (e.g., Chen and Huang 2010)

It is critical to obtain sufficient and reliable wind records before the analysis of joint distribution of wind speed and direction and hence the estimate of basic wind speeds. Conventionally, the original wind records are collected from selected weather stations. There are several issues in such a data collection, such as the frequency changes of elevation of the wind recording instruments, the altering of the surrounding terrain, the reasonable conversion of the wind records from the weather station location to the bridge site. The rapid development of the Structural Health Monitoring System (SHMS) in civil engineering provides another promising approach to efficiently obtain the original wind data for the analysis of basic wind speed. Most of the SHMSs have anemometers which are available to monitor the wind speed in three directions (Xu *et al.* 2001, Ko and Ni 2005, Fujino *et al.* 2009, Ou and Li 2010, Cho *et al.* 2010), thus can provide recorded real-time data for the analysis of wind speed and direction characteristics as well as their parameters. In such a case, the aforementioned issues resulting from wind data of the weather station are circumvented. For instance, based on Wind and Structural Health Monitoring System of Tsing Ma suspension bridge, Xu *et al.* (2001) comprehensively analyzed the wind characteristics of Typhoon Victor and the simultaneous structural responses of Tsing Ma suspension bridge. Liu *et al.* (2009) discussed natural wind characteristics at Xihoumen Bridge to provide reliable parameters for wind-resistant evaluation. In order to obtain the turbulent characteristics at Sutong bridge site, Wang *et al.* (2013) conducted a research on long-term monitoring of wind characteristics with recorded real-time wind data from SHMS.

Fig. 1 Configuration of SCB

In this study, a world-famous long-span cable-stayed bridge, the Sutong Cable-stayed Bridge (SCB) in China is taken as an example. After the commonly used joint probability distribution models of wind speed and direction is discussed, the joint probability distribution and the design basic wind speed at bridge site are investigated based on the long-term recorded wind data from the SHMS of SCB. The reliability of the recorded wind data and the efficiency of this proposed methodology are verified. Results indicate that the joint probability model of the extreme wind speed at SCB site fits well with the Weibull model, and that the calculated basic wind speed is reduced by considering the influence of wind direction. The objective of this study is to better understand the wind characteristics of the SCB site, and provide more accurate wind parameters for wind-resistance design of other engineering structures near the bridge site.

2. Engineering background

2.1 Description of SCB

Connecting Suzhou and Nantong cities of Jiangsu Province of China, SCB is a two-tower two-cable, steel box girder cable-stayed bridge with a main span of 1088 m. It was the longest cable-stayed bridge in the world when it was open to traffic in 2008. In addition, the bridge had three other No.1s in the world including the main tower height of 306 m, the cable-stayed length of 580 m and the group pile foundation's plane size of 113.75 m×48.1 m. The overall configuration of SCB is shown in Fig. 1.

2.2 Climate at the bridge location

Located in the lower reach of the Yangtze River in Jiangsu Province, the SCB is near the entrance of the Yangtze River to the Yellow Sea, as shown in Fig. 2. The bridge site belongs to mid-latitude zone, and this area is greatly influenced by the southern subtropical humid monsoon climate. Monsoon circulation has a significant influence on the seasonal changes of local weather patterns. Unlike the climate in continental and marine areas, typhoon climate from eastern ocean in summer and the north wind from the northwest Siberia in winter generate the primary wind loads which act on SCB dominantly. As a typical example, Fig. 3 shows the moving route of Typhoon Kalmaegi which passed the site of SCB in July of 2008.

2.3 Layout of Anemometers on SCB

To monitor the wind environment of the bridge site, four 3D ultrasonic anemometers (ANE) are installed in the SHMS of SCB (Wang *et al.* 2013). Wind angle 0° is defined as north and 90° as east, rotating in a clockwise direction. In order to record the wind direction accurately, spherical coordinates are chosen for data output. Sampling frequency of anemometers is set as 1 Hz for the convenient data storage and management. The layout of anemometers is shown in Fig. 4: two of them are installed at upstream (MS4) and downstream (MS4') side respectively at the midpoint of the deck (76 m in elevation), and the other two are at the top of north (MS2) and south (MS6) towers (306 m in elevation), respectively.

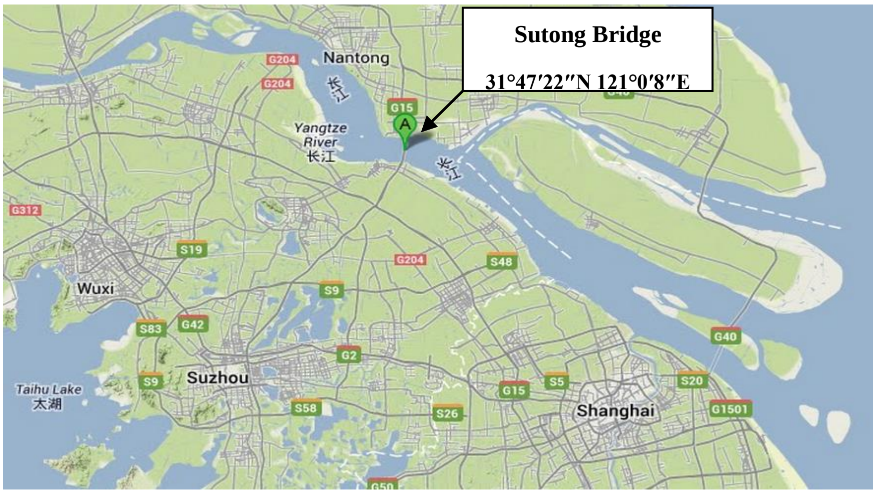


Fig. 2 Location of SCB

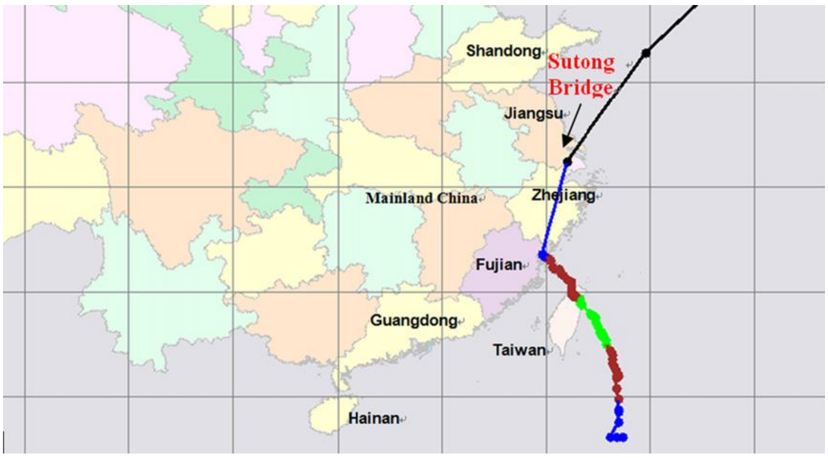


Fig. 3 Moving route of Typhoon Kalmaegi

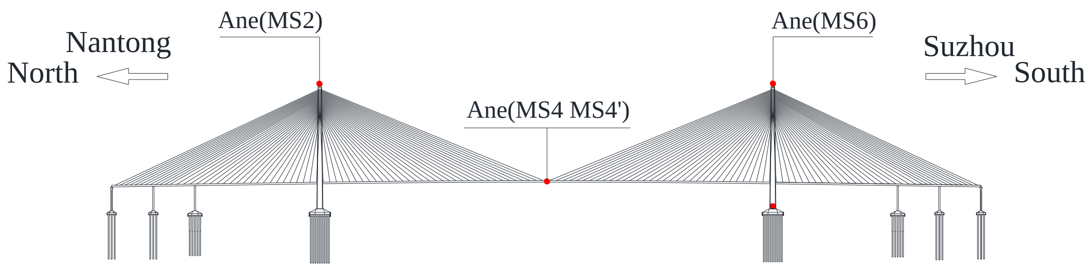


Fig. 4 Layout of anemometers on SCB (Unit: m)

3. Statistical analysis of joint probability distribution of wind speed and direction

Joint probability distribution model can reflect joint distribution pattern of both wind speed and direction. Assuming wind speed and direction of the same site are independent, the extreme value distribution function can be expressed as (Ge and Xiang 2002)

$$F(u,\theta) = f(\theta) P_U (U < u, \theta) \tag{1}$$

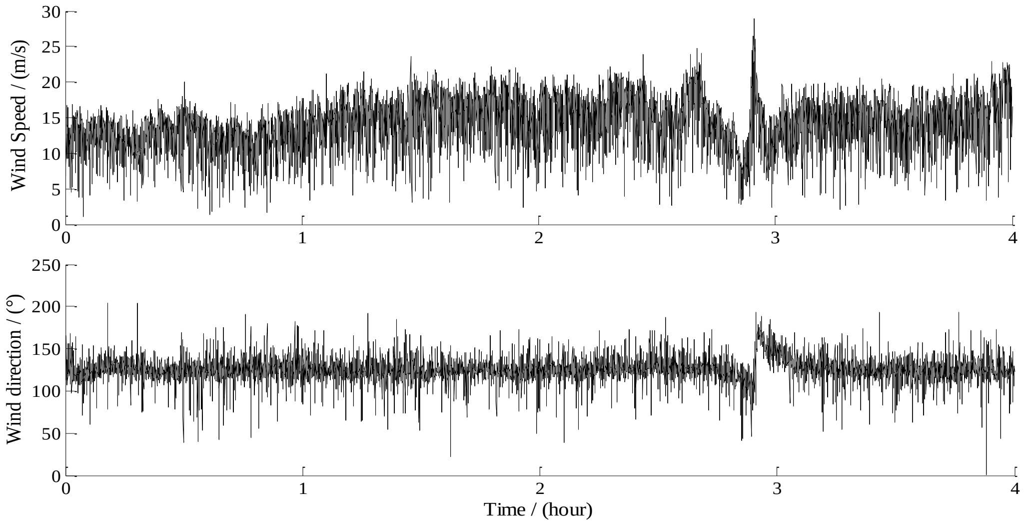
where θ is the wind direction; $f(\theta)$ is the wind direction frequency function which reflects the effect of wind direction; u is the wind speed and U is a variable which is smaller than u in the probability function; $P_U(U<u, \theta)$ represents the function of wind speed distribution in various directions, which can be fitted from wind speed data of each direction. The adopted model may have some limitations due to the abovementioned independent assumption, but the contributions of wind speed and direction to the joint probability distribution model can be explicitly established in such a case (Ye and Xiang 2011).

3.1 Wind speed samples from SHMS

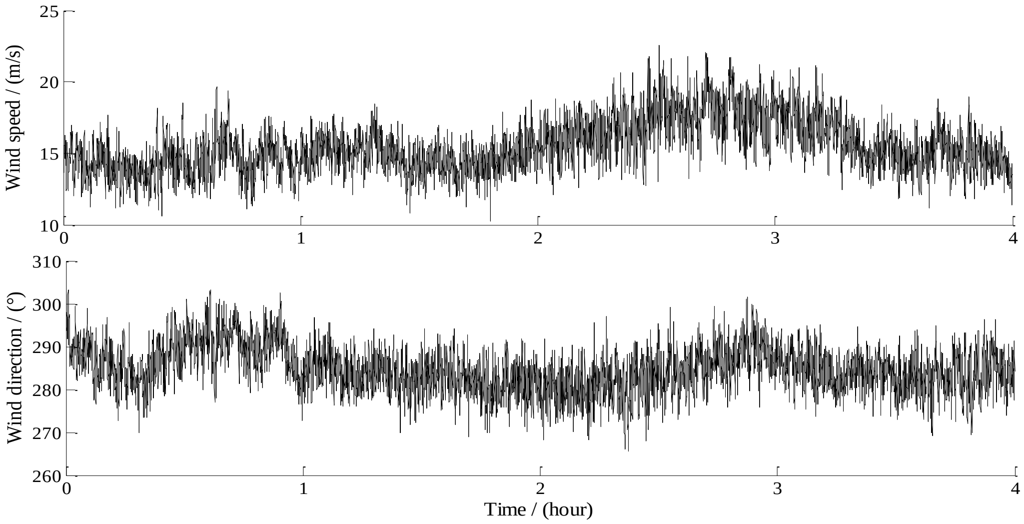
The daily maximum wind speeds in 16 principal compass directions are generated for analyzing the joint distribution of wind speed and direction. A logical sampling approach is to extract the same number of extreme value samples among wind speed data according to different directions. However, due to the nonuniform distribution of the maximum wind speed in various directions, the number of extreme value samples of some wind directions is small and hence the number of extreme value samples that can be extracted from the data is limited. To obtain more samples, extreme value samples at each wind direction are extracted directly from the whole wind speed data. The wind direction frequency function is introduced to consider the difference among the numbers of samples in different directions.

Wind speed samples used in this study are extracted from the daily maximum wind speed monitored at SCB site, available from January 2008 to December 2011 (averaging time interval: 10 min). Fig. 5 shows some typical samples of the original recorded wind speed and direction from the data base of SHMS. Using the multistage extremum sampling method (Ge and Xiang 2002), the maximum wind speed is picked to compose extreme samples. Because 4-year wind speed data are available, the large sampling variability will exist if the traditional annual maxima approach is used. To expand the sample size, a four-day period time is selected for the extraction of maximum wind speed (Yang *et al*. 2002). Similar treats have been adopted by other researchers. For example, based on order maxima, Coles and Walshaw (1994) derived the directional extreme wind speed from 6-year wind speed data.

It should be mentioned that extreme wind events (e.g., typhoons and hurricanes) and well behaved climates are usually treated separately in the prediction of the basic wind speed (Simiu and Scanlan 1978). The SCB site is a special area that dominated by both the monsoon climate and typhoons. The typhoons generated on the Pacific Ocean will attack the SCB site for several times every year. As a result, both the well-behaved climates and extreme wind events are included in the probability model.



(a) Sample of Typhoon Fung-Wong (2008-7-30T00:00-2008-7-30T04:00)



(b) Sample of Typhoon Meari (2011-6-26T03:30-2011-6-26T07:30)

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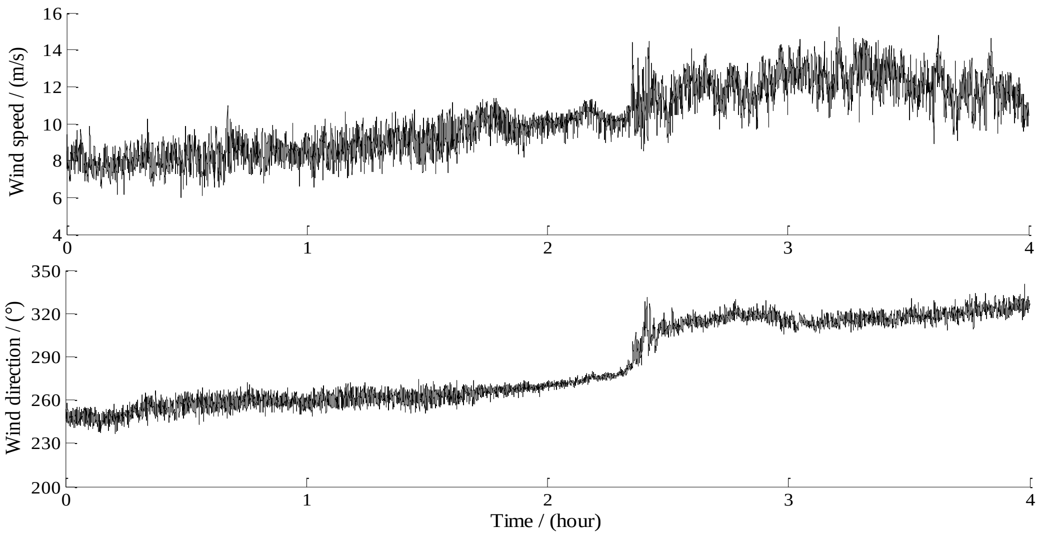
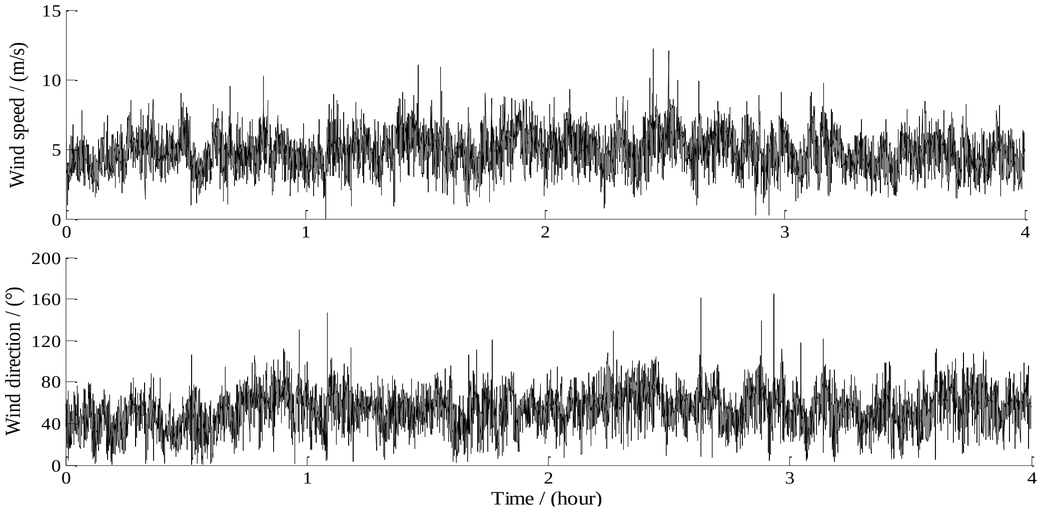


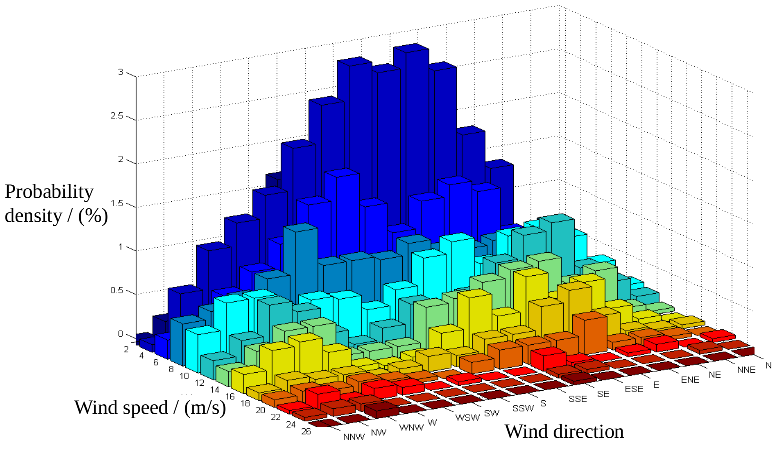
(c) Sample of Northwestern wind in winter (2010-12-02T16:00-2010-12-02T20:00)



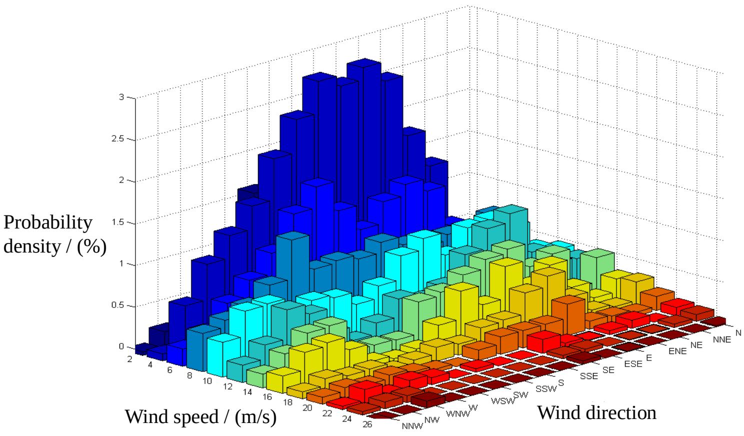
(d) Sample of Daily Wind (2009-10-10T08:00-2009-10-10T12:00)

Fig. 5 Samples of wind speed and direction from the data base

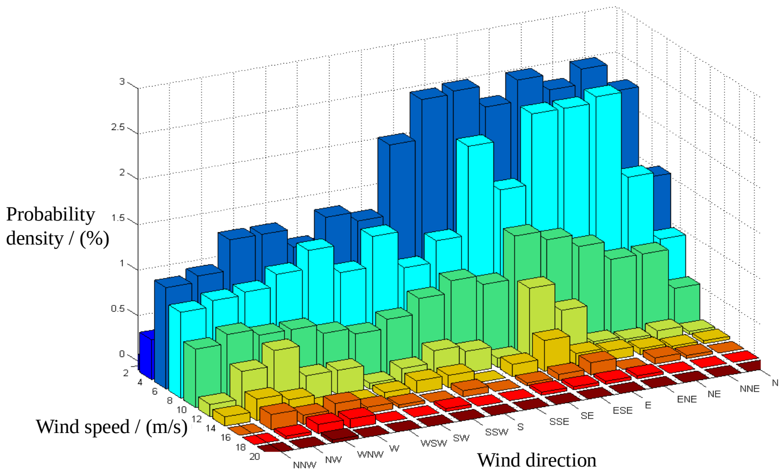
The extreme wind speed samples recorded at the main deck center and the top of towers are statistically analyzed. The number of wind extremes lying in each wind speed interval at each direction is counted. Hence the occurred frequencies of various wind speeds and directions at the bridge site are presented by probability density function (PDF) using histogram, as shown in Fig. 6. The total number of samples is assumed to be 100%.



MS2



MS6



MS4

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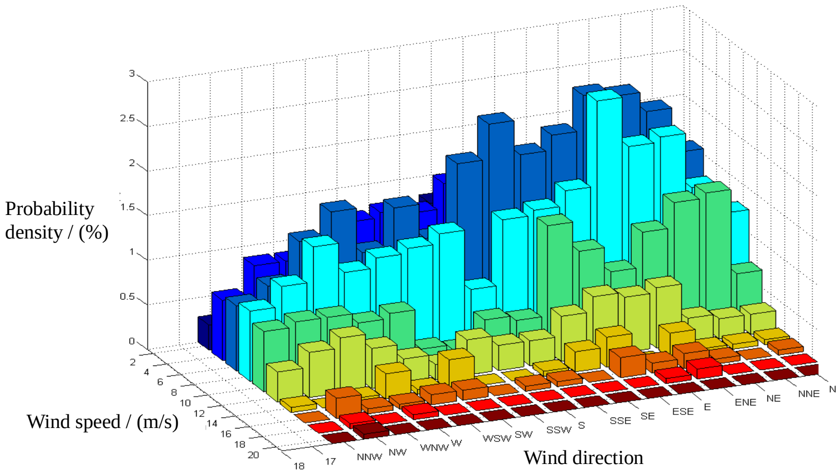


MS4'

Fig. 6 Occurrence probability of extreme wind speed in various wind speeds and directions

3.2 Estimation of joint probability distribution of wind speed and direction

Based on the data presented in Fig. 6, the probability distribution model of extreme wind speed considering wind direction can be fitted. Two assumptions are adopted in the estimation of the distribution model (Ge and Xiang 2002): (1) wind speed at the same position but in different directions follows the same extremum probability distribution model, and the optimal extreme value probability distribution model is fitted based on the wind speed samples in all directions; (2) the parameters of extremum probability distribution model of mean wind speed at the same position but in different directions are independent of each other. Three joint distribution models of wind speed and direction can be described as

Frechet Distribution

$$P(U > x, \theta) = f(\theta) \cdot \left\{ 1 - \exp\left[-\left(\frac{x}{a(\theta)} \right)^{-\gamma(\theta)} \right] \right\} \tag{2}$$

Gumbel Distribution

$$P(U > x, \theta) = f(\theta) \cdot \left\{ 1 - \exp\left[-\exp\left(-\frac{x - b(\theta)}{a(\theta)} \right) \right] \right\} \tag{3}$$

Weibull Distribution

$$P(U > x, \theta) = f(\theta) \cdot \exp\left[-\left(\frac{x}{a(\theta)} \right)^{\gamma(\theta)} \right] \tag{4}$$

where $a(\theta)$, $b(\theta)$ and $\gamma(\theta)$ are scale, location and shape parameters, respectively. All these parameters are functions of wind direction. The wind direction frequency function $f(\theta)$ reflects the distribution of wind speed in various directions, and can be obtained by statistically analyzing the occurrence frequency of extreme wind speed samples in each concentrated direction.

There are various methods to fit the above mentioned three joint probability distribution models (Hong *et al.* 2013, Harris *et al.* 2014). This study chooses the least square method which is extensively used to evaluate the parameters. As the parameters of the above mentioned three joint probability distribution models are all the functions of wind direction, they should be calculated in each direction respectively. Only two parameters are included in each joint probability distribution model, thus we can use linear method to evaluate each parameter. The format of the liner function is $y=kx+d$, hence, the two parameters can be calculated as

$$\begin{cases} k = \dfrac{\sum x_i \sum y_i - n\sum x_i y_i}{\left(\sum x_i\right)^2 - n\sum x_i^2} \\ d = \dfrac{\sum x_i y_i \sum x_i - \sum y_i \sum x_i^2}{\left(\sum x_i\right)^2 - n\sum x_i^2} \end{cases} \tag{5}$$

where x is the independent variable; y is the dependent variable; and n is the sample size.

According to the statistical chart of occurrence probability of extreme wind speed in various wind speeds and directions (Fig. 6), parameters based on the above three probability distribution models is fitted with samples in all directions (called Omni-direction below, without considering the effect of wind direction). Results of each parameter are shown as Table 1. Variable r, which could be obtained by Probability Plot Correlation Coefficient (PPCC) method (Simiu and Filliben 1976), is the correlation coefficient measuring the match degree. A closer value of r to unity indicates a better fit of the distribution.

Table 1 indicates that the fitting results of the same parameter in each distribution model are almost the same for MS4 and MS4'. The slight differences between MS2 and MS6 may be owing to the influence of elevation. Among three probability distribution models, Weibull distribution provides the best approximation to the extreme wind speed samples according to the value of correlation coefficient r. The parameter estimation of Weibull joint probability distribution model in each direction is shown in Table 2-5. The parameter estimation results of the other two models are also included for comparison and to provide references to future researches.

Table 1 Distribution parameters of three probability models in each position

Position	Frechet Distribution			Gumbel Distribution			Weibull Distribution		
	a	γ	r	a	b	r	a	γ	r
MS2	4.41351	2.60984	0.85641	3.04691	5.76948	0.97162	7.80935	1.51495	0.99259
MS6	4.44400	2.63731	0.88451	3.13215	5.83648	0.97887	7.83666	1.52442	0.99496
MS4	3.95690	3.66698	0.90825	1.85717	4.95955	0.98466	6.81834	2.14243	0.99761
MS4'	3.95260	3.53307	0.90732	1.93169	4.94151	0.98777	6.75584	2.04426	0.99964

Table 2 Results of parameter estimation of MS2

Wind direction	$f(\theta)$	Frechet Distribution		Gumbel Distribution		Weibull Distribution	
		a	γ	a	b	a	γ
N	0.02597	6.93360	2.51794	3.68070	8.12952	12.14464	2.58436
NNE	0.02219	5.19236	5.78249	2.62935	7.47718	9.75283	2.36608
NE	0.04936	5.24687	3.47027	3.72281	8.00654	9.93025	2.02519
ENE	0.07285	5.12425	2.24577	3.26259	6.96924	9.80171	1.85347
E	0.09270	4.66679	1.73716	4.35779	5.94336	9.41701	1.55152
ESE	0.09486	4.60426	2.23153	3.34713	6.22680	8.67177	1.59092
SE	0.09083	4.23875	2.05048	3.95886	5.14289	8.06424	1.46110
SSE	0.08666	3.64104	1.88937	3.49764	4.33268	6.93862	1.45251
S	0.08325	3.41763	2.03831	3.43057	3.70634	6.29119	1.38071
SSW	0.07852	3.14686	2.24637	2.95889	3.06428	5.38153	1.35837
SW	0.06949	3.15251	2.30116	3.09930	2.97508	5.49071	1.39127
WSW	0.06039	3.54147	2.09184	3.59010	3.71203	6.61734	1.42305
W	0.05936	4.17464	1.78219	4.05788	5.14408	8.17983	1.39381
WNW	0.05256	5.03143	2.00012	3.82658	6.36308	9.82125	1.84726
NW	0.04055	5.74436	2.04959	3.41032	6.12602	10.52217	1.85050
NNW	0.02045	5.84753	2.09881	3.43457	6.82672	10.73192	2.02890

3.3 Calculation of basic wind speed

Based on the obtained joint probability distribution of wind speed and direction, the basic wind speed in corresponding recurrence interval considering the effect of wind direction can be calculated. The probability that extreme wind speed V exceeds basic wind speed U_r in one direction throughout the year can be expressed as

$$P(V > U_r, \theta) = C_N^1 \cdot P(U > U_r, \theta) = N[P(U > U_r, \theta)] \tag{6}$$

where N is the occurrence number of the strong winds within one year (N is equal to 91.25 in this study).

Taking Weibull distribution as an example, the recurrence interval R (year) and the basic wind speed should meet the following equation

$$\frac{1}{R} = Nf(\theta)\exp\left[-\left(\frac{U_r}{a(\theta)}\right)^{\gamma(\theta)}\right] \tag{7}$$

Table 3 Results of parameter estimation of MS6

Wind direction	$f(\theta)$	Frechet Distribution		Gumbel Distribution		Weibull Distribution	
		a	γ	a	b	a	γ
N	0.00835	6.41620	2.60701	3.79695	6.92605	10.60760	2.34786
NNE	0.02109	5.18584	2.34960	3.60441	6.59402	10.18354	2.18550
NE	0.04877	5.08418	2.22560	5.13956	6.58571	9.76946	1.98620
ENE	0.07294	4.78387	2.34714	3.00589	6.49636	9.00504	1.78107
E	0.09446	4.47619	1.57893	4.40082	5.71411	9.04372	1.41484
ESE	0.09666	4.50615	2.32580	3.24411	6.12366	8.36466	1.55644
SE	0.09271	4.31022	2.25350	3.82300	5.26568	8.03920	1.46411
SSE	0.08831	3.83525	1.76179	3.96028	4.61824	7.50591	1.37227
S	0.08480	3.49874	2.00307	3.56502	3.83612	6.51539	1.37939
SSW	0.07997	3.12473	2.41480	3.22482	2.71244	5.20731	1.27674
SW	0.07074	3.03812	2.39822	3.05654	2.63798	5.10972	1.32477
WSW	0.06151	3.62314	2.18135	3.66098	3.68297	6.78818	1.47543
W	0.06107	4.21264	1.88714	4.08260	5.10228	8.15307	1.42649
WNW	0.05448	5.22512	2.13967	4.20310	6.65734	10.38528	1.84702
NW	0.04262	5.45323	1.86791	4.33300	7.24047	10.85129	1.72313
NNW	0.02153	6.00091	2.15160	3.84411	7.92774	11.71727	2.28175

Hence, the basic wind speed considering the effect of wind direction can be expressed as

$$U_r = a(\theta)\left[\ln\left(RNf(\theta)\right)\right]^{\frac{1}{\gamma(\theta)}} \tag{8}$$

Eq. (8) shows that the influence of wind direction frequency function $f(\theta)$ on basic wind speed is reflected by reducing the recurrence interval, while N plays the role of recurrence interval multiplier.

According to Eq. (8) and the evaluated parameters of Weibull joint distribution, basic wind speed in each direction at the bridge site is calculated. The results are shown as Table 6. It should be mentioned that data in the “Omni-direction” line are basic wind speeds calculated by traditional method without considering the influence of wind direction. In order to reflect the distribution of basic wind speeds in various directions, the wind rose charts are plotted, as shown in Fig. 7.

Table 4 Results of parameter estimation of MS4

Wind direction	$f(\theta)$	Frechet Distribution		Gumbel Distribution		Weibull Distribution	
		a	γ	a	b	a	γ
N	0.03308	4.85333	4.84723	1.45965	4.94964	6.59616	2.95082
NNE	0.06379	3.76661	3.46158	3.06488	4.53005	6.66920	2.64434
NE	0.07999	3.68836	3.19215	1.84842	4.42525	6.52139	2.37325
ENE	0.08269	3.73397	3.48296	1.87213	4.42746	6.60134	2.29315
E	0.08876	4.04965	3.08920	2.10420	4.96922	7.29420	2.34420
ESE	0.08640	4.15683	3.08098	2.06391	5.22303	7.48161	2.39295
SE	0.07864	3.80370	3.29818	2.01872	4.45419	6.86328	2.38580
SSE	0.06750	3.62887	2.49921	1.83417	4.34187	6.19177	2.40554
S	0.06480	3.60514	2.68692	2.21505	4.25839	6.32903	1.97721
SSW	0.05569	3.62856	3.04490	2.13631	4.25220	6.27492	1.92781
SW	0.05265	3.32538	2.94903	2.01724	3.77957	5.60910	1.85171
WSW	0.05299	3.62230	2.76939	2.13719	4.30720	6.34533	2.01681
W	0.05535	3.72694	2.30588	2.88861	4.31657	6.84130	1.75193
WNW	0.05400	4.15877	2.57212	2.74193	5.13123	7.59415	1.86653
NW	0.04927	4.15183	2.52631	2.45224	5.31284	7.52037	1.94228
NNW	0.03443	4.22391	2.69464	1.96910	5.14859	7.35224	2.96673

From Table 6 and Fig. 7, we can conclude:

(1) In both cases of 10-year and 100-year recurrence intervals, the basic wind speeds on top of the towers is larger than those of the main deck center. In the four positions, all basic wind speeds in 100-year recurrence interval are larger than those of 10-year case. There is a remarkable similarity among the results of calculated basic wind speed for MS2 and MS6 in different directions. Apparent correlation among the results of calculated basic wind speed for MS4 and MS4' can also be observed in each direction. These results suggest the reliability of the field measurements of SHMS in SCB.

(2) Most basic wind speeds considering the effects of wind direction presented in Table 6 are smaller than those without the wind direction considered. However, several exceptions are observed. In the case of 100-year recurrence interval, the basic wind speeds of MS6, MS4 and MS4' respectively in E, WNW and NW directions, with the value of 33.573 m/s, 20.060 m/s and 19.396 m/s, are a bit larger than those neglecting the effects of wind direction, which are 31.530 m/s, 19.061 m/s and 19.365 m/s respectively. This is related to the occurrence probability of the obtained extreme wind speed samples as shown in Fig. 6.

(3) As indicated in Fig. 7, the main strong winds of SCB site are southeast wind and northwest wind. This observation relates to the climatological condition at the bridge site, especially the typhoon climate from eastern ocean in summer and the north wind from Siberia in the northwest of China in winter.

(4) There are some differences between the results of MS4 and MS4' which may mainly result from the shielding effects of bridge structure itself on anemometers. These can be reduced by cautiously choosing installation positions and inspecting the monitored data.

3.4 Comparison with design basic wind speed in specification

According to Wind-Resistance Design Specification for Highway Bridges (JTG/T D60-01-2004) in China, the design basic wind speed, which is in 100-year recurrence interval, of SCB at the height of 7.1 m is 28.6 m/s. The design basic wind speeds on the deck center and the top of towers can be calculated as

$$V_{Z_2} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} V_{Z_1} \tag{9}$$

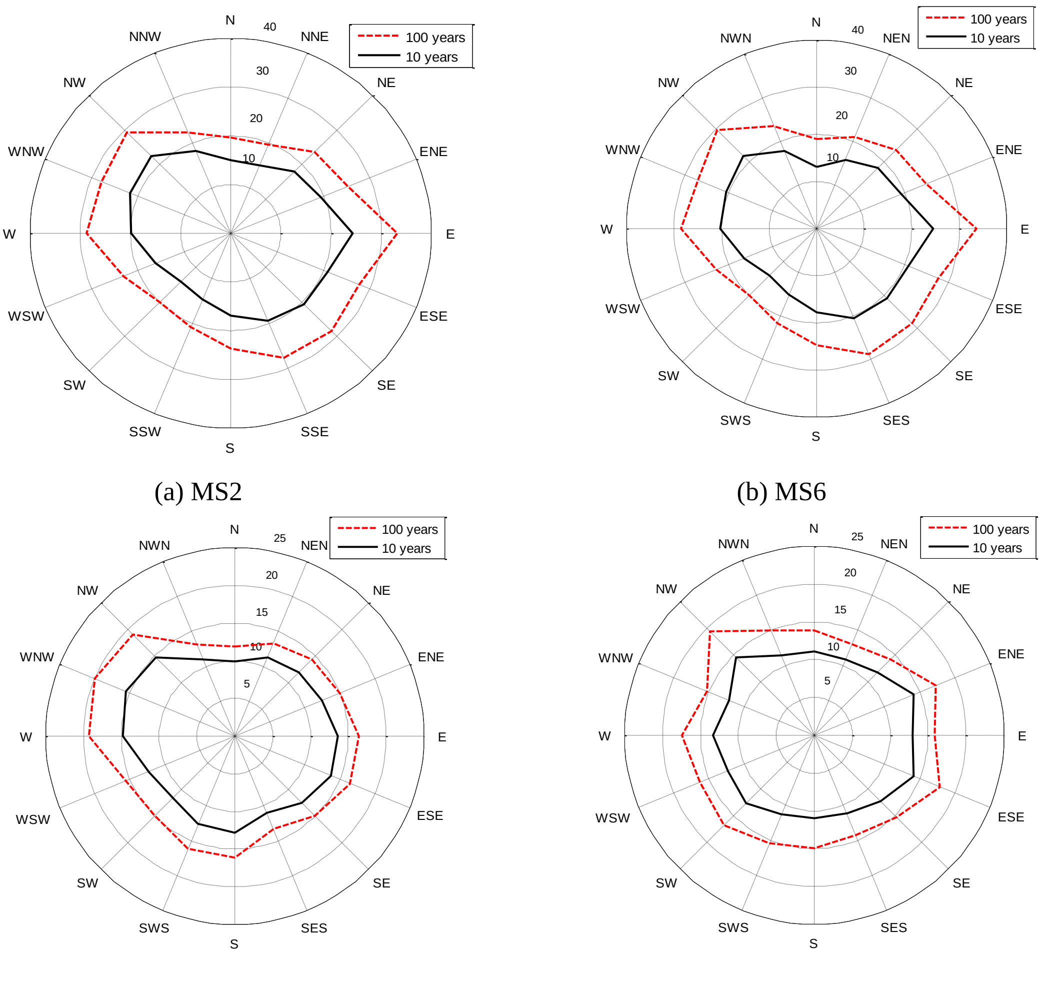
Table 5 Results of parameter estimation of MS4'

Wind direction	$f(\theta)$	Frechet Distribution		Gumbel Distribution		Weibull Distribution	
		a	γ	a	b	a	γ
N	0.03937	3.99147	2.81316	2.12993	4.84309	7.16616	2.53432
NNE	0.06693	3.88993	3.07016	1.62660	4.84614	6.75014	2.71369
NE	0.07987	3.87064	3.17908	1.83132	4.75366	6.82578	2.44688
ENE	0.08436	4.25442	2.60124	2.54758	5.21764	7.82455	2.27775
E	0.08212	3.99342	3.01288	2.17543	4.84408	7.25530	2.32246
ESE	0.08099	4.01326	2.24399	2.66274	4.88442	7.30155	2.01684
SE	0.07593	3.91325	2.36117	2.21264	4.77794	6.90374	2.23937
SSE	0.06805	3.47028	2.95013	2.04637	3.97453	6.02923	2.06763
S	0.06356	3.07140	2.80812	2.09477	3.35944	5.04160	1.62721
SSW	0.05399	3.08767	1.99846	2.34683	3.54603	5.46839	1.67331
SW	0.05624	3.53958	2.26142	2.64304	4.13275	6.43699	1.82168
WSW	0.05399	3.54892	2.44076	2.45040	4.14604	6.30060	1.82324
W	0.05512	3.97170	2.59215	2.49962	4.85623	7.16168	1.95313
WNW	0.05568	3.95844	2.82274	2.01464	4.95656	7.01391	2.24441
NW	0.04837	4.15035	2.41982	2.96313	5.03547	7.70391	1.86170
NNW	0.03543	3.88064	2.45855	1.96566	4.90412	6.84350	2.11503

where Z_1 and Z_2 are heights above ground; V_{z_1} and V_{z_2} are corresponding wind velocities; α is an exponent dependent upon roughness of terrain and is taken as 0.12 in this study. The calculated design basic wind speeds on the deck center and the top of towers are 38.06 m/s and 44.93 m/s, respectively. As indicated in the results of this study, the basic wind speeds considering or neglecting the effects of wind direction are both smaller than the design basic wind speed in specification. This suggests a conservative safety coefficient used in the design of SCB. As a result, the safety coefficient can be improved by considering the influence of wind direction, and then a more reasonable basic wind speed in wind-resistance design of SCB can be obtained. It should be noted that the predicted basic wind speed (especially in the case of 100-year recurrence interval) is just for reference due to the limited monitored data. The results presented in this study remains to be further improved by long-term monitoring data from SHMS of SCB in the future.

Table 6 Calculated basic wind speed in various directions based on Weibull distribution

Wind direction	MS2 (m/s)		MS6 (m/s)		MS4 (m/s)		MS4' (m/s)	
	10 years	100years	10years	100years	10years	100years	10years	100years
N	14.92699	19.69776	13.18994	19.08432	9.92241	11.85388	11.15674	13.91311
NNE	15.14800	19.68337	15.75308	21.06658	11.25811	13.37342	10.82347	12.98605
NE	17.97711	23.77777	18.17888	23.53932	11.96175	14.37102	11.75081	14.27372
ENE	19.47008	25.26762	19.15466	24.94204	12.41004	14.98743	14.11363	17.35181
E	24.37712	33.14402	24.49155	33.57305	13.62111	16.34223	12.89968	15.81451
ESE	20.85280	27.69522	20.76432	27.62292	13.75843	16.46084	14.13931	17.88987
SE	20.75593	28.36903	20.98737	28.49801	12.52753	15.04525	12.42360	15.40058
SSE	19.48034	27.61722	20.71319	28.79852	11.07440	13.35351	11.22943	14.24983
S	16.91784	23.64620	17.75484	24.70962	12.77375	16.06978	10.98178	14.93198
SSW	14.67625	20.79217	15.20360	21.82189	12.63929	16.11295	11.33561	15.45553
SW	14.17214	20.03663	14.01085	20.02634	11.53642	14.89867	12.65731	16.78274
WSW	16.25984	23.07776	16.37090	22.78086	12.31278	15.56694	12.30082	16.34939
W	19.92706	28.77885	20.23763	28.49771	14.77043	19.30095	13.41513	17.47429
WNW	21.64388	27.90064	20.60175	27.01589	15.58527	20.05984	12.12662	15.25502
NW	22.31890	29.20908	21.68975	29.49289	14.82113	18.97882	14.57332	19.39643
NNW	18.27754	22.40946	17.85695	23.55072	11.07999	13.20257	11.44122	15.01313
Omni-direction	27.61892	34.89751	26.62877	31.52952	16.61961	19.06138	16.62942	19.36459



(d) MS4'

Fig. 7 Wind rose charts of the basic wind speed of 10-year and 100-year recurrence intervals

4. Conclusions

Using the wind data monitored by Structural Health Monitoring System of Sutong Cable-stayed Bridge, the analysis on joint distribution of wind speed and direction at the bridge site is conducted. The basic wind speed in each direction is predicted based on the probability theory. The results suggest the following conclusions:

(1) Based on the calculated correlation coefficient r of the Probability Plot Correlation Coefficient (PPCC) method, Weibull joint probability distribution model provides a better approximation to the joint distribution function of wind speed and direction at the bridge site than the other two models.

(2) In both cases of 10-year and 100-year recurrence intervals, basic wind speeds on top of the

towers are larger than those of the main deck center, which mainly relates to the wind velocity profile in the atmospheric boundary layer. In the four positions, basic wind speeds in 100-year recurrence interval is larger than those of 10-year case, which agrees with the concept of exceedance probability.

(3) When the influence of the wind direction is considered, a more reasonable basic wind speed which is a little smaller than that from the current specification is obtained. Similar conclusion has been suggested by Simiu and Filliben (1981). Therefore, consideration of the effects of wind direction on the estimates of basic wind speed can reasonably reduce the safety coefficient of traditional methods, and benefit the economic design of the wind-resistant structures.

(4) The main strong winds at SCB site are southeast wind and northwest wind. This correlates with the climatological condition at the bridge site, especially the typhoon climate from eastern ocean in summer and the north wind from Siberia in the northwest of China in winter.

(5) Predicted basic wind speed considering the effects of wind direction or not is smaller than the design basic wind speed in Specification of China, which indicates high safety in the design of SCB. But in a contrary point, too large safety coefficient always leads to uneconomical design. So conducting a refinement research on joint distribution of wind speed and direction seems more reasonable and valuable.

These observations suggest the effectiveness and reliability of the monitored data in the estimates of the basic wind speed. However, it should be noted that the collected wind data from SHMS of SCB is very limited (4 years) due to its short operation time. As more and more monitored data acquired from SHMS in the future, analysis of the joint distribution of wind speed and direction at the bridge site can be further improved.

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