

Article

Parametric Study on the Aerodynamic Characteristics of Wind Guide Barriers for a Train–Bridge System

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Abstract: This paper presents a new type of wind guide barrier (WGB). Through wind tunnel experiments, the key parameters of three types of WGB were studied, as well as their effects on the aerodynamic characteristics of a high-speed train and blunt body box girder system, while the bridge deck wind field was investigated. The results show that the shielding effect is the main factor affecting the windproof performance of the WGB. When the WGB is installed, the mean wind pressure distribution on the train is comparable to that of using a vertical wind barrier while reducing barrier resistance and the resistance of the bridge–barrier system. At the same time, the WGB can guide the oncoming flow, resulting in an increase in the streamwise and vertical wind velocity ratios on the bridge deck, as well as an increase in the maximum aerodynamic coefficient on the train.

Keywords: wind guide barrier; train–bridge system; aerodynamic characteristics; wind field; wind tunnel experiment



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1. Introduction

With the construction and development of railways, it is inevitable that railway lines will pass through areas prone to frequent wind disasters, such as coastal areas and mountainous canyons. At the same time, new high-speed trains (HST) are becoming faster and lighter, which increases the operational risks of trains under strong crosswinds. Train accidents such as overturning and derailments occur frequently. Therefore, ensuring the operational safety of HST under strong wind conditions has become an important concern for high-speed railway operating departments. Compared with establishing a wind monitoring and early warning system and optimizing the aerodynamic shape of HST, setting up wind barriers is considered to be a more economical and applicable method to ensure the safe operation of HST. Therefore, research on the windproof performance of wind barriers is increasingly valued.

The shielding effect of wind barriers creates a relatively safe local wind environment for HST [1]. Researchers believe that the reduction of mean wind velocity and the variation of turbulence are two important factors that affect windproof performance [2–4]. Barcala et al. [5] used a visualization method to study the effect of wind barrier height and porosity on the flow field structure around bridges. Zhang et al. [6] tested the wind velocity behind the wind barrier through wind tunnel experiments and found that low porosity can reduce wind velocity and lead to high turbulence. Kozmar et al. [7] observed the distribution of mean wind velocity and vorticity behind the wind barrier using the particle image velocimetry (PIV) method; high turbulence and low wind velocity were observed near the bridge deck, with the wind velocity recovering at a height of 1 m. Similarly, by observing the wake structure after installing four types of wind barriers using the PIV method,

Çoskun et al. [8] believed that jet–wake–wall interaction had a significant influence on the mean wind characteristics and fluctuating wind characteristics. Gu et al. [9] proposed a corrugated wind barrier and believed that the regular bending of the guide plate could reduce the intensity and kinetic energy of turbulence. Based on this research, Gu et al. [10] conducted wind tunnel experiments considering wind barriers of different lengths and evaluated the influence of wind barrier length on the aerodynamic performance of trains, pointing out that at wind angles of 20° and 30°, the train would obtain relatively unfavorable aerodynamics. Xiang et al. [11] evaluated the windproof performance of wind barriers using the data envelopment analysis (DEA) method, indicating that reasonable wind barrier height and porosity would enable HST to have better aerodynamic performance, and other studies have reached similar conclusions [12,13].

Bridges account for over 50% of newly built railway lines in China, as bridges are better adapted to complex geological structures and provide significantly improved ride comfort. However, the widespread use of bridges also brings new issues. Research by Zhang et al. [14] showed that wind barriers transmitted wind loads to bridges, which significantly increased the bridge's lateral force coefficient, as well as the train's lateral force and lift coefficients on the bridge. Buljac et al. [15] also pointed out that installing wind barriers will reduce the flutter stability of bridges with typical cross-sections, but the galloping stability remains essentially unchanged. Guo et al. [16] found that the porosity of wind barriers significantly affects the vertical displacement of bridges and the derailment coefficient of trains. Ogueta-Gutiérrez et al. [17] found that wind barriers with straight or curved pipes do not significantly change the aerodynamic performance of trains. Additionally, Guo et al. [18] noted that the relative position of trains on bridges has a significant impact on the aerodynamic characteristics of the train–bridge system. Yu et al. [19] conducted wind tunnel experiments on a non-uniform cross-section box girder and found that the cross-sectional shape of the bridge greatly affects the wind velocities above the track. To improve the wind resistance of trains and bridges, extensive research has been conducted. Ren et al. [20] found that wind barriers with lower porosity at lower positions have better shielding effects by changing the porosity of different parts of the wind barrier. Dai et al. [21] proposed a variable-shape glass-fiber-reinforced plastic (GFRP) wind barrier that can reduce wind loads on bridges. Liu et al. [22] effectively improved the vortex-induced vibration performance of bridges by arranging wind barriers according to certain rules. Taylor et al. [23] found that the turning effect of wind barrier blades significantly regulates the flow field on the bridge in their study of the aerodynamic performance of pedestrian bridges. Based on Taylor's work, He et al. [24,25] proposed a new type of louvered wind barrier and found that louvered wind barriers with a certain inclination angle can regulate the surface wind pressure distribution of trains, thereby reducing the train's moment coefficient under the premise of minimal aerodynamic changes to the bridge.

This paper studies a new type of WGB that deflects the airflow horizontally for aerodynamic design. This wind barrier has been applied to many new high-speed railway bridges. Through wind tunnel experiments, the study investigates the effects of three WGB parameters on the aerodynamic characteristics of HST and bridges. To reveal the windproof performance of the new WGB, we measured the mean wind pressure and pulsating wind pressure on the surface of the train and bridge. In addition, the wind field characteristics on the bridge deck were also tested, and the wind velocity and turbulence field after the wind barrier were analyzed, including the three-direction wind velocity components and turbulence intensity, to comprehensively evaluate the windproof performance. The rest of this paper is organized as follows: Section 2 introduces the outline of the experimental procedure. Section 3 describes the effect of the WGB on the aerodynamic characteristics of the train–bridge system. Section 4 analyzes the effect of the WGB on the wind field characteristics around the bridge deck. Finally, conclusions are drawn in Section 5.

2. Outline of the Experimental Procedure

2.1. Design Parameters of WGB

The design parameters of the new WGB are shown in Figure 1. This WGB is mainly composed of a guide plate, longitudinal connecting rods, and anchor devices. The guide plates are uniformly connected to the longitudinal connecting rods at a spacing of D_1 to form a whole and are anchored to the foundation to be connected to the bridge. The guide plate consists of a main windward surface, a secondary guide angle, and reinforcement ribs on both sides. The shielding effect of the WGB is mainly provided by the main windward surface, and the transverse wind deflection angle θ_1 of the main windward plate is set to guide the transverse wind direction to the side. The upper part of the windward plate is provided with a guide angle with a width of h_1 , which deflects the airflow inward by an angle of θ_2 to guide it upwards and reduce the wind pressure on the barrier. In addition, there are pressure relief holes on the main windward plate and the secondary guide angle. The wind deflector adopts an outward inclination of 10° , which can enhance the wind resistance effect and reserve more operation space on the bridge. The distance D between the WGB and the centerline of the track can be freely adjusted according to engineering needs.

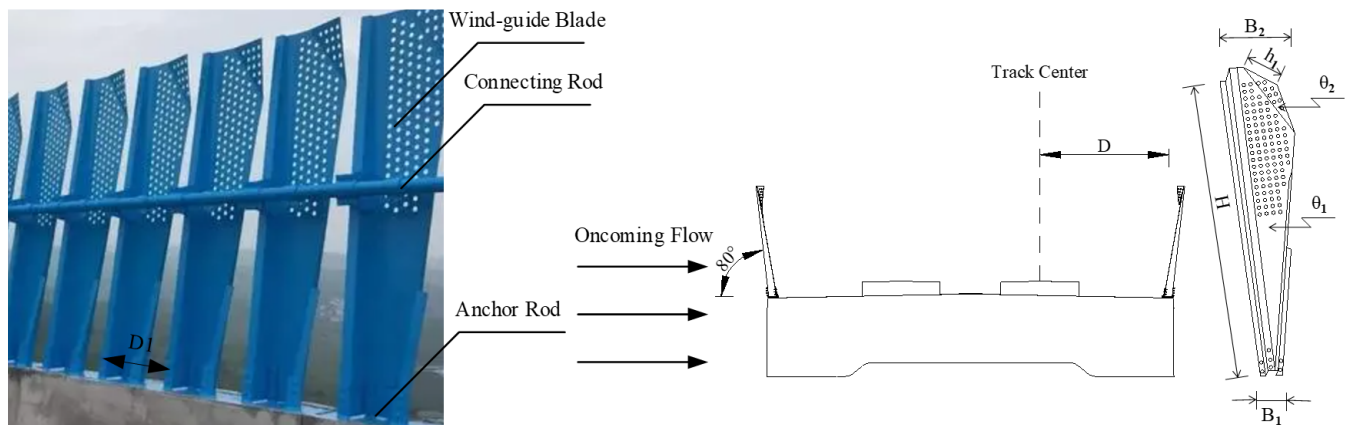


Figure 1. Design parameters of WGB.

2.2. Section Model and Wind Velocity Measuring Points

As shown in Figure 2, we used prototypes of the CRH380 HST and a blunt box girder bridge to conduct wind tunnel experiments. To avoid distortion of test results due to the Reynolds number effects, HST and bridge models were made at a large scale of 1:15. Under a uniform oncoming flow of 12 m/s, the model Reynolds number can reach 1.9×10^5 . At this time, the bridge model is 0.23 m high and 0.97 m wide, and the train model size is 0.233 m (height) $\times$ 0.225 m (width). We set the measuring sections at 1/4, 1/2, and 3/4 of the model. Thirty measuring points were arranged for each train section, and 42 measuring points were arranged for each bridge section. To avoid the influence of distortion effects, the length of all pressure measurement tubes was set to 0.5 m. According to Xiang et al. [11], the aperture size of the wind barrier may affect the test results. Considering that the aperture of the wind barrier model will be smaller than 2 mm after being scaled proportionally, it will affect the formation of the jet through the pressure relief hole. Therefore, under the premise of ensuring the same area of the ventilation surface, the pressure relief holes on the barrier are enlarged and rearranged in the corresponding positions. The wind tunnel experiments were carried out in the high-speed test section of the wind tunnel laboratory at Central South University. The size of the test section is 15.0 m (length) $\times$ 3.0 m (width) $\times$ 3.0 m (height). Considering the limitation of the maximum (max) blockage ratio of the wind tunnel experiment, the model length is defined as 2 m. The model is placed at a height of 1.6 m from the ground, and large end plates are placed on both sides to effectively avoid the interference of end effects and wind tunnel wall effects on the test results. All

models are made of high-strength ABS sheets to ensure sufficient rigidity. The wind field test uses a mobile testing system independently developed by Central South University, which can accurately control the spatial position of the Cobra probe through the mobile measurement frame and self-developed control software. The wind velocity point layout scheme is shown in Figure 3, and a gradually denser layout is adopted from the top to the bottom. A total of 4 test surfaces and 44 wind velocity measurement points are arranged from the windward side to the leeward side of the track centerline. The sampling frequency of the Cobra probe manufactured and calibrated by Turbulent Flow Instruments (TFI) Company is set to 2048 Hz, and the sampling time was 20 s. Each measurement point collects 40,960 data points to ensure the reliability of wind velocity test results.

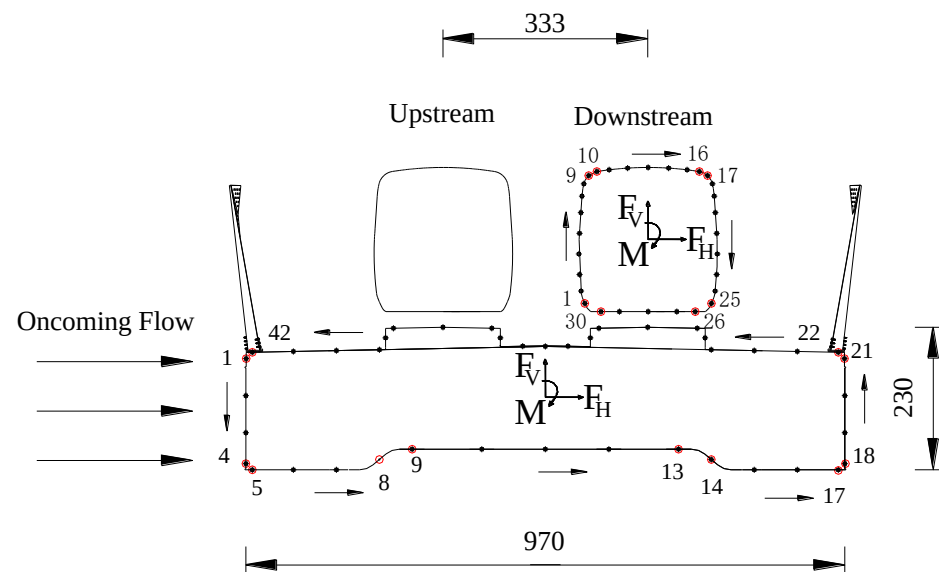


Figure 2. Arrangements of pressure taps on the train and bridge cross-section (unit: mm).

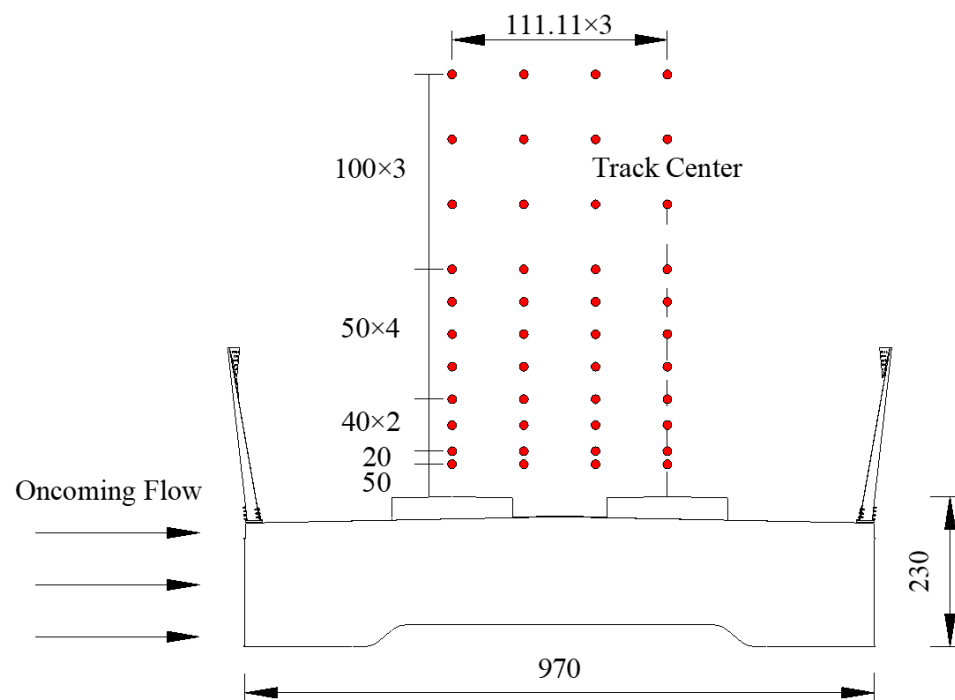


Figure 3. Arrangement of wind velocity measuring points (unit: mm).

The following aspects will be tested in the experiments:

(1) Pressure measurement on trains and bridges. The pressure distribution on the surfaces of trains and bridges under crosswind was tested using PSI pressure scanning valves placed inside the model.

(2) Force measurement on bridges and wind barriers. Two ATI-type scales were installed on both sides of the model end plate to measure the aerodynamic forces of the bridge–barrier system.

(3) Wind velocity measurements on the bridge deck. A mobile testing system developed by Central South University was used to test the wind velocity on the bridge deck using a Cobra probe.

Considering the installation situation on the bridge in practical engineering, the effects of the upper width of the railing, the deflection angle of the secondary guide wind angle, the height of the barrier, the distance from the centerline of the track, and the installation spacing were only considered in this study under the conditions of $B_2 = 540$ mm, $\theta_2 = 20^\circ$, $H = 3000$ mm, $D = 3200$ mm, and $D_1 = 500$ mm. The effects of five types of WGB on the aerodynamic characteristics of the train and bridge are considered, including three parameters: the angle θ_1 of the main deflector plate, the size h_1 of the upper deflector angle, and the WGB root width B_1 . In addition, tests were also conducted for the cases where no barriers were installed and where vertical wind barriers were installed, with the ventilation rate of the vertical wind barrier being the same as that of type 4, and the types of WGB tests have been listed in Table 1. Considering the significant influence of the train position on the windproof performance, this study investigated the cases where the train was located in windward, leeward, and without the train.

Table 1. Types of WGB tests.

Wind Barrier Types	Width of WGB Root	Angle of Main Deflector Plate	Size of the Upper Deflector Angle
	B_1 (mm)	θ_1 (°)	h_1 (mm)
1		No barrier	
2		Vertical wind barrier (30% ventilation rate)	
3	300	20	350
4	300	10	350
5	300	20	500
6	350	10	350
7	250	10	350

2.3. Data Processing

The mean wind pressure coefficient $\bar{C}_{Pi}$ and fluctuating wind pressure coefficient $\tilde{C}_{Pi}$ (standard deviation) of measuring point i can be obtained from the converted wind pressure measured by the scanning valve according to Formulas (1) and (2).

$$\bar{C}_{Pi} = \frac{\bar{P}_i - P_0}{0.5\rho U_H^2} \quad (1)$$

$$\tilde{C}_{Pi} = \frac{1}{0.5\rho U_H^2} \sqrt{\{\sum (P_i - \bar{P}_i)^2\} / (N - 1)} \quad (2)$$

where $\bar{P}_i$ and P_0 are the mean wind pressure and static pressure, respectively; and ρ and U_H are the air density ($\rho = 1.255$ g/cm³) and wind velocity ($U_H = 12$ m/s) during the experiment, respectively.

The aerodynamic coefficients of the train–bridge system can be approximately obtained by integrating the wind pressure coefficients at each measuring point. The aerodynamic force of the WGB can be obtained by subtracting the aerodynamic force of the bridge

from the force measured by the ATI-type scale on the bridge–barrier system. The definition of the aerodynamic coefficients is as follows:

$$C_H = \frac{2F_H}{\rho U^2 H} \approx \sum C_{Pi} L_i \cos \alpha_i / H \quad (3)$$

$$C_V = \frac{2F_V}{\rho U^2 B} \approx \sum C_{Pi} L_i \sin \alpha_i / B \quad (4)$$

$$C_M = \frac{2M}{\rho U^2 B^2} \approx \sum (C_{Pi} L_i \cos \alpha_i Y_i + C_{Pi} L_i \sin \alpha_i X_i) / B^2 \quad (5)$$

where C_H , C_V , and C_M are the lateral force coefficient, lift coefficient, and moment coefficient in the body axis system, respectively; F_H , F_V , and F_M are the aerodynamic forces measured by the ATI-type scale, respectively; L_i is the integration length represented by measurement point i ; α is the outer normal vector angle of the pressure measuring hole in the model section; H and B are the characteristic height and width of the train and bridge, respectively; the torsional moment coefficient of the train–bridge system is calculated with the centroid of the train and bridge as the reference point.

The original data collected by the Cobra probe includes a matrix of time series sequences of wind velocity in three directions: streamwise direction (u), bridge transverse direction (v), and bridge vertical direction (w). After removing bad data points, the mean wind velocity for each direction is calculated by taking the mean of the valid data points. The vector sum of the three mean wind velocity $\bar{u}$, $\bar{v}$, $\bar{w}$ is used to obtain the overall mean wind velocity $\bar{V}$. The total turbulence intensity I_{total} is equal to the ratio of the turbulent pulsation velocity to the mean velocity, I_{total} is calculated according to Equation (10).

$$u = \bar{u} + u' \quad (6)$$

$$v = \bar{v} + v' \quad (7)$$

$$w = \bar{w} + w' \quad (8)$$

$$\bar{V} = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2} \quad (9)$$

$$I_{total} = \sqrt{\frac{1}{3}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})} / |\bar{V}| \quad (10)$$

3. Train–Bridge System Aerodynamic Characteristics

3.1. The HST Aerodynamic Characteristics

3.1.1. Aerodynamic Coefficients of HST

The aerodynamic coefficients acting on a train can intuitively reflect the windproof performance of wind barriers. Figures 4 and 5 show the mean and extreme aerodynamic coefficients of the train when it is located on the windward and leeward sides of the bridge. The red and blue lines in Figures 4 and 5, respectively, represent the mean aerodynamic coefficient of the train without barriers and with a vertical wind barrier installed. For both train–bridge cases, installing a vertical wind barrier can effectively reduce the train's drag. Moreover, when a type 4 WGB is installed, the mean aerodynamic coefficient of the train is close to that when a vertical wind barrier is installed, indicating that WGB can provide a similar windproof performance for trains as vertical wind barriers.

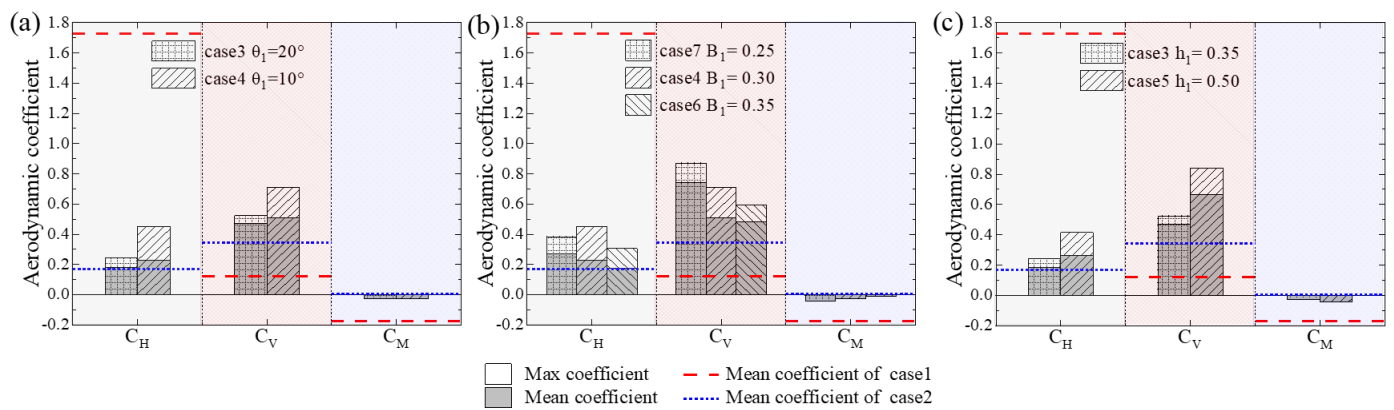


Figure 4. Effect of WGB parameters on HST aerodynamic coefficients (windward): (a) angle of main deflector plate θ_1 ; (b) width of WGB root B_1 ; (c) size of upper deflector angle h_1 .

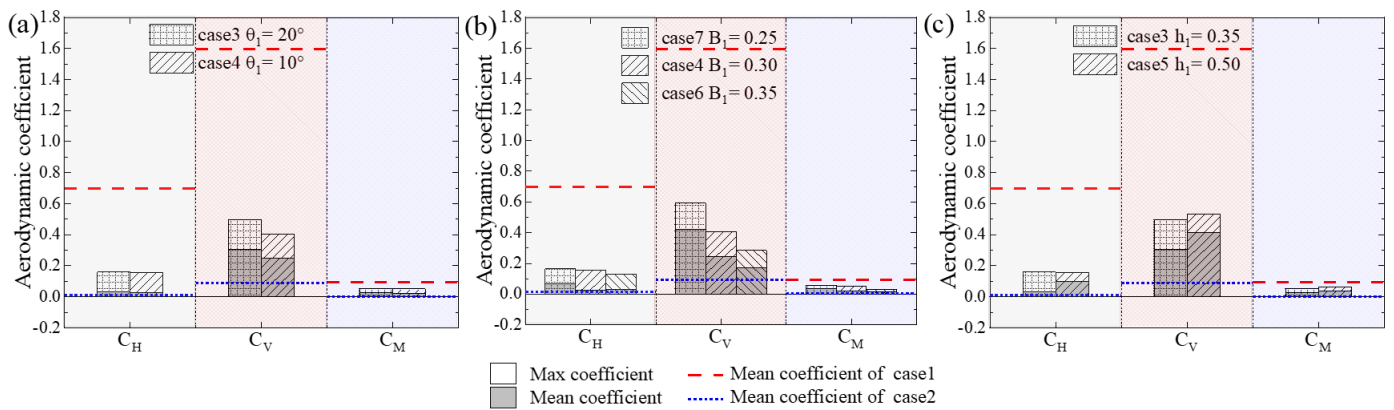


Figure 5. Effect of WGB parameters on HST aerodynamic coefficient (leeward): (a) angle of main deflector plate θ_1 ; (b) width of WGB root B_1 ; (c) size of upper deflector angle h_1 .

In order to facilitate the comparison of the effects of different wind barrier parameters on the aerodynamic coefficients of the train, the comparison cases of each parameter were separately plotted. As shown in Figure 4a, when θ_1 is slightly adjusted, the mean aerodynamic coefficient of the train remains almost unchanged, but the extreme aerodynamic coefficient of the train is greatly affected by the angle of the windward surface. When $\theta_1 = 20^\circ$, the C_H extreme value increases from 0.24 to 0.45, and at the same time, the C_V extreme value increases from 0.52 to 0.71. As shown in Figure 4b, when B_1 is increased from 0.25 m to 0.3 m, the mean C_H and mean C_V of the train will be reduced to varying degrees, but the extreme C_H of the train will increase. At the same time, it should be noted that when B_1 is further increased, the mean aerodynamic coefficient of the train does not change significantly, so the optimal value of B_1 should be between 0.25 m and 0.3 m. As shown in Figure 4c, when h_1 is increased from 0.35 m to 0.5 m, the mean and extreme aerodynamic coefficients of the train will increase. The max CV of the train increases by 60%, which will increase the train's derailment coefficient. Overall, B_1 and h_1 are WGB parameters that have a relatively large impact on the aerodynamic coefficients of the train, while θ_1 has a relatively small impact. When optimizing the WGB parameters, the adjustment of the first two parameters should be emphasized. It should be noted that the extreme aerodynamic coefficient is sometimes several times larger than the mean aerodynamic coefficient, which means that the extreme aerodynamic coefficient may become a controlling factor in wind barrier design.

When the train is on the leeward side of the track, due to the influence of the bridge deck on the wind field, different lane positions can also cause differences in the aerodynamic characteristics of trains [24]. As shown in Figure 5, the effects of various WGB parameters

on the mean aerodynamic coefficient of the train are similar. However, the magnitude of the mean aerodynamic coefficient and the difference in the mean aerodynamic coefficient caused by the parameter changes are greatly reduced compared to when the train is on the upstream side. This may be because the entire train is in the low-pressure wake of the barrier, away from the flow separation point.

3.1.2. Wind Pressure Distribution on HST

Testing the surface pressure distribution of trains can help understand the reasons for changes in train aerodynamics. Figure 6 shows the distribution of mean wind pressure on HST upstream. When the train is on the upstream side of the track, Figure 6a shows that after installing the WGB, the leeward part of the train roof and bottom, as well as the mean wind pressure on the leeward side of the train, remain almost unchanged, but the mean wind pressure on the windward side of the train changes from positive to negative. Compared with vertical wind barriers, the installation of the guide vanes does not significantly change the overall wind pressure distribution of the train, which verifies the view that WGBs have the same train protection effect as the vertical wind barriers mentioned earlier. It is worth noting that when the WGBs are installed, there is an increase in suction force at the shoulder of the train, which may be due to the upward deflection effect of the secondary deflection angle on the airflow. When $\theta_1 = 10^\circ$, as shown in Figure 6b, compared with $\theta_1 = 20^\circ$, the barrier blocks more airflow, resulting in lower pressure in the low-pressure area behind the barrier, which enhances the overall negative pressure of the train. The shoulder part is more sensitive to the changes in the inflow as it is immersed in the separated airflow, so it shows more obvious differences, which can also be observed in cases when h_1 is changed. Surprisingly, as shown in Figure 6c, changing B_1 does not significantly affect the mean wind pressure on the bottom of the train. When B_1 is increased from 0.25 m to 0.3 m, only the trend of the separation point moving up and the weakening of the suction force at the shoulder of the train can be observed, and further increasing B_1 will not significantly change the mean wind pressure on the train.

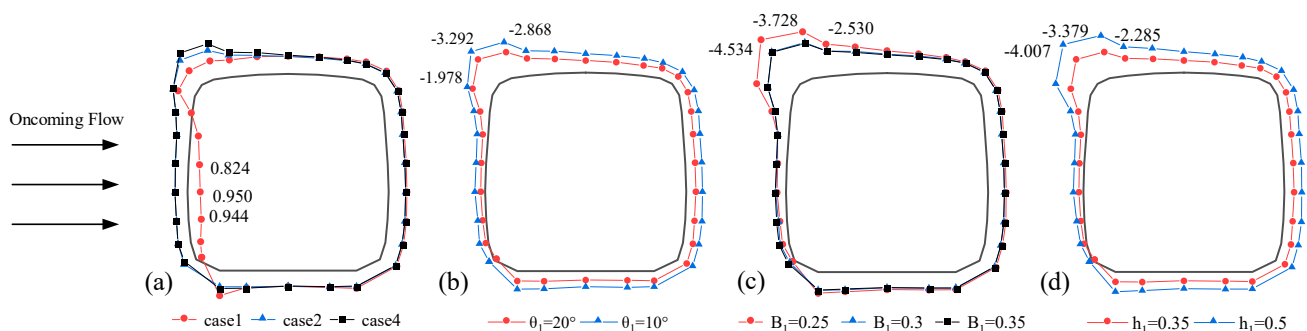


Figure 6. Effect of WGB parameters on HST mean pressure (windward): (a) without a wind barrier; (b) angle of the main deflector plate θ_1 ; (c) width of the WGB root B_1 ; (d) size of the upper deflector angle h_1 .

When HST is on the downstream side of the track, as shown in Figure 7, compared with on the upstream side, the positive pressure on the windward side of the train decreases, and the negative pressure at the shoulder of the train increases to -7.328 . After installing the WGB, the separation of airflow at the shoulder of the train essentially disappears, and the overall aerodynamic level of the train is reduced, with no significant pressure jumps at each measurement point, indicating that the various WGB used in the test can meet the windproofing needs of downstream trains. Overall, when HST is on the upstream side, it is the worst bridge–train system case and should be given priority consideration in design.

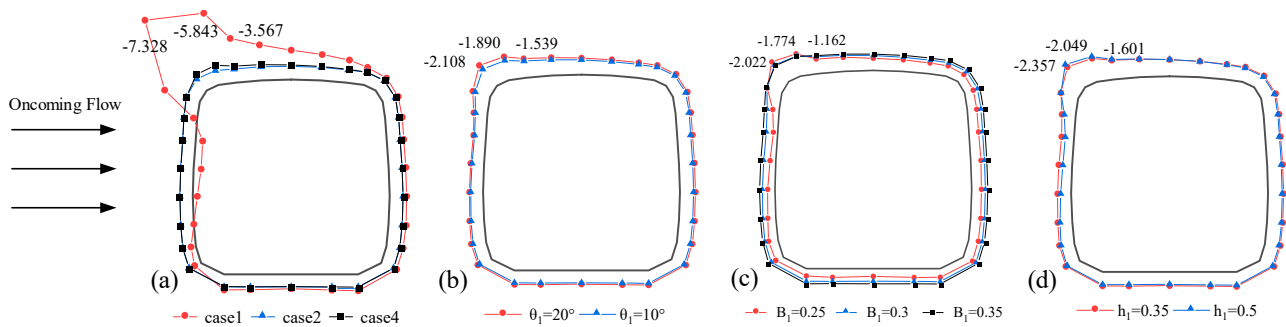


Figure 7. Effect of WGB parameters on HST mean pressure (leeward): (a) without a wind barrier; (b) angle of the main deflector plate θ_1 ; (c) width of the WGB root B_1 ; (d) size of the upper deflector angle h_1 .

To further analyze the causes of the extreme aerodynamic forces on the train, we plotted the fluctuating wind pressure coefficient at each measurement point (Figures 8 and 9). For ease of observation, the figures also show the differences in fluctuating wind pressure coefficients under different parameter configurations. When various types of WGB are installed, the max fluctuating wind pressure coefficient values are all found at measurement point 9. The max fluctuating wind pressure coefficient in all cases is less than 0.3 and only greater than 0.1 near the train shoulder. This indicates that the guide function of the WGB mainly affects the train shoulder and does not cause an increase in turbulence at the bottom of the train or on the leeward side. The variation in the fluctuating wind pressure coefficient at the train shoulder is the main cause of the extreme aerodynamic forces on the train. Overall, θ_1 and h_1 are the most important factors affecting the fluctuating wind pressure coefficient. A smaller B_1 and a larger θ_1 both increase turbulence at the train shoulder and increase the sensitivity of the flow field at the train shoulder to other WGB parameters.

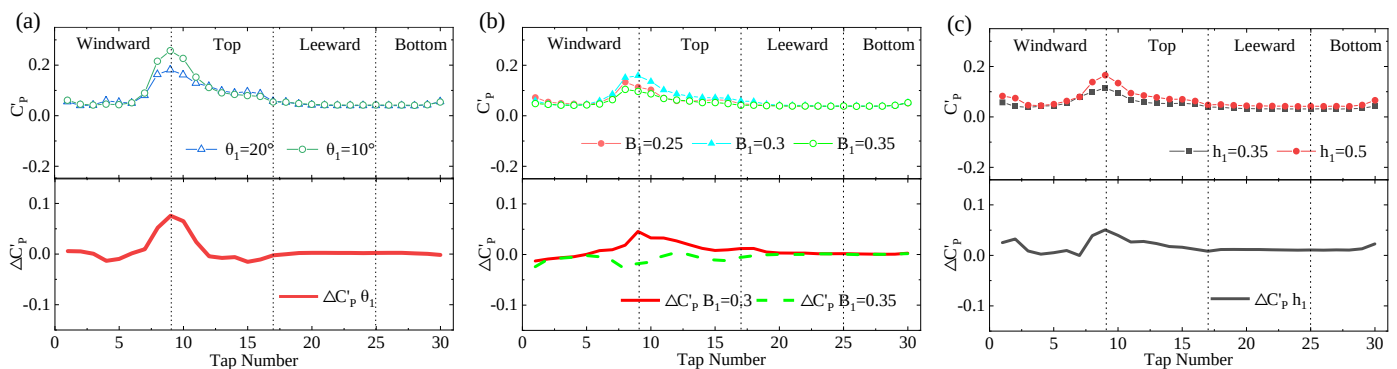


Figure 8. Effect of WGB parameters on HST fluctuating pressure (windward): (a) angle of the main deflector plate θ_1 ; (b) width of the WGB root B_1 ; (c) size of the upper deflector angle h_1 .

3.2. The Bridge Aerodynamic Characteristics

3.2.1. Aerodynamic Coefficients of Bridge

Wind barriers can ensure that trains travel in a safe wind environment, but when installing them on flexible bridges, the height of the wind barrier installed may approach or even exceed the height of the girder, which undoubtedly greatly increases the blunt characteristics of the barrier-bridge system, resulting in a significant change in the aerodynamics of the system. Figure 10 illustrates the C_V and C_H of the bridge-barrier system, as well as the C_H of the WGB with different installations. Notably, the aerodynamic coefficient of the bridge is higher without the train or when the train is located downstream, but decreases when the train is upstream due to the forward separation point of the airflow. Generally speaking, the C_H of the WGB roughly follows the law of increasing with B_1 and decreasing with θ_1 and h_1 . Compared with the vertical wind barrier, the installation of

a WGB (type 4) with the same ventilation rate can reduce the max resistance and barrier resistance of the bridge–barrier system under various train–bridge combinations by 12% and 32%, respectively. Ultimately, the use of a WGB is more beneficial for the structural safety of both the bridge and wind barriers.

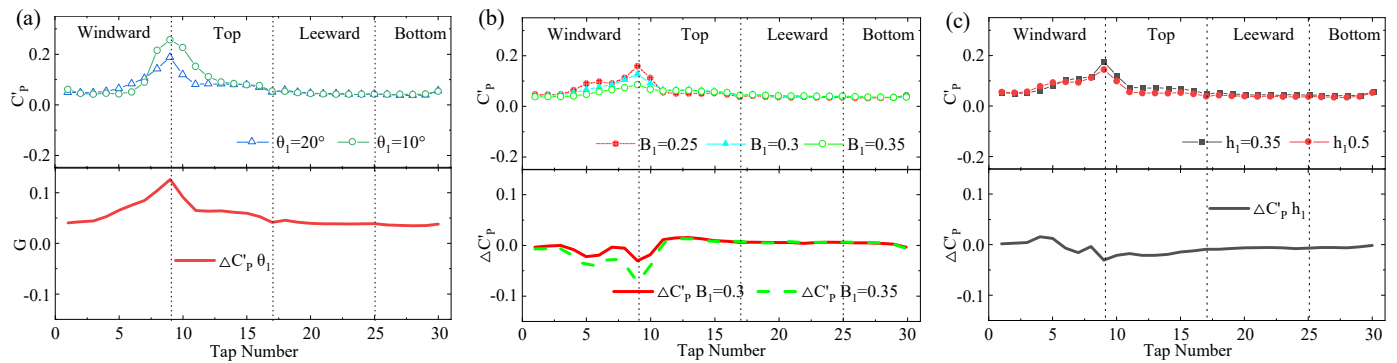


Figure 9. Effect of WGB parameters on HST fluctuating pressure (leeward): (a) angle of the main deflector plate θ_1 ; (b) width of the WGB root B_1 ; (c) size of the upper deflector angle h_1 .

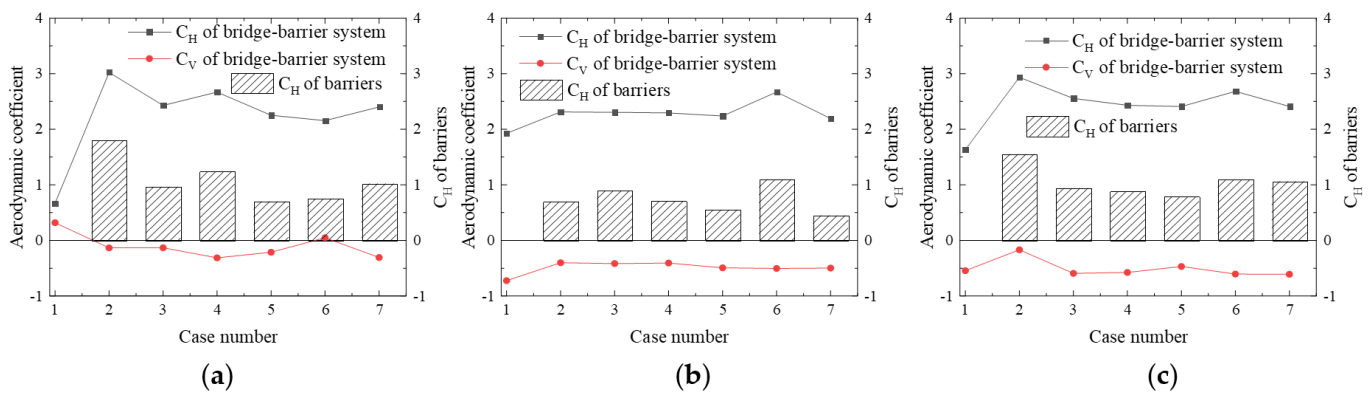


Figure 10. Aerodynamic coefficients of bridge and barrier: (a) without train; (b) the train is located windward; (c) the train is located leeward.

3.2.2. Wind Pressure Distribution on Bridge

As shown in Figure 11, the bridge is divided into 12 zones based on the variation of the cross-section. Zone I is the windward side, zones II–IV are the bottom side, zone V is the leeward side, and zones VI–IX are the top side. For the bare bridge, positive wind pressure occurs throughout the windward side, with the max positive pressure appearing at measuring point 2 and the wind pressure coefficient reaching 0.94. The entire bottom and top of the bridge exhibit negative pressure, with a significant negative pressure zone appearing at the front edge of zones II–III on the bottom and the front edge on the top. The extreme negative pressure coefficients are -1.56 and -2.03 , respectively, while the negative pressure decreases gradually from the rear to the leeward side. When WGBs are installed on the bridge, the positive pressure on the windward side decreases, the negative pressure on the bottom side increases, and the strong negative pressure zone on the bridge surface is suppressed. Meanwhile, the negative pressure decreases, leading to an increase in bridge C_H and a decrease in C_V . When there are trains on the bridge, the wake width of the train–bridge system increases, and the extreme wind pressure coefficient in zone IX changes from -0.83 to 0.53 when perforated wind barriers are installed. The pressure in zones VIII and VII (the ballast) is enhanced due to the acceleration of the train's pressure airflow, especially when the train is located on the windward side of the track, and the extreme negative pressure increases from -1.03 to -1.45 . Compared to the vertical wind

barrier, the installation of WGB can suppress the strong negative pressure on the ballast and reduce the influence of train position on the wind pressure distribution of the bridge.

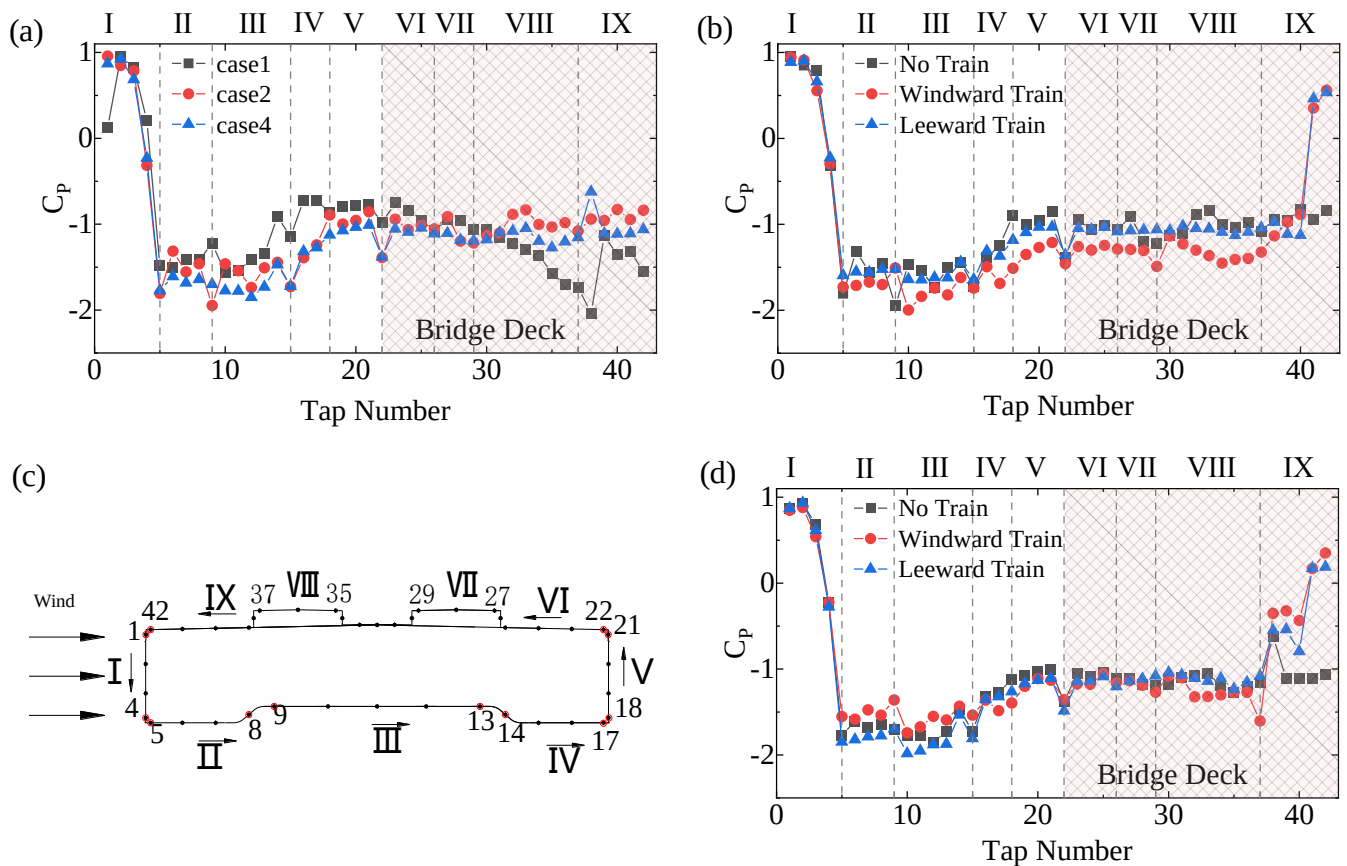


Figure 11. Wind pressure distribution on the bridge: (a) with or without wind barriers (for upstream trains); (b) installing a WGB for different train and bridge combinations in Case 2; (c) bridge pressure zoning; (d) installing a WGB for different train and bridge combinations in Case 4.

As shown in Figure 11, when there is no train on the bridge and various types of WGB are installed, the overall distribution of wind pressure on the bridge is consistent: the entire windward surface shows positive pressure, with the max positive pressure appearing at the 2# measuring point on the windward surface; except for the 8#, 9#, 14#, and 15# measuring points in the corner area where the negative pressure is relatively small, the entire bottom surface shows strong negative pressure; the leeward side of the bridge shows relatively weak negative pressure, and the max negative pressure on the bridge surface appears near the 22# measuring point at the rear corner of the bridge, while the minimum negative pressure appears on the side of the windward track bed at the 38# point. From Figure 12, it can be seen that adjusting θ_1 and h_1 has almost no effect on the surface wind pressure distribution of the bridge. When B_1 is increased, the airflow passing through the bottom of the wind barrier is reduced, the forward flow on the windward surface is slowed down, and the wind pressure on the windward surface is reduced. At the same time, the separation of the airflow in the system accelerates, resulting in an increase in negative pressure on the bottom surface and bridge surface.

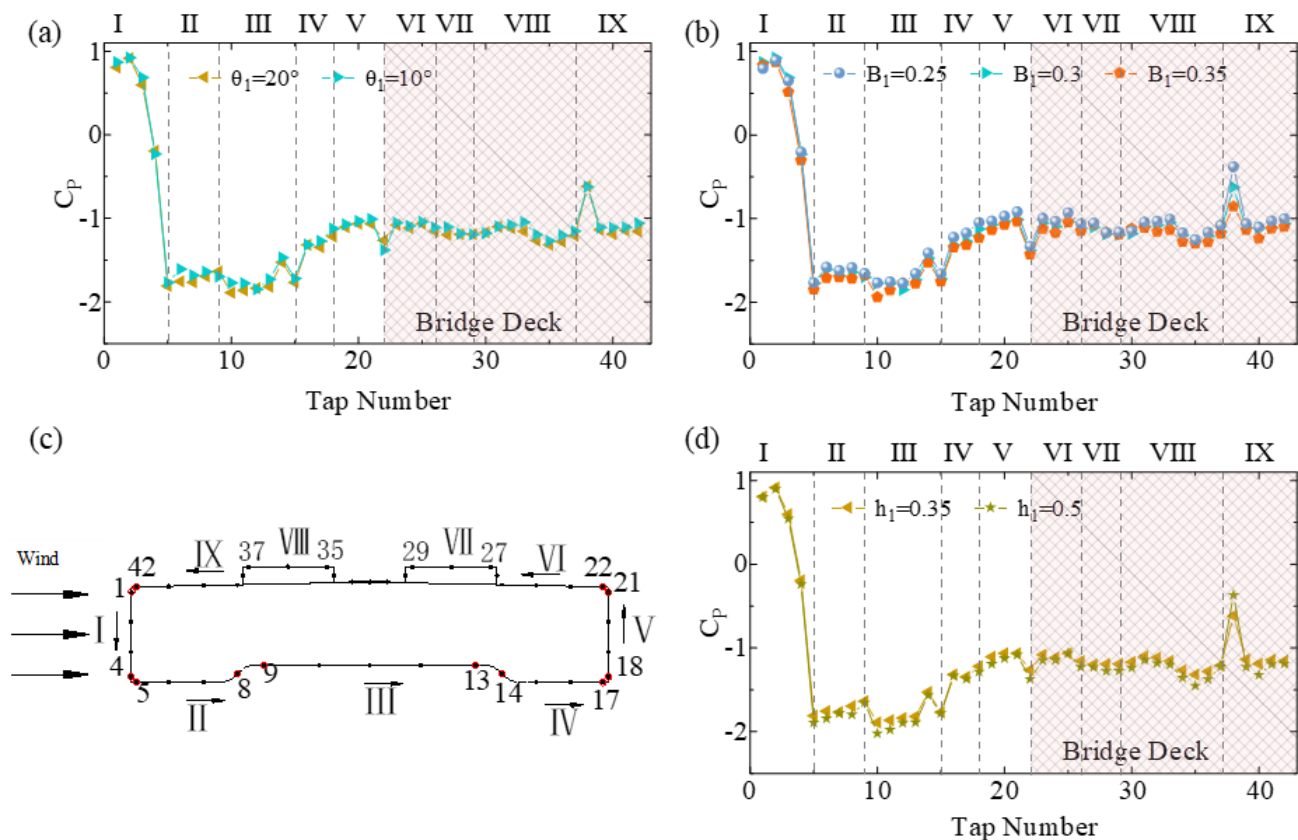


Figure 12. Effect of WGB parameters on bridge wind pressure distribution: (a) angle of the main deflector plate θ_1 ; (b) width of the WGB root B_1 ; (c) pressure distribution zones on the bridge; (d) size of the upper deflector angle h_1 .

In summary, the wind-guiding effect of the WGB suppresses pressure fluctuations at the track, but adjusting the flow parameters such as θ_1 and h_1 will not have a significant impact on the overall wind pressure distribution of the bridge, while changes to some parameters such as B_1 will affect the separation and flow around the oncoming airflow.

4. Flow Field Characteristics behind the WGB

4.1. Mean Wind Characteristics

4.1.1. Streamwise Velocity (u) Distributions

To investigate the effect of WGB on the flow field of bridge deck wake, this paper presents the contour lines of the three-direction wind velocity components in various cases. It can be seen in Figure 13 that the shielding effect of WGB is worse due to vertical wind barriers. Due to the flow around the WGB, a shear layer is formed above the barrier, and its height increases gradually from upstream to downstream. Moreover, the airflow passing through the gap at the bottom of the WGB forms a jet, which creates a high-speed area with a wind velocity ratio of over 0.6 at the bottom of the barrier. This jet may cause an increase in negative pressure at the bottom and windward sides of the train, leading to a decrease in C_V and an increase in C_H . The increased shielding area in the upper part of the WGB, coupled with the backflow effect behind the barrier, results in relatively lower wind velocity in that area.

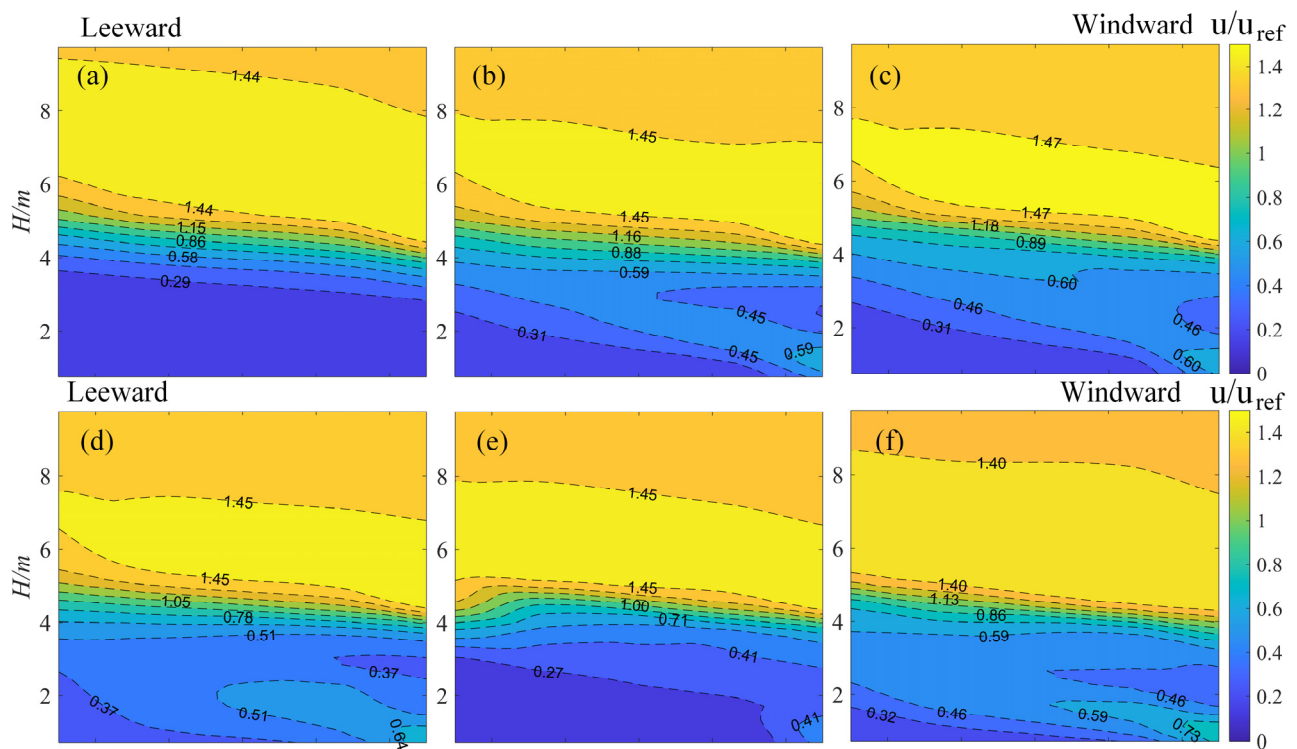


Figure 13. Effect of various WGB cases on streamwise wind velocity for the bridge deck: (a) Case 2; (b) Case 3; (c) Case 4; (d) Case 5; (e) Case 6; (f) Case 7.

Regarding the effect of θ_1 , the test results of Cases 3 and 4 show that increasing θ_1 will reduce the shielding efficiency of WGB, and the flow velocity in the backflow area near the top of the barrier gradually decreases. Regarding the effect of h_1 , the test results of Cases 3 and 5 show that when h_1 increases, the projected windward area of the barrier decreases, and the bluff body characteristics weaken. Therefore, the total wind velocity within the height range of the barrier increases, and the airflow passing through the bottom of the barrier to the bridge deck enhances, resulting in an increase in wind velocity near the bridge deck. However, the wind velocity at the 1.65 m position on the windward side of the track is locally reduced due to the backflow effect behind the barrier. Regarding the effect of B_1 , the test results of Cases 4, 6, and 7 show that as B_1 increases, the blocking effect of the WGB increases, and the jet at the bottom gradually weakens, effectively reducing the wind velocity in the flow direction near the bridge deck. When B_1 increases from 250 mm to 300 mm, the influence on the external flow field above the shear layer is more obvious, and when B_1 increases from 300 mm to 350 mm, the effect on the flow field near the top of the WGB is more obvious.

4.1.2. Transverse Velocity (v) Distributions

Figure 14 shows the effect of various WGB cases on the transverse wind velocity on the bridge deck. It can be observed that as the distance from the WGB increases, the transverse wind velocity gradually decreases. Compared with a vertical wind barrier, the flow-deflecting effect of WGB is significantly enhanced within the train height range. However, high transverse wind velocity still appears near the windward side of the bridge deck due to the influence of jet flow. Large-scale transverse airflow deflection also appears above the top of the WGB and below the shear layer, with a max transverse wind velocity of up to -0.25 . Since there is no abrupt change in wind velocity in the external flow field of the shear layer, and the transverse wind velocity contour lines exhibit a trend of decreasing speed with increasing distance from the wind barrier in the external flow field, the difference in transverse wind velocity may be caused by changes in the pressure gradient.

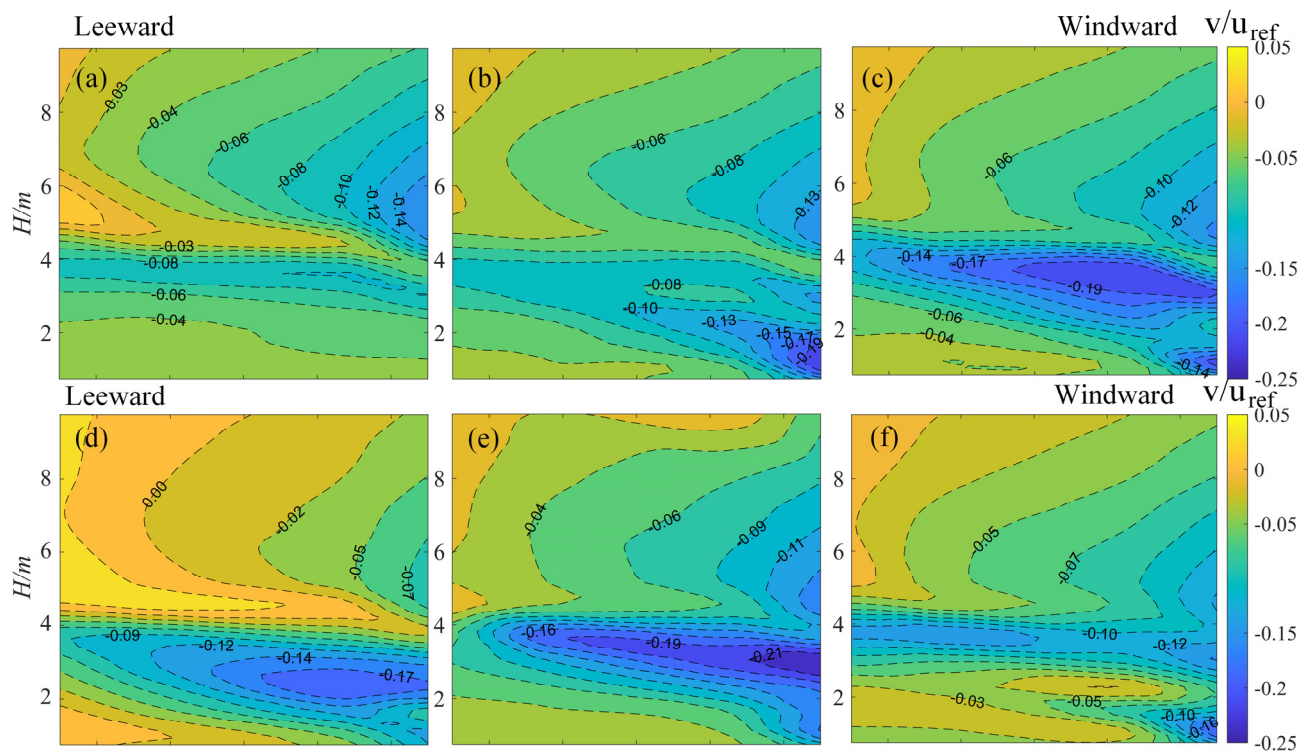


Figure 14. Effect of various WGB cases on transverse wind velocity for the bridge deck: (a) Case 2; (b) Case 3; (c) Case 4; (d) Case 5; (e) Case 6; (f) Case 7.

Regarding the effect of θ_1 , the test results of Cases 3 and 4 show that as θ_1 increases, the transverse wind velocity in the root of the WGB increases, and the absolute value of the transverse wind velocity at 1.65 m increases from -0.10 to -0.19 . At the same time, the transverse wind velocity in the backflow area near the top of the barrier slightly decreases, ultimately resulting in a decrease in the flow-deflecting effect. Regarding the effect of h_1 , the test results of Cases 3 and 5 show that, compared with θ_1 , changing h_1 leads to greater differences in transverse wind velocity, indicating that h_1 is crucial for the airflow deflection effect of the WGB. Compared with $h_1 = 350$ mm, when $h_1 = 500$ mm, the max transverse wind velocity on the windward side decreases by more than 0.1, and the max value appears at a height of 1.65 m above the windward sidetrack. Regarding the effect of B_1 , the test results of Cases 4, 6, and 7 show that as B_1 increases, the airflow deflection effect of the WGB gradually strengthens, and the transverse wind velocity on the upstream side of the WGB increases within the height range of the WGB, enhancing the flow-deflecting effect. However, the trend of the transverse wind velocity on the downstream side is opposite to that on the upstream side, which may be due to the influence of the downstream barrier.

4.1.3. Vertical Velocity (w) Distributions

Figure 15 shows the effect of various WGB cases on the vertical wind velocity on the bridge deck. It can be observed from Figure 15 that a higher vertical wind velocity occurs near the windward side of the bridge deck, which gradually decreases with increasing distance from the barrier, showing a trend of decreasing with distance. The distribution of vertical wind velocity is similar to that of transverse wind velocity, with a max wind velocity ratio of 0.18, slightly smaller than the lateral wind velocity ratio. Compared with vertical wind barriers, the vertical flow guidance effect of WGB with a height of more than 4 m is comparable to that of vertical wind barriers.

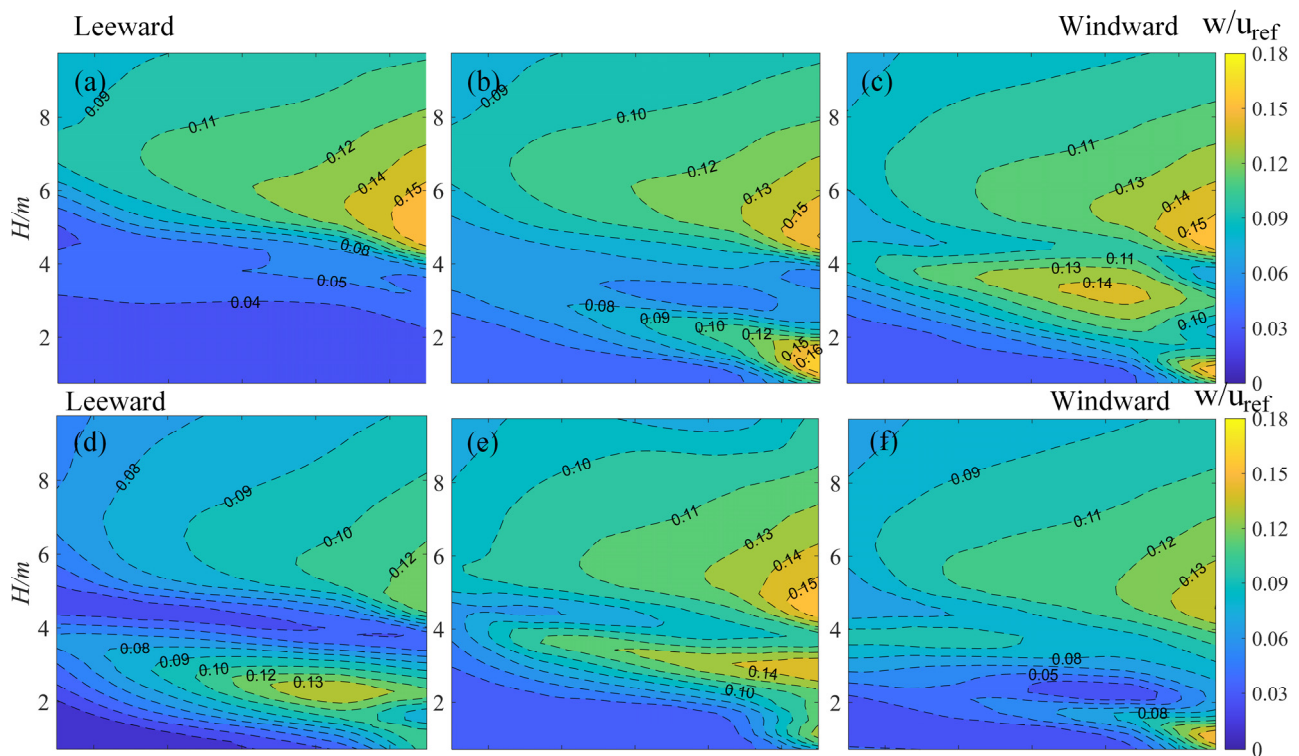


Figure 15. Effect of various WGB cases on vertical wind velocity for the bridge deck: (a) Case 2; (b) Case 3; (c) Case 4; (d) Case 5; (e) Case 6; (f) Case 7.

Regarding the effect of θ_1 , the test results of Cases 3 and 4 show that increasing θ_1 leads to an increase in the vertical wind velocity ratio in the root of the WGB. The vertical wind velocity ratio at 1.65 m increases from 0.1 to 0.15, which reduces the vertical flow guidance effect. At the same time, the vertical wind velocity in the backflow area near the top of the WGB gradually decreases. Regarding the effect of h_1 , the test results of Cases 3 and 5 show that changing h_1 leads to greater differences in the distribution of vertical wind velocity, similar to that of lateral wind velocity. Compared with $h_1 = 350$ mm, when $h_1 = 500$ mm, the max vertical wind velocity ratio on the windward side decreases by more than 0.07, and the max vertical wind velocity also occurs 1.65 m above the windward side of the track. Regarding the effect of B_1 , the test results of Cases 4, 6, and 7 show that increasing B_1 can effectively reduce the wind velocity near the bridge deck and enhance the flow guidance effect at a height of 3 m to 4 m. When B_1 is increased from 250 mm to 300 mm, it has a more significant effect on the external flow field above the shear layer. When B_1 is increased from 300 mm to 350 mm, it has a more significant effect near the top of the WGB.

4.2. Turbulence Characteristics

Figure 16 shows the effect of various WGB cases on the turbulence intensity around the bridge deck wind field. It can be observed from Figure 16 that the WGB causes higher turbulence intensity in the wind field compared to the vertical wind barrier. The larger zones of turbulence occur near the bridge deck, the shear layer near the middle jet, and the flow around the top of the barrier after the installation of WGB. The height of the shear layer is 4.5 m, and the zone below it is considered the effective windproof zone.

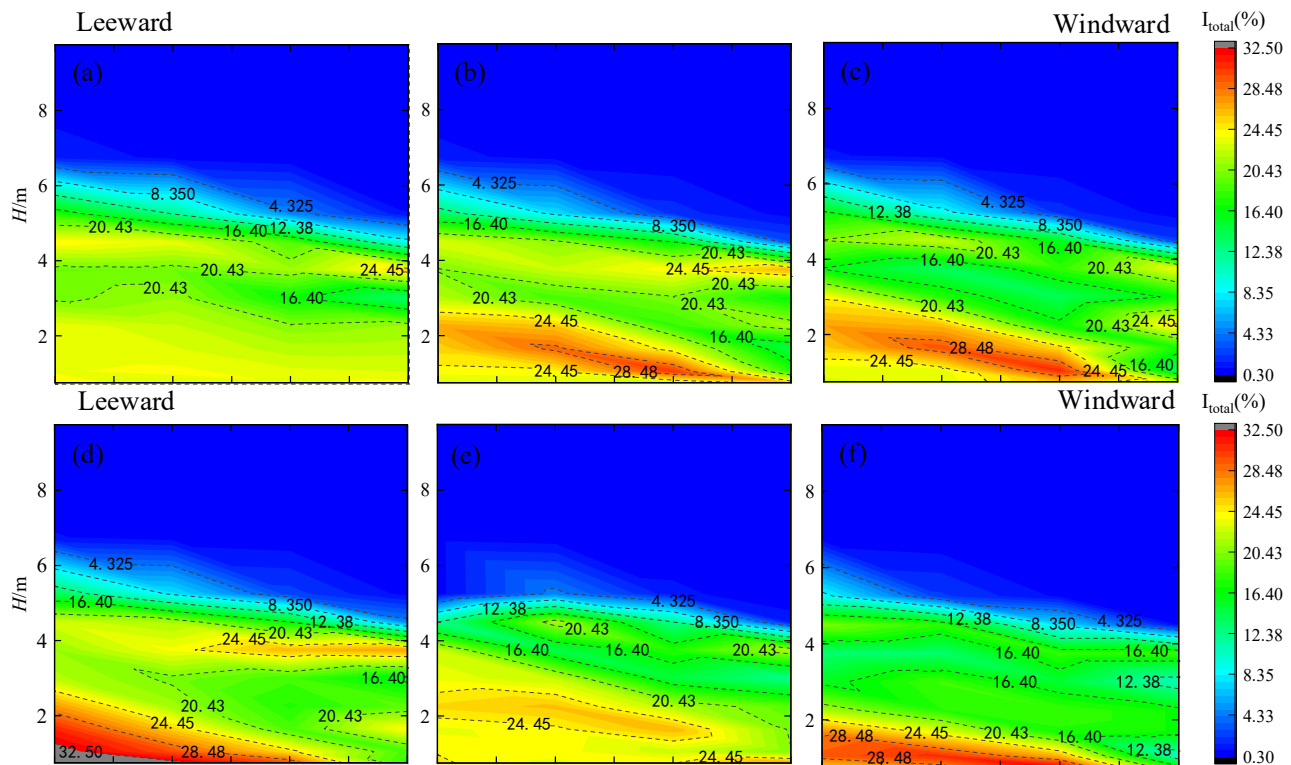


Figure 16. Effect of various WGB cases on turbulence intensity for the bridge deck wind field: (a) Case 2; (b) Case 3; (c) Case 4; (d) Case 5; (e) Case 6; (f) Case 7.

Regarding the effect of θ_1 , the test results of Cases 3 and 4 indicate that changing θ_1 does not significantly affect the turbulence intensity of the bridge wind field, but it will change the position of the stronger turbulence zone. Specifically, increasing θ_1 will shift the position of the stronger turbulence zone upward in the middle jet of the WGB. Regarding the effect of h_1 , the test results of Cases 3 and 5 show that the max turbulence intensity occurs near the surface layer of the bridge and the bottom of the shear layer around the top of the barrier when h_1 is changed. When $h_1 = 500$ mm, the turbulence intensity near the downstream side of the bridge surface reaches 32.5%, and the wind velocity ratio is also higher than when $h_1 = 350$ mm, which is not beneficial to windproofing. Regarding the effect of B_1 , the test results of Cases 4, 6, and 7 show that for the upstream track, the turbulence intensity near the bridge surface increases with the increase in B_1 , and the turbulence intensity at the top of the WGB reaches a max at 300 mm. For the downstream track, within the shear layer range, the turbulence intensity gradually decreases as B_1 increases, and when the size increases from 300 mm to 350 mm, the height of the turbulence boundary layer decreases to 5 m.

5. Conclusions

This study investigates the effects of three main design parameters of the WGB, including the main wind deflector plate θ_1 , the upper deflector angle size h_1 , and the root width B_1 , on the aerodynamic characteristics of a train–bridge system through wind tunnel experiments. This study combines analysis of the mean and fluctuating wind pressure coefficients on the train and bridge surfaces, tests of the aerodynamics of the bridge and barrier, and wind field analysis on the bridge deck to draw the following conclusions:

(1) The WGB is a better wind barrier solution for bridges. It provides comparable windproof performance for the train while reducing barrier resistance and the resistance of the bridge–barrier system by 32% and 12%, respectively.

(2) The effect of changing θ_1 on the aerodynamic characteristics of the train–bridge system is not significant. The design parameters B_1 and h_1 for the WGB have a significant

impact on the mean aerodynamic coefficients of the train. Changing each installation parameter will affect the pulsating wind pressure at the shoulder of the train, and the extreme aerodynamic coefficients of the trains can also change, reaching up to 60%.

(3) The WGB can effectively reduce the wind velocity on the bridge and has a strong guiding effect on the airflow. The max values of the transverse wind velocity ratio and vertical wind velocity ratio behind the WGB can reach 0.25 and 0.17, respectively.

(4) Changing θ_1 has a small effect on the wind field on the bridge, while h_1 has a significant effect on the transverse and vertical guiding effects. When h_1 is reduced, the max value of the transverse wind velocity ratio increases by more than 0.1. Increasing B_1 enhances the blocking and guiding effects and suppresses the intensity of the jet near the bridge surface, which is beneficial for the windproofing of the train.

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