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State-of-the-art review on typhoon wind environments and their effects on long-span bridges

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ABSTRACT

After more than 40 years of economic reforms, the Chinese economy has rapidly developed, and large populations and wealth have been concentrated around the southeastern Chinese coastline where, unfortunately, typhoons frequently occur. Many long-span bridges are potentially threatened by wind hazards. Owing to special spiral wind fields and mesoscale localized strong wind features, typhoon-induced wind has created several new challenges when analyzing wind engineering for long-span bridges. This paper reviews the state-of-the-art research on the typhoon wind field characteristics and typhoon-induced structural responses of long-span bridges, including the following four aspects. First, typhoon hazard simulation techniques, including full-track methods and typhoon wind field models, are outlined in chronological order. Second, typhoon turbulence characteristics, including nonstationarity, non-Gaussian forces, strong turbulence intensity and nonsynoptic spectra, are presented. Third, advanced actively controlled multiple-fan and airfoil cascade wind tunnels and computational fluid dynamics are employed to simulate a typhoon field. Fourth, typhoon wind-induced long-span bridge buffeting analysis methods for considering nonstationary and non-Gaussian features are introduced. Finally, several prospective research areas concerning the wind-induced performance of long-span bridges under typhoon climatic conditions are proposed.

1. Introduction

Bridges are key nodes and hubs of transportation networks and play important roles in promoting urban development, the construction of modern industrial systems, and urban planning. However, China's long coastline is located on the northwest Pacific coast, and the frequent occurrence of destructive typhoons every year threatens economic and social development and public safety and property. This has become a major social problem in China and around the world (Zhao, 2022). Many studies have shown that typhoons are natural disasters that cause the most human casualties and the greatest property losses. Typhoon means mesoscale tropical cyclones, and it has different names for South Pacific (cyclone) and Atlantic, East Pacific (hurricane). (For this review, typhoon is used thoroughly.) With global warming, both the frequency and intensity of typhoons are increasing (Emanuel, 2005; Knutson et al., 2010). Moreover, most of China's economic center of activity is located in eastern coastal areas along the northwest Pacific Ocean, where typhoons occur most frequently. Many superlarge cross-sea bridges, such as the Hong Kong-Zhuhai-Macao Bridge, Xihoumen Bridge and Nansha Bridge, face the threat of typhoons landfall.

In 1940, the old Tacoma Bridge collapsed due to severe wind-induced vibration under strong winds of less than 20 m/s, thus initiating the discipline of wind engineering (Xiang and Ge, 2007). After over 80 years of development, structural wind engineering has become an interdisciplinary field encompassing structural engineering, fluid mechanics, stochastic vibration, meteorological science, and mathematical statistics (Simiu and Scanlan, 1996). The Davenport wind load chain (Nicholas, 2012), which includes the wind climate, wind environment, wind load, and wind-induced response, forms the modern wind engineering framework. However, most existing wind resistance theories

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and experimental methods are based on the conventional monsoon climate, which is easily observed and occurs with high frequency. Monsoon is large-scale meteorological phenomenon with a long duration, large influence range, obvious seasonal characteristics, and high occurrence frequency. An large wind climate observation database has been formed, and well-established wind tunnel tests, theoretical analyses and numerical simulation methods have been widely employed successively to ensure the safety and reliability of bridge engineering structures against wind.

However, typhoon is mesoscale cyclonic wind phenomenon that originates in the tropical ocean, moves across the ocean, and eventually lands in coastal areas, accompanied by heavy rainfall, storm surges and flood disasters (Duan et al., 2012; He et al., 2020a). Compared with that of monsoons, the occurrence frequency of typhoons is low, but the intensity is high, and disasters caused by wind are significant. After long-term and long-distance stable development, the wind field structure is relatively stable. Typhoon is mesoscale spiral wind field that is constantly changing with the evolution of typhoon intensity, and the wind field structure is unstable, with obvious nonstationarity (Wang et al., 2016; Huang et al., 2016), non-Gaussian force (Zhao et al., 2019a) and greater turbulence intensity (Pan et al., 2016a; Song et al., 2010). Traditional wind tunnel test techniques and theoretical analysis methods cannot fully reflect typhoon characteristics, which also have obvious regional characteristics, and typhoon observation data in different regions are difficult to collect (Li et al., 2015a). Therefore, the existing methods may underestimate the disaster impact of typhoons on bridge structures, which may lead to wind safety hazards in bridges in coastal typhoon areas.

In recent years, scholars have conducted extensive research on typhoon disaster simulations, typhoon wind field characteristics, wind tunnel test techniques, and wind-induced response analyses, achieving productive results. This paper reviews the research progress on the wind resistance performance of long-span bridges under typhoon conditions.

2. Simulation and prediction of wind speed

In the current wind-resistance standard, the prediction of extreme wind speed is mostly derived from meteorological wind speed measuring stations, and a large amount of monsoon data every year ensures the accuracy of extreme wind speed data. However, owing to the scarcity of typhoon data, solely using historical data cannot reliably predict extreme wind speeds, so it is necessary to carry out typhoon numerical simulations to generate typhoon wind speed samples manually.

2.1. Track and intensity simulation

The earliest simulation method of typhoon path and intensity was the single-point simulation method established by Russell (1969). This method first summarized the probability distribution model of key parameters such as the typhoon generation rate, location, central pressure difference, maximum wind speed radius and typhoon moving speed. The Monte Carlo method was used to simulate and generate many typhoon disaster samples, thereby obtaining typhoon disaster data for this area (Russell, 1971). Since then, many scholars have researched this model. In 1980, Batts et al. (1980) took the lead in applying this method to the entire eastern coastline and Gulf coast of the United States. In 1983, Georgiou discussed the problem of calculating a designed wind speed via a mathematical model (Georgiou et al., 1983), advocated a comprehensive consideration of the occurrence of tropical cyclones from the two aspects of time and space, and improved the probability distribution function of several parameters in the probability model. In 1995, Vickery and Twisdale (1995) studied a local path simulation model of a tropical cyclone after landfall by using newly collected data and predicted the designed wind speed on the basis of a new model. In China, Ou et al. (2002) used tropical cyclone data from the northwest Pacific to carry out a designed wind speed analysis of important coastal cities in 2002.

Zhao et al. (2005a,b, 2007) established a Monte Carlo method using parametric perturbation. First, a sensitivity analysis of the wind field parameters was carried out, and numerous random tropical cyclone paths were obtained by using historically measured tropical cyclone paths and disturbance center positioning parameters. Table 1 lists the typhoon parameters probability distribution model of the single-point simulation method suggested by different models.

The single-point simulation method was widely used in the late 20th century when computing power was relatively weak, but its obvious disadvantage was that it could not obtain a reliable probability distribution model of typhoon parameters for middle and high latitudes with less typhoon data, so it was gradually replaced by a more reasonable full-path model.

In 2000, Vickery et al. (2000) proposed a full-path simulation method, which abandoned single-point simulation that focused solely on the deficiencies of local areas and instead focused on the evolution of typhoons in the entire ocean, simulating the whole life process of typhoon generation, development and decay. The full path simulation method can be summarized in three steps: 1) define the initial position and initial intensity; 2) iteratively simulate typhoon movement and intensity change; and 3) determine landing or attenuation at sea. The simulation of typhoon movement and intensity is the core strategy of this method.

$$\Delta \ln c_{i+1} = a_1 + a_2\psi + a_3\lambda + a_4 \ln c_i + a_5\theta_i + \epsilon_c \tag{1}$$

$$\Delta\theta_{i+1} = b_1 + b_2\psi + b_3\lambda + b_4 c_i + b_5\theta_i + b_6\theta_{i-1} + \epsilon_\theta \tag{2}$$

$$\ln I_{i+1} = c_0 + c_1 \ln I_i + c_2 \ln I_{i-1} + c_3 \ln I_{i-2} + c_4 T_s + c_5 \Delta T_s + \epsilon_I \tag{3}$$

where c represents the moving speed, θ represents the moving direction, ψ represents latitude, λ represents longitude, I represents the relative intensity depending on the central pressure difference Δp, T represents the sea surface Kelvin temperature, ϵ represents random error terms, and a_1 to a_5, b_1 to b_6, and c_0 to c_5 are model constants based on the geographical location of the typhoon. This is generally obtained according to the regression of typhoon historical data. ϵ_c, ϵ_θ, and ϵ_I are the residual items and are used for stochastic simulation in the typhoon model. Vickery only considered the influence of sea surface temperature in the initial model but accounted for the influence of wind shear parameters on typhoon intensity in subsequent studies (Vickery et al., 2009b,a).

The parameters of the model generally divide the whole ocean region into a $5^\circ \times 5^\circ$ grid and carry out multiparameter linear regression

Table 1
Probability distribution of typhoon simulation parameters from different models.

Model	Batts et al. (1980)	Georgiou et al. (1983)	Vickery and Twisdale (1995)	Ou et al. (2002)
Generation time		Poisson		
Generation ratio	Poisson		Poisson	Poisson
Generation location		Polynomial + Von Mises	Uniform + Normal	Empirical distribution + Normal
Central pressure difference	Lognormal	Weibull	Weibull	Lognormal
Maximum wind radius	Lognormal	Lognormal	Lognormal	Lognormal
Moving speed	Normal	Lognormal	Lognormal	Lognormal

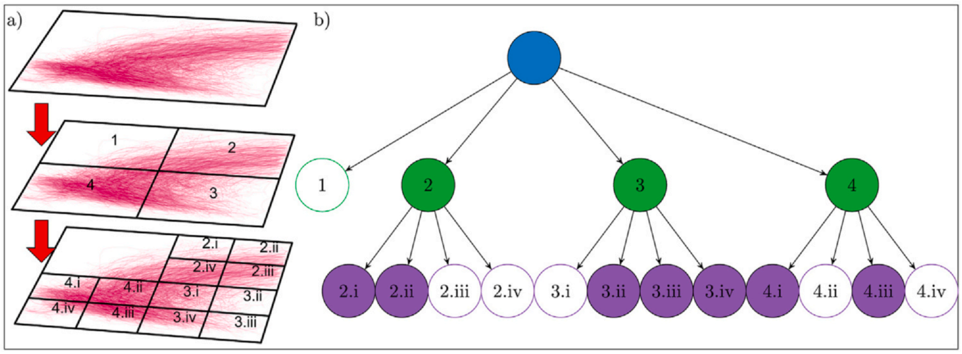


Fig. 1. Schematic visualization of quadtree segmentation (Cui et al., 2021b).

for the historical data of eastward and westward typhoons. Owing to the very uneven distribution of typhoon data over the ocean (Cui and Caracoglia, 2019), there are insufficient typhoon data for statistical regression in many ocean blocks. Cui et al. (2021b) proposed the quadtree method, as shown in Fig. 1, to carry out an adaptive dynamic division of ocean areas and determine typhoon simulation parameters via Bayesian optimization. Fang et al. (2021a) developed a geographically weighted regression method to simulate typhoon disasters in the Northwest Pacific Ocean.

As soon as the full-path simulation method was proposed, it was widely accepted, and different scholars carried out substantial studies on this model. For example, Powell et al. (2005) and Emanuel et al. (2006) proposed a similar Markov chain model, which makes the next state of a typhoon depend on the state of the previous step. Cui and Caracoglia (2018) proposed a typhoon track model based on random Brownian motion and an intensity model of the autoregressive process. Chen and Duan (2018b) established an improved typhoon track model considering historical air flow data at different pressure heights. Li and Hong (2015) and James and Mason (2005) simplified the Vickery typhoon track model from different perspectives. To make the typhoon data more evenly distributed on the ocean surface, Hall and Jewson (2007) improved the typhoon generation method by using the kernel function probability model instead of the random extraction of historical data in the original model. The full-path simulation method proposed by Vickery has been widely used in recent years to simulate the impact of global warming on typhoon disasters in the Atlantic (Mudd et al., 2014b,a; Cui and Caracoglia, 2016) and Northwest Pacific (Chen et al., 2021; Chu et al., 2021) owing to its simple mathematical model reflecting the impact of key meteorological parameters. The influences of El Niño (Chen and Duan, 2018a) and ocean feedback (Shen and Wei, 2021) on typhoon disasters were also analyzed.

The intensity attenuation model after typhoon landfall is very important for analyzing the impact of typhoons on inland disasters. At present, Vickery's exponential filling model is widely accepted:

$$\Delta p(t) = \Delta p_0 \exp(-at) \tag{4}$$

where Δp_0 is the central pressure difference and a is the decaying rate, which is generally believed to be related to typhoon intensity and should be determined according to historical typhoon data (Zhao et al., 2024).

Recently, a physical model of tropical cyclone central pressure filling at landfall was proposed in Sparks and Toumi (2022), whose pressure decaying formula is

$$\Delta p(t) = \Delta p_0 [1 + (k - 1)at]^{1/(1-k)} \tag{5}$$

where a is the decaying rate and k is the pressure distribution factor. When $k = 2$, Eq. (5) can be reduced to Eq. (4).

2.2. *Wind field simulation*

The wind field model, which translates the typhoon intensity into the wind speed field, is a key part of typhoon risk assessment. In the horizontal direction, the wind field structure can be roughly divided into the eye area, the wall area and the peripheral diffusion area. The air flow is almost stationary at the eye area, rapidly increases to the maximum value in the wind wall, and then gradually decreases along the peripheral diffusion area. On the other hand, the pressure drop Δp is lowest at the eye and gradually increases along the periphery. The typhoon structure diagram is shown in Fig. 2.

In the early typhoon wind field model, the two-dimensional height-average model was generally used to average the moment of inertia of the flow along the height, assuming that the gradient wind height remains unchanged. The earliest two-dimensional typhoon wind field was proposed by Batts et al. (Batts et al., 1980). Taking typhoon wind speed as the superposition of rotational wind speed and translational wind

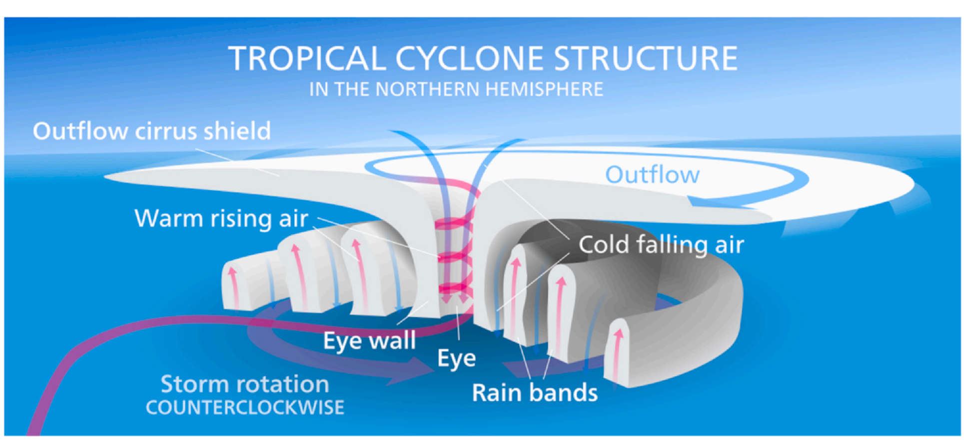


Fig. 2. Conceptual plot of the typhoon structure (Kelvinsong, 2012).

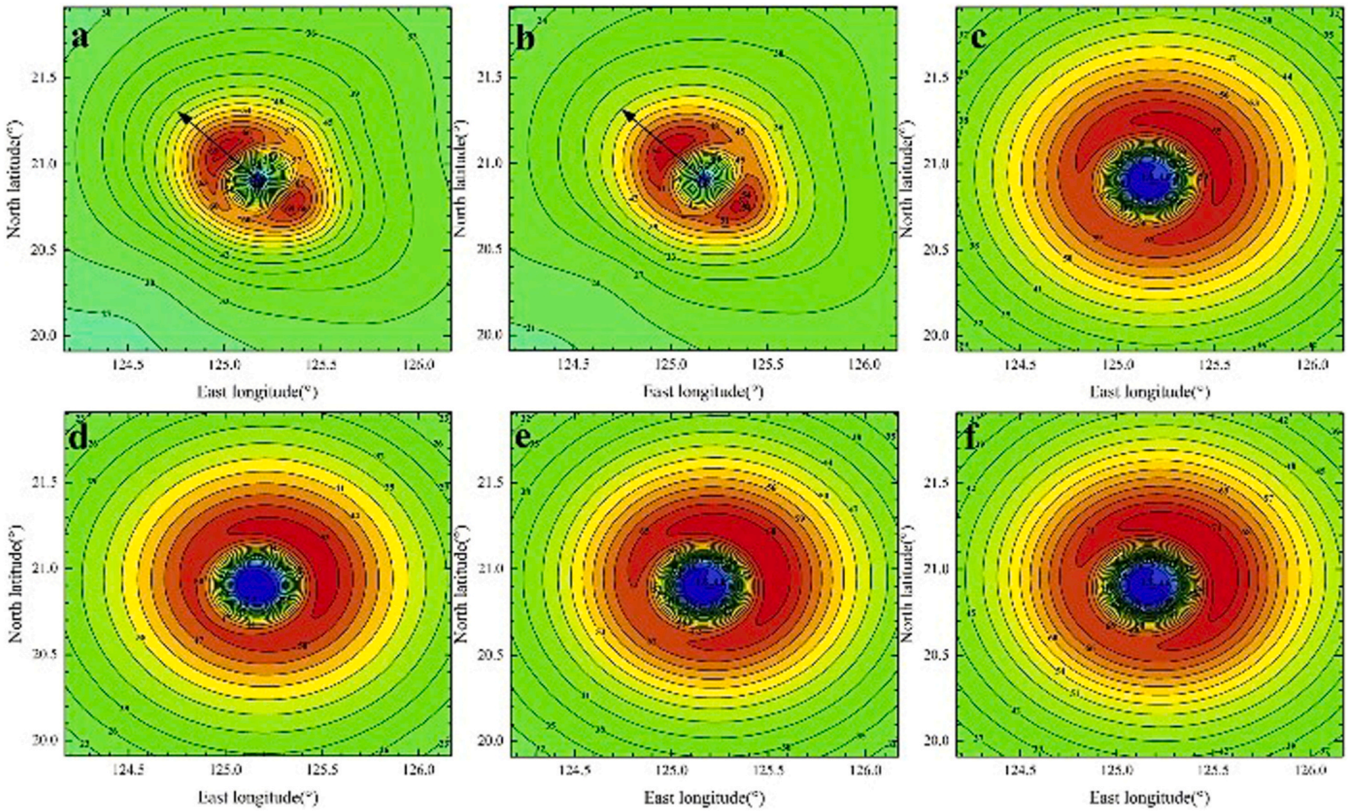


Fig. 3. Comparison of the wind field of Typhoon Jangmi0815 with simulated wind fields (Fang et al., 2018a).

speed, the analytical expression of the wind speed field at gradient wind height can be obtained as follows:

$$V_g = \frac{1}{2}(c\sin\alpha - fr) + \sqrt{\frac{1}{4}(c\sin\alpha - fr)^2 + \frac{100B\Delta p}{\rho}\left(\frac{R_{\max}}{r}\right)^B \exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right]} \tag{6}$$

where c is the moving speed, α is the angle between the azimuth angle and the moving direction, r is the distance to the typhoon center, $R_{\max}$ is the maximum wind space radius, and B is the pressure field shape parameter. Among them, $R_{\max}$ and B are the two most important typhoon wind field parameters, which are generally related to the typhoon center pressure difference and latitude. Different scholars have presented various expressions of $R_{\max}$ and B, such as Batts et al. (1980) and Vickery and Twisdale (1995), on the basis of different regions and typhoon records. In 2009, Vickery et al. (2009b) proposed a new B parameter expression, which greatly improved simulation accuracy. In 2013, Zhao et al. (2013) presented $R_{\max}$ and B expressions applicable to the Northwest Pacific coastal area on the basis of the meteorological data of typhoons in China.

In recent years, with improvements in computing resources, three-dimensional (3D) wind field models have gradually become mainstream. To solve the 3D wind speed field, Meng et al. (1995) and Kepert (2001); Kepert and Wang (2001) first proposed that the Navier-Stokes equation can be directly used in polar coordinates to solve the 3D momentum conservation equation. Fang et al. (2018a) proposed a probabilistic coupling model of the air pressure field and wind speed field, clearly indicating that eddy viscosity affects the velocity field by changing the air pressure field, and introduced a wind pressure field, drag coefficient and humidity correction factor dependent on the height term. Therefore, a barometric field model (Fang et al., 2018b) and an iterative model (Fang et al., 2021b) of typhoon wind field parameters with typhoon tracks for the southeastern coast of China were proposed and verified with the measured wind field (Fig. 3).

Hong et al. (2019) proposed a fast numerical algorithm to determine a (3D) typhoon field via the finite difference method. Wu and Huang (2019) incorporated the correlation between gradient wind and surface wind into a (3D) typhoon field. He et al. (2019) verified the variation law of various meteorological elements along the altitude direction in a 3D typhoon field by using sounding balloon meteorological data. Snaiki and Wu (2020) reported that vertical convection contributed to the momentum of typhoon flow in the supergradient region, thus affecting the wind speed distribution outside the typhoon. Yang et al. (2021) proposed that the influences of vertical convection and vertical diffusion on the typhoon wind field should be considered simultaneously. In general, with the development of computer technology and meteorological observations, 3D typhoon models can increasingly accurately reflect the dynamic role of meteorological elements in the evolution of typhoon wind fields, which greatly improves the accuracy of such models.

2.3. Extreme wind speed calculation

After the typhoon wind speed is calculated via the typhoon path-intensity model and the typhoon wind field model, the designed wind speed of different recurrence periods should be calculated via the probabilistic extreme value model. In the traditional method, the annual extreme wind speed is fitted by the probabilistic model through the independent identically distributed hypothesis, and the extreme wind speed in different recurrence periods is obtained. However, for areas affected by typhoons (Fig. 4), the extreme wind speed contains at least two meteorological characteristics-monsoon and typhoon-at the same time, which does not meet the same distribution assumption. Therefore, it is necessary to develop a mixed climate extreme wind speed algorithm that includes multiple meteorological models. In 2003,

Fig. 4. Multiple wind climate categories (Cui et al., 2021a).

Ge et al. (2003) took the lead in using a typhoon numerical model and predicted extreme wind speeds via the transboundary peak method and independent storm method. Cui et al. (2021a) used machine learning models to establish intelligent classification algorithms for wind disasters by integrating multiple meteorological elements, increasing the efficiency of extreme wind speed prediction in mixed climates. Lombardo et al. (2009) used high-resolution meteorological records from the United States to establish an automatic classification algorithm for wind and climate, and then Chen and Lombardo (2020) established an intelligent classification algorithm for wind and climate through one-dimensional convolutional neural networks. Moreover, the classification method of wind disasters should be changed according to the climatic characteristics of different regions, such as the Mediterranean coast (De Gaetano et al., 2014) and South America (Vallis et al., 2019). Ma et al. (2022) established a calculation method of time-varying extreme wind speed by using a mixed climate model, noting that the dynamic characteristics and wind resistance performance of long-span suspension bridges gradually change with the erection process of main beams during the construction period, which reduces the demand for the wind resistance performance of bridge structures during the construction period, speeds up the construction period and reduces the construction cost.

3. Special wind environment characteristics of typhoons

Existing wind resistance analysis methods handle monsoon wind fields well, but typhoons, as mesoscale spiral wind fields, have unique characteristics in terms of average and fluctuating winds. Recent advances in observational technology, such as weather balloons, Doppler radar, and ultrasonic anemometers, have improved the understanding of typhoon wind characteristics. Especially for near the typhoon wall, the wind properties differs greatly comparing with monsoon, but, for outer regions far away from typhoon center, which are mainly governed by exposure/terrain conditions.

3.1. Average wind characteristics

3.1.1. Unique wind profiles

Early studies described typhoon profiles via traditional power functions because of the limited observation heights. Numerous records have shown that typhoon profile exponents are greater than those of monsoons (Xiang and Ge, 2007). However, for different typhoons or at different times of the same typhoon, the power law exponent of the wind profile shows significant variability (Zhao et al., 2016). With the development of high-altitude detection equipment in later stages, the increase in the power law exponent of typhoon wind profiles has been attributed to the "low-level jet" phenomenon. Powell et al. (2003) observed average wind profiles of multiple typhoons via high-altitude released radiosondes, confirming that the gradient wind associated with the "low-level jet" is concentrated at heights of approximately 500–600 m, as shown in Fig. 5. Shu et al. (2018) indicated through Doppler wind radar at the Hong Kong Observatory that the gradient wind associated with a low-level jet can reach as low as 200 m. Li et al. (2019) observed ultralow-level jets below 100 m in the eyewall region of landfalling typhoons. Zhao et al. (2019b) characterized the low-level jet features around Typhoon Mangkhut's periphery via Doppler wind radar (Fig. 6) and proposed empirical profile formulas. Vickery et al. (2009b) integrated the low-level jet phenomenon with traditional power law formulas and proposed an improved wind profile design formula suitable for engineering applications.

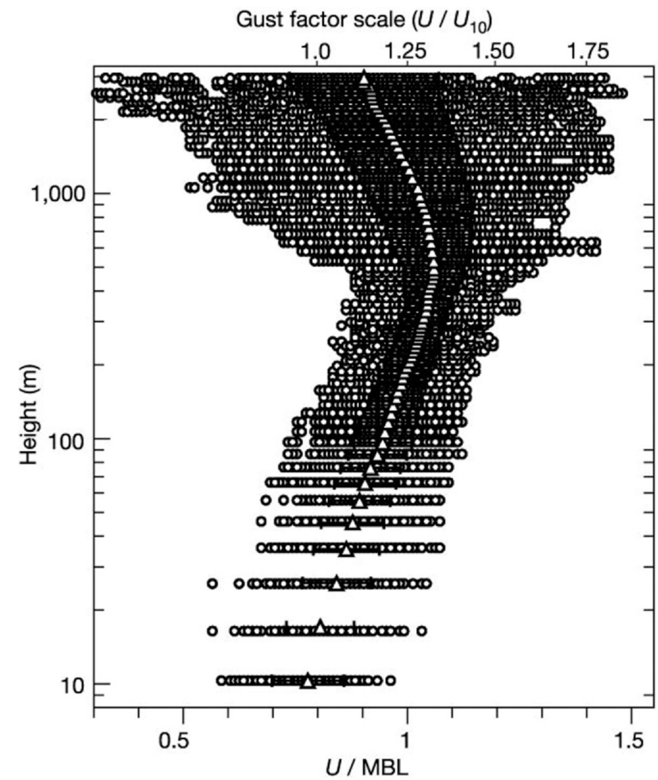


Fig. 5. Low-level jet features in typhoon wind profiles in Powell et al. (2003) (U means individual wind speeds measurements and MBL means their averaged values).

3.1.2. Nonstationary average wind characteristics

Typhoons exhibit distinctive characteristics not only at spatial scales but also at temporal scales owing to their movement and varying intensity. Chen and Xu (2004), on the basis of high-altitude typhoon observation data, proposed an analysis method for nonstationary wind speeds via empirical mode decomposition. They compared stationary

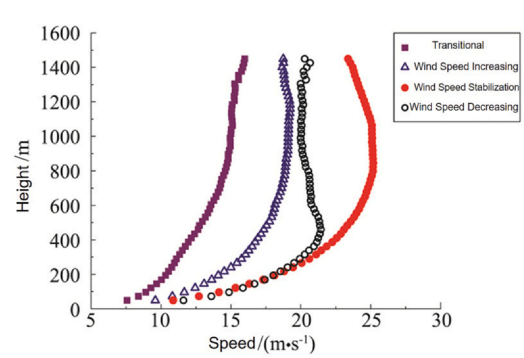


Fig. 6. Average vertical wind profiles for each phase (Zhao et al., 2019b).

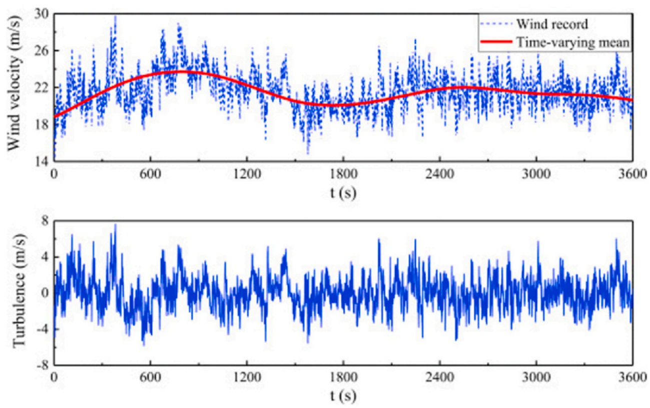


Fig. 7. Nonstationary wind record and nonstationary turbulence (Tao and Wang, 2019).

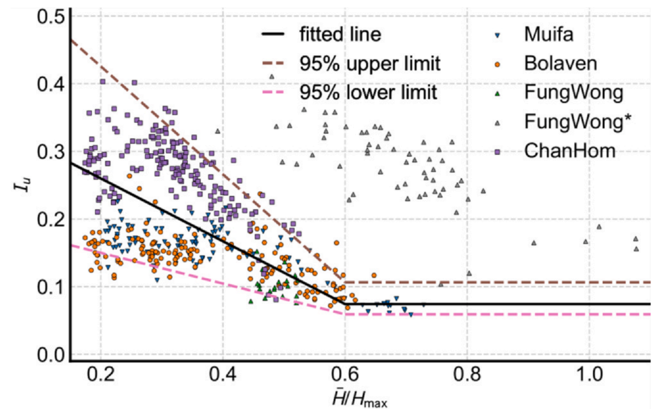


Fig. 8. Relationship between the turbulence intensity and normalized wind speed in the tangential direction (Zhao et al., 2019a) ($\bar{H}/H_{max}$ means wind speeds at the measurement location normalized with respect to the maximum wind speeds near typhoon center).

and nonstationary methods for wind field simulation, highlighting that nonstationary methods can more accurately simulate long-duration typhoon wind fields. In recent years, with the widespread application of structural health monitoring equipment, typhoons passing through multiple large-span bridge construction sites have been captured (Wang et al., 2016). Cai et al. (2022) proposed on optimal time-varying mean wind speed to simulate the nonstationary typhoon wind field.

In addition to horizontal wind speeds, another significant characteristic that distinguishes typhoons from traditional monsoons is the pronounced large angle of attack effect caused by strong upward vertical airflow near the typhoon center. Zhao, on the basis of observations during the landfall of Typhoon Hagupits (0814), documented significant large angle of attack characteristics near the eyewall of the typhoon, emphasizing the substantial impact of typhoons on the wind safety of large-span bridges (Zhao et al., 2021).

3.2. Turbulence characteristics of typhoons

In recent years, the widespread use of high-frequency wind speed observation devices, such as the Shenzhen Meteorological Gradient Observation Tower (Chen et al., 2022) and structural health monitoring systems (He et al., 2017,2020b) extensively installed on large-span bridges, has advanced research on the turbulent characteristics induced by typhoons.

3.2.1. Nonstationary turbulence characteristics

Owing to the correlation between turbulence and mean wind, the nonstationary characteristics of typhoon turbulence under long-term moment conditions have received significant attention. Huang and Gu utilized autoregressive moving average methods to describe the nonstationary features of typhoon turbulence (Huang and Gu, 2019). They subsequently analyzed the time-varying spectra and coherence of Typhoon Hato via the S-transform (Huang et al., 2020). Tao and Wang focused on the increased energy in a high-frequency inertial subrange and conducted an analysis via evolutionary spectra (Tao and Wang, 2019). They further performed a nonstationary spectral analysis of turbulence correlations in the along-wind and crosswind directions within typhoon wind fields (Tao et al., 2020b). Fig. 7.

However, simulating nonstationary turbulent fields with time-varying spectral characteristics requires simultaneous calculations in both the time and frequency domains. Therefore, many scholars have proposed various fast simulation methods. Huang (2014) developed a multidimensional nonstationary wind field simulation technique that combines wavelet transform and spectral methods. Wang et al. (2019) used nonnegative matrix factorization to simulate nonstationary turbulent fields induced by typhoons. Tao et al. (2021) developed a rapid simulation technique based on reduced-order 2D Hermite interpolation. Huang et al. (2021) developed a conditional simulation method based on time-varying autocorrelation functions. Jiang et al. (2022) accelerated matrix decomposition calculations in nonstationary wind fields via interpolation methods.

3.2.2. Turbulence statistical characteristics

In addition to the nonstationary characteristics of typhoon turbulence, various statistical features of turbulence, including the turbulence intensity, integral scale, spectral parameters, extreme value factors, and non-Gaussian characteristics (Pan et al., 2016b), also significantly differentiate typhoons from traditional monsoons. Cao et al. (2009), on the basis of data from an ultrasonic anemometer on Miyakojima Island during the passage of Typhoon Meranti (0314), obtained comprehensive typhoon data and first reported multiple turbulence statistical features of typhoons. Li et al. (2015a) compared the turbulence characteristics between Pacific typhoons and Atlantic hurricanes. Many studies have focused on the turbulence characteristics of various typhoons, including Typhoon Mangkhut (He et al., 2020a), Typhoon Parrot (Song et al., 2010), Typhoon Bailu (Dai et al., 2021), Typhoon York (Mao et al., 2021), and Typhoon Chan-hom (Huang et al., 2018). The statistical regularities of typhoon turbulence characteristics can be roughly summarized into three points: .

1. Typhoon turbulence intensity and the integral scale exceed those of monsoons (Sharma and Richards, 1999).
2. The spectral characteristics of typhoons differ significantly from those of benign monsoons, with higher low-frequency energy resulting from typhoon turbulence (Schroeder et al., 2009). In the high-frequency inertial subrange, the energy decrease trend does not satisfy the Kolmogorov frozen turbulence hypothesis, exhibiting a decay rate steeper than $-5/3$ (Xu and Zhan, 2001).
3. Typhoon turbulence exhibits non-Gaussian high-order moments but lacks regularity (Cao et al., 2009; Li et al., 2015a).

The studies on typhoon turbulence characteristics mentioned above were conducted at single locations for individual typhoons. While typhoon turbulence features exhibit similar trends, the diversity in size and intensity results in a varied manifestation of typhoon characteristics, making it challenging to generalize regular patterns in typhoon turbulence features.

Zhao et al. (2019a), by summarizing four typhoon records passing through the Xihoumen Bridge, studied the variation patterns of typhoon turbulence characteristics within the wind field structure. They introduced two indicators, normalized distance and normalized wind speed, and analyzed the relationship between typhoon turbulence intensity in the along-wind direction and normalized wind speed, as shown in Fig. 8.

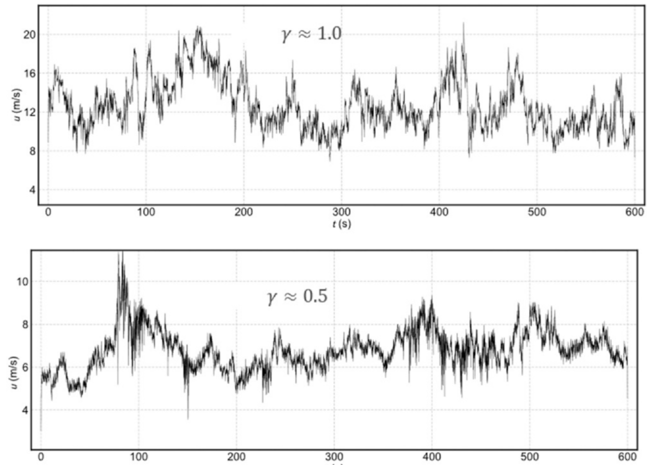


Fig. 9. Typhoon turbulence sample with a skewness of 1 (Zhao et al., 2019a).

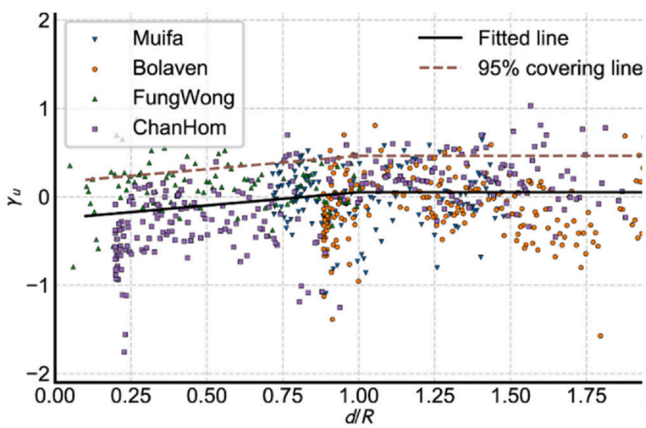


Fig. 10. Relationship between the turbulence skewness and normalized distance in the along-wind direction (Zhao et al., 2019a).

The study also highlighted that typhoon turbulence exhibits significant non-Gaussian characteristics. As shown in Fig. 9, the short-duration high-speed gusts caused by positively skewed turbulence have a nonnegligible effect on structures (Lei et al., 2024). Fig. 10 illustrates the relationship between the along-wind turbulence skewness and the normalized distance. Although most turbulence skewness values are near zero, some turbulence segments have skewness values greater than 0.5, and some even approach 1.

3.2.3. Turbulence spectrum characteristics

Owing to the spiral of a typhoon's wind field, airflow cannot form stable structures as it does in linear wind fields. Numerous typhoon observation records report that typhoon turbulence results in significantly greater low-frequency energy than monsoon turbulence does. Sharma and Richards noted that the instability of airflow causes this pronounced low-frequency energy (Sharma and Richards, 1999). Zhao et al. (2019a) proposed a two-parameter model specifically addressing the low-frequency characteristics of typhoon turbulence. Fig. 11, 12.

In the eyewall region, owing to the influence of complex flow structures such as roll vortices, the inertial subrange of the turbulence spectrum does not satisfy the Kolmogorov frozen turbulence hypothesis. Li et al. (2015b) provided a theoretical framework for the spectral characteristics of the high-frequency inertial subrange on the basis of measured typhoon data.

In summary, the instability characteristics caused by various spiral airflow structures in the typhoon wind field result in the average wind

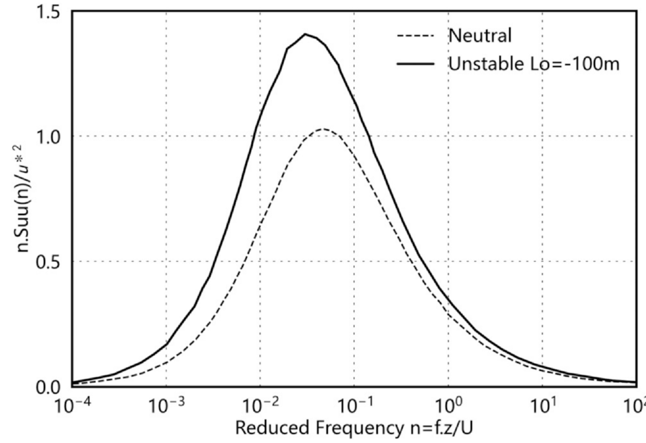


Fig. 11. Turbulence spectra of the wind under neutral and unstable atmospheric conditions (Sharma and Richards, 1999).

and turbulence exhibiting nonstationary, non-Gaussian, strong turbulence, and large angle of attack characteristics. These factors pose new challenges to the safety of wind-resistant structures.

4. Wind tunnel test and numerical simulation of nonsynoptic wind environments

The traditional ABL wind tunnel was developed on the basis of linear monsoon characteristics and uses rough elements and wedges to simulate the wind profile and turbulence profile characteristics of the ABL (Cermak, 2003). The characteristics of typhoons described in the previous section pose new challenges to wind tunnel test technology.

4.1. Wind tunnel test technology

In the early stage of typhoon research, owing to the limitations of experimental conditions, traditional ABL wind tunnel technology was only used to simulate specific typhoon characteristics. To study the influence of typhoon wind fields on the wind resistance of the Xinguang Bridge in Guangzhou, Wang et al. (2009) used dense rough elements and wedges as in Fig. 13(a) and successfully realized a strong turbulence flow field under typhoon conditions. Because Xinguang Bridge is located on open water, the turbulence profile of category A basic terrain was used as the synopic winds, and the measured typhoon records as the typhoon turbulence profile. The two different turbulence profiles are plotted in Fig. 13(b).

To better reproduce the nonstationary and non-Gaussian turbulence characteristics in the typhoon wind field, Cao et al. (2002) developed a multiple-fan active control wind tunnel, as shown in Fig. 14. The wind tunnel is composed of multiple fans arranged in an array and controlled by independent servo motors. In the test, the fan speed is actively controlled by measuring the difference between the wind field characteristics and the target characteristics so that the measured wind field can reach the target wind field characteristics.

Cui et al. (2021c) proposed the double iteration method of the wind spectrum and skewness to generate non-Gaussian turbulence for the first time by using a multiple-fan active wind tunnel. At the same time, they also used a similar method to transform the iterative formula into the time domain and simulate nonstationary airflow as in Fig. 15. Recently, multiple-fan active wind tunnels have been equipped with an active grid array (Zhao et al., 2024). The vertical turbulence is generated by the up and down swing of the grids so that the wind tunnel has the ability to simulate a 2D turbulent flow field. Fig. 16.

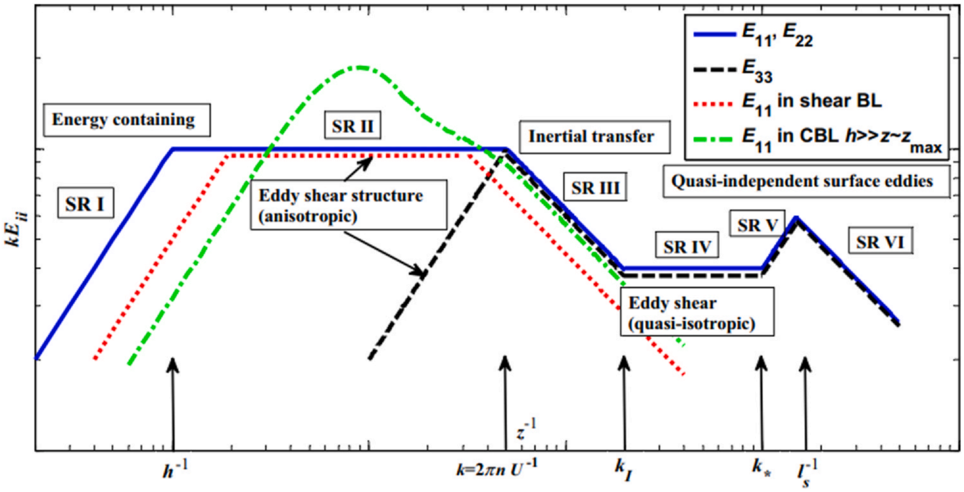
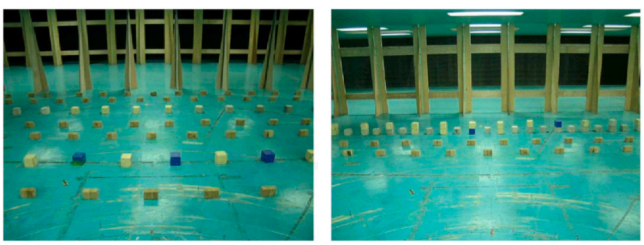
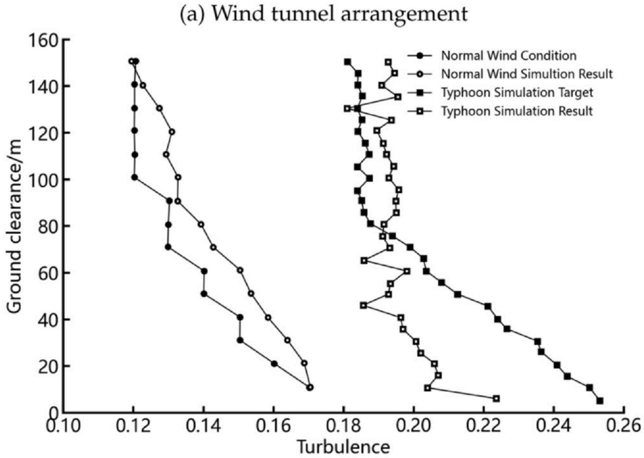


Fig. 12. Conceptual plot of the typhoon turbulence spectrum in the inertial subregion (Li et al., 2015b).



(a) Wind tunnel arrangement



(b) Turbulence profile simulation

Fig. 13. Simulation of strong turbulence in the ABL (Wang et al., 2009).

4.2. Numerical simulation technologies

On the basis of the development of computational fluid dynamics (CFD) and computer technology, numerical simulations have been widely used in the study of small-scale nonsynoptic winds, including tornadoes, downbursts, and canyon winds (Kataoka et al., 2020). However, because a typhoon is a mesoscale flow field with a vortex, the scale is in the range of 500–1000 km, so the whole typhoon wind field cannot be directly simulated via CFD. The weather research and forecasting (WRF) model is widely used in meteorological simulations and weather forecasting. In recent years, the WRF model has also been widely used in the simulation of typhoon disasters (Huang et al., 2018,2024). Unfortunately, the spatial and temporal scales of WRF simulations are large, and the characteristics of turbulence at high frequencies cannot be reproduced. Singh et al. (2020) developed a hybrid simulation technology of CFD and WRF. The simulation results of the WRF model are used as the boundary conditions of the CFD simulation, and the high-frequency characteristics of turbulence are simulated by perturbation, as shown in Fig. 17. Zhang et al. (2022) used the same technique to analyze the characteristics of the urban wind environment under a typhoon climate.

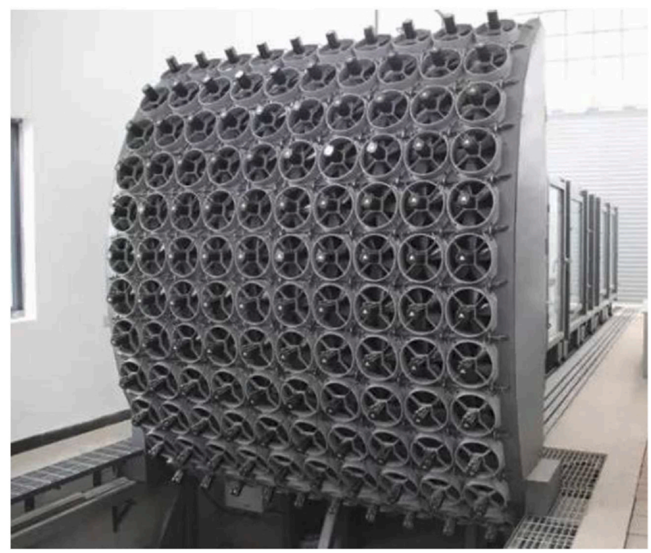


Fig. 14. Actively controlled multiple-fan wind tunnel (Tongji Wind Engineering, 2017).

In summary, owing to the characteristics of nonstationarity, non-Gaussian forces, and strong turbulence in nonsynoptic turbulence, several challenges have been posed to wind tunnel test techniques and numerical simulation methods. Although many scholars have tried to use different methods to simulate typhoon characteristics, many deficiencies still need to be overcome in the future.

5. Wind-induced response of bridges under nonsynoptic wind

The traditional frequency domain analysis method is based on stationary Gaussian turbulence. It is necessary to propose a useful method for buffeting analysis under non-Gaussian and nonstationary turbulence under typhoon conditions. Different scholars have proposed different solutions from various points.

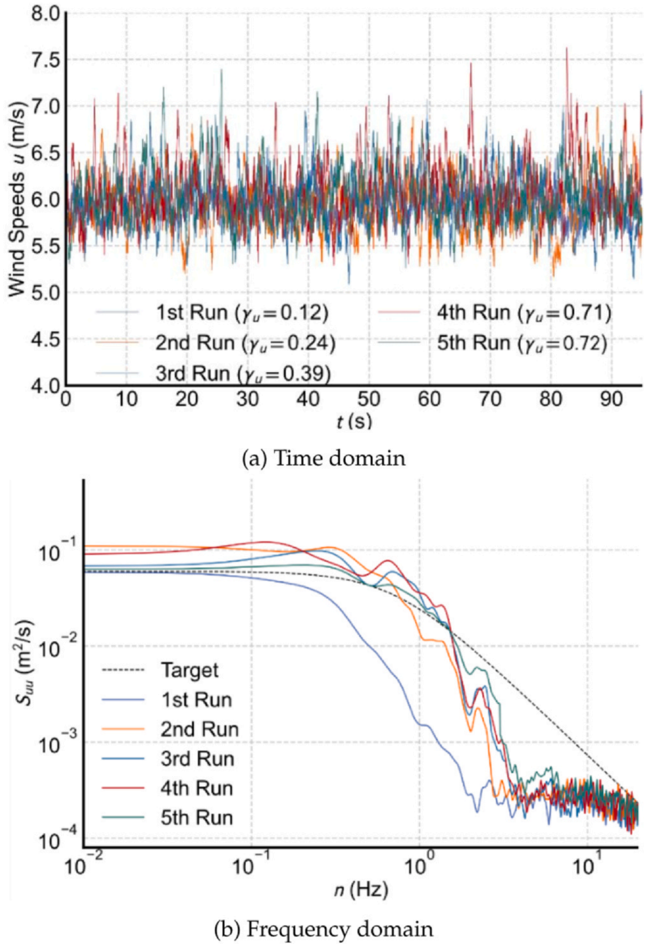


Fig. 15. Iteration method for generating non-Gaussian turbulence (Cui et al., 2021c).

5.1. Theoretical analysis

Similar to the analysis of typhoon climates, the buffeting response of long-span bridges under nonstationary winds is first considered. Chen (2015) determined the dynamic parameters via a stationary process and then used the time-frequency analysis method to calculate the nonstationary dynamic response. Hu et al. (2013) established the evolutionary spectrum method of bridge buffeting by using the virtual excitation method proposed by Lin and Zhang (2004) and then obtained the corresponding time-varying extreme value calculation formula (Hu and Xu, 2014). Tao et al. (2020a) also analyzed bridge buffeting under the action of a time-varying wind spectrum and time-varying self-coherence.

In recent years, buffeting analysis of bridges under non-Gaussian turbulence has attracted increasing attention. Cui et al. (2021d) studied the influence of non-Gaussian turbulence on the buffeting response of long-span bridges via the time domain method and noted that the buffeting variance and extreme value are improved under the action of positive skewness turbulence. Afterward, Cui et al. (2022) proposed a state augmentation method under non-Gaussian random excitation based on stochastic differential equations, which greatly improved the computational efficiency and transformed traditional frequency domain discretization into a set of linear equations. This method accurately analyzes the propagation law from the excitation non-Gaussian feature to the response non-Gaussian feature and indicates that positive skew turbulent flow increases the extreme value of structural responses by nearly 1.8 times. Fig. 18 shows the increasing effect of non-Gaussian turbulence under different wind speeds and turbulence skewness values. Xu et al. (2022) obtained the probability density distribution function of the buffeting response under non-Gaussian turbulence by using probability density evolution theory and noted the significant influence of non-Gaussian turbulence on extreme responses.

Fig. 16. Airfoil cascade in the TJ-5 wind tunnel (Zhao et al., 2024).

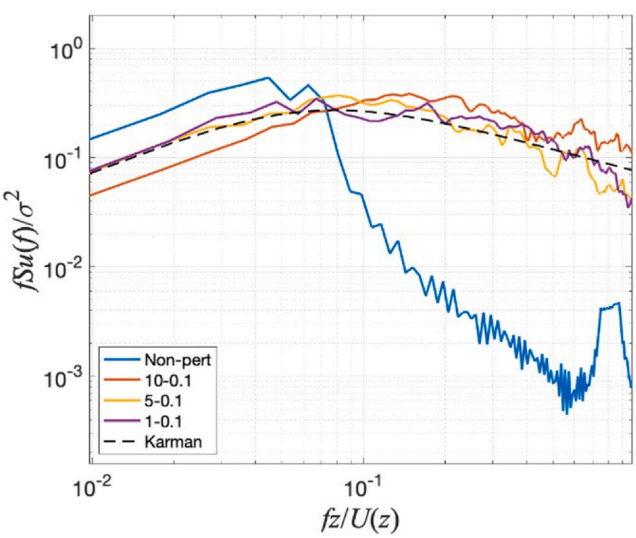


Fig. 17. CFD-WRF hybrid simulation of turbulence in a typhoon wind field (Singh et al., 2020).

5.2. Wind effect prediction via artificial intelligence

With the development of artificial intelligence and the wide application of long-span bridge health monitoring systems (Bao and Li, 2021; Zhang et al., 2024), many machine learning and artificial intelligence algorithms

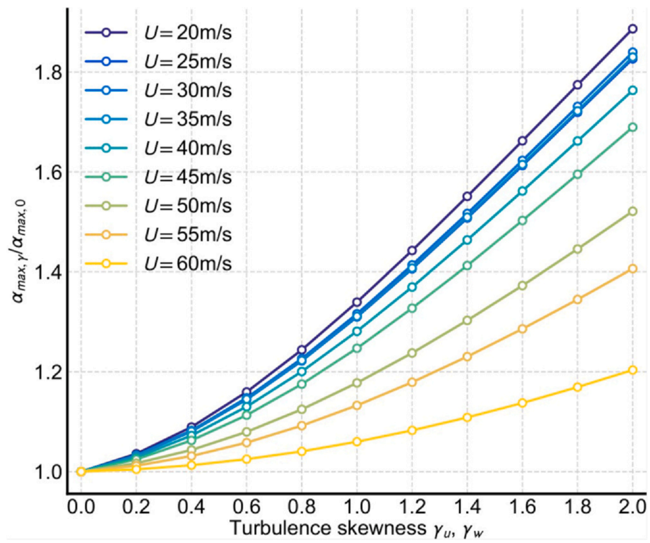


Fig. 18. Extreme buffeting response affected by turbulence skewness (Cui et al., 2021d).

have been used to predict the wind-induced responses of bridge structures in typhoons. Zhang et al. (2021) established a probabilistic framework for typhoon wind-induced bridge response via Bayesian optimization. Liu et al. (2021) established a piecewise polynomial regression prediction method for the buffeting response of long-span bridges under multiple typhoon records and successfully reproduced the dynamic influence of the historical super typhoon Hagupit on the Xihoumen Bridge. Castellon et al. (2021) compared the calculation accuracy and computational efficiency of artificial neural networks, support vector machines and traditional buffeting theory for the wind-induced response analysis of bridges. Although artificial intelligence technology is developing rapidly, the calculation of bridge structural response is still in its infancy. Fig. 19.

5.3. Field measurement

At present, mainstream wind measurement equipment involves fixed-point observations, but the number of typhoons that can be captured is limited; in particular, it is difficult to obtain wind speed data near the center of a typhoon. Sounding observations are also possible, but these disposable equipment types cannot be reused, and the cost of equipment loss is high. Structural health monitoring systems are available, but they cannot obtain high-altitude wind environment information. Therefore, it is necessary to develop a vehicle-mounted mobile observation platform that is characterized by a flexible arrangement and can track wind disaster information at any time. More importantly, on the basis of wind environment observations and structural vibration monitoring, the two are organically combined to further analyze the aerodynamic and aeroelastic parameters of the bridge structure, which is equivalent to a wind tunnel test of full-scale structures using a natural wind field. Zhao and Ge (2019) independently developed and built an all-weather multifunctional mobile wind tracking platform, which has three basic functions: wind disaster environment observation, structural response monitoring and real-time effect analysis. The wind chasing platform is mainly composed of a wind environment observation component, including Doppler radar and ultrasonic anemometers, and a structural effect monitoring component, including a video dynamic imager, synthetic aperture radar and distributed wind pressure sensor. The observation data of the two are summarized in real time in a vehicle measurement and control management platform, and the influence of a typhoon on the bridge structure is analyzed in real time. Besides bridges, the field measurements on buildings have been various types of buildings, such as tall buildings (Li et al., 2011, 2007; Ibrahim et al. 2024) and low-rise structures (Wang et al., 2022; Masters et al., 2010).

Fig. 19. All-weather multifunctional mobile performance monitoring vehicle (Tongji Wind Engineering, 2018).

6. Summary and outlook

Modern bridge wind resistance theories and corresponding wind tunnel testing methods have accelerated the rapid development of large-span bridges in China in recent years. However, existing wind resistance design methods for large-span bridges are based on traditional monsoon climates. Many of China's superlarge-span sea-crossing bridges are located in typhoon-prone areas along the southeast coast, necessitating an analysis of bridge wind resistance safety performance under typhoon conditions. Over the past decade, numerous scholars have researched the following four areas to address the series of challenges posed by the unique spiral wind field structure of typhoons:

1. developed a simulation method for the full-path movement and intensity of typhoons, as well as a 3D wind field model. Using the Monte Carlo method, synthetic typhoon data were generated and then combined with traditional monsoon climate wind speed records to calculate extreme wind speeds for different return periods under mixed climate conditions;
2. on the basis of measured typhoon data, summarized the characteristics of nonstationary turbulence, non-Gaussian distributions, strong turbulence, and unique wind spectra in typhoon-specific wind fields. The variation patterns of typhoon turbulence statistical parameters within the wind field were established via the normalized typhoon intensity and normalized distance as indicators;
3. to simulate the unique wind environment of typhoons, various wind tunnel testing techniques have been developed. Tongji University constructed a multiple-fan active control wind tunnel that successfully simulated nonstationary and non-Gaussian wind fields. Additionally, a multiscale wind field numerical simulation technique using WRF-CFD was established;
4. due to the nonstationary, non-Gaussian, and strong turbulence characteristics of typhoon turbulence, traditional frequency domain analysis methods are no longer applicable. Time-frequency analysis methods and virtual excitation methods have been used for calculating structural responses under nonstationary wind fields. Moment expansion methods and probability density evolution theories have been employed for analyzing structural buffeting under non-Gaussian turbulence. Various artificial intelligence methods are gradually being applied to wind-induced response analysis. Recently developed mobile tracking observation platforms can simultaneously measure wind environments and structural wind-induced responses, directly observing the impact of unique wind environments on structural wind-induced vibrations.

In the past decade, research on the wind resistance of large-span bridges in typhoon environments has developed rapidly and has been applied to many completed and under-construction sea-crossing bridges. However, compared with structural theories under traditional monsoon climates, many theoretical and practical deficiencies remain. Future research aims to improve the theoretical wind resistance system for large-span bridges in typhoon environments in the following ways:

1. In terms of typhoon simulation, it is necessary to improve computational efficiency while considering more meteorological environmental factors, such as the impact of climate change on the movement path, intensity, and frequency of typhoons. It is also crucial to extend simulations beyond regional ocean scales to encompass global typhoon disasters.
2. Most existing characteristics of typhoon turbulence are based on actual wind speed measurements, which show significant variability. It is urgent to establish a theoretical framework for turbulence variations in spiral wind fields on the basis of turbulence theory, thereby unifying measurement results from different regions and various typhoon records.
3. Although there are preliminary capabilities for wind tunnel tests and numerical simulations of typhoon wind fields, identifying wind load models and parameters for bridge sections under unique typhoon turbulence conditions remains challenging. Currently, models for bridge wind loads are still approximated on the basis of monsoon climate conditions.
4. Current analyses of wind-induced responses under unique typhoon wind fields have focused mainly on random buffeting analysis. The effects of typhoon-specific wind fields on bridge aerodynamic self-excited forces have not been adequately considered. In particular, the impact of strong turbulence under typhoon conditions on static wind stability and flutter stability has not yet been addressed within existing theoretical frameworks.

CRediT authorship contribution statement

Lin Zhao: Writing – original draft, Conceptualization. **Wei Cui:** Writing – review & editing. **Genshen Fang:** Formal analysis. **Shuyang Cao:** Formal analysis. **Ledong Zhu:** Formal analysis. **Lili Song:** Data curation. **Yaojun Ge:** Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Yaojun Ge is an advisory editorial board member, Shuyang Cao and Ledong Zhu are editorial board members, Lin Zhao is an associate editor for Advances in Wind Engineering and they were not involved in the editorial review or the decision to publish this article.

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