Influence of height of earth embankment type windbreak wall on flow field characteristics and catenary wind-induced displacement

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\textbf{ABSTRACT}

This paper aims at ensuring the safety of catenary operation, by considering the flow field characteristics of the specific railway terrain and the wind-induced displacement of the catenary contact wires. Combining fluid and structure analyses, the improved delayed detached eddy simulation (IDDES) method based on the $\kappa$-$\omega$ turbulence model was used to explore the flow field characteristics at the position of the contact wire area before and after the windbreak wall was increased. The finite element analysis method was used to study the wind-induced displacement, and the relationship between the raising height, the wind speed, and the displacement was comprehensively analyzed. The simulation results were verified by field tests. The results showed that after the raising height was increased by 1 m, the horizontal wind speeds at the contact wire positions above two railway lines were reduced by 94.26\% and 95.60\%, respectively. With the decrease in the horizontal wind speed, the value of the wind-induced displacement in lateral direction was significantly reduced as well. Moreover, the response of the wind speed on the midpoint was more sensitive than that at the hanging point.

\textbf{ARTICLE HISTORY}

Received 6 October 2020
Accepted 23 March 2021

\textbf{KEYWORDS}

Railway; windbreak wall; flow field; catenary displacement

\section{1. Introduction}

Due to the complex terrain conditions and cold air currents in Siberia, the Baili Wind Region of the Lanzhou-Xinjiang Railway in China has high wind speeds that persist for long periods and vary rapidly. For 100 days per year, the wind level exceeds grade 8 that defined as strong wind with the wind speed range 17.2–20.7 m/s according to Beaufort Scale (Royal Meteorological Society, 2018). Strong winds have caused more than 30 train-overturning accidents over 40 years, resulting in significant economic losses and negative social impacts (Ge & Jiang, 2009).

Many scholars have suggested that to cope with severe weather, which includes wind and sandstorm, to ensure the safe operation of trains in strong winds, and to improve the aerodynamic performances of trains, wind-breaks should be built along the railways (Baker, 1986; Barcala & Meseguer, 2007; Bocciolone et al., 2008; G. Chen et al., 2019; Chu et al., 2013; He et al., 2014; T. Liu et al., 2018; Niu et al., 2018; Yao et al., 2020). Xinjiang has a special geographical location and a complex climatic environment. In recent years, the Urumqi Railway Bureau together and other agencies have built a series of windbreak walls based on local resources and terrain, reducing the impact of strong winds on the train operational safety and improving railway transportation efficiency to some extent. At present, the types of wind-break walls of the Lanzhou-Xinjiang Railway mainly include earth embankment type, road cutting type, reinforcement type, ‘L’ type, and bridge types with holes (J. Zhang et al., 2017). The establishment of wind walls, such as reinforcement type wind walls, can improve the aerodynamic performance characteristics, including the lateral forces and overturning moments of trains, in crosswind environments to a certain extent (Y. Li, 2012; F. Liu, 2006). Some earth embankment windbreak walls (EEWWs), which are the main type along the railways in Xinjiang, are inclined on the windward side of the EEWW. The flow crosses the top and enters the lines, sometimes carrying gravel blown by the strong wind, which will also act on the trains, resulting in poor shielding effects and affecting the operation significantly (Liu,
To ensure the economic benefits and safety of the Lanzhou-Xinjiang railway transportation, it is crucial to improve the EEWW's effects. Some typical windbreak wall along the Lanzhou-Xinjiang Railway is shown in Figure 1.

Although many previous studies have used wind tunnel tests to analyze the aerodynamic performances of trains or cars under crosswinds (Baker, 2010; Baker & Humphreys, 1996; Zhang et al., 2018; Li, Qin, & Zhang, 2019), there have been few studies on the aerodynamic performances of trains under EEWW conditions or involving the optimization of EEWW. Liu used the train’s overturning moment as a performance criterion and found that a reasonable height increase of symmetrical EEWW was 0.28 m (Liu et al., 2012). Zhang and Liu studied the aerodynamic force and moment coefficient of a train with different slope angles of the EEWW and concluded that the optimum windward angle was 57°, while both the windward and leeward slope angles were 69° (Zhang & Liu, 2012). Both of these studies on EEWW optimization examined the box wagons used for freight transportation with low operating speeds. However, for passenger cars that need to run at ordinary speeds, the compromise of the running speed will inevitably cause an economic loss. Therefore, for single passenger trains, Zhang and Liu carried out a multistep design of the EEWW and concluded that after the design was adopted, the aerodynamic force of the train was significantly reduced, and the shielding effect was improved. However, this study only accounted for the impact on the aerodynamic performance of the train and ignored the impact on the flow field at the catenary and the condition of the catenary system after the optimization (Zhang & Liu, 2014). Zhang used two types of designs to optimize the EEWW and comprehensively considered the lateral wind speed at the catenary position, but this did not thoroughly reveal the relationship between the wind speed and displacement (Zhang et al., 2017).

The increase in the height of the windbreak wall has a certain protective effect on the train operation, but its leeward side flow field will also change accordingly, and this may cause additional wind loads to act on the catenary system and disturb the flow field stability. This issue has attracted the attention of many scholars. Kozmar explored the flow field structures of bridges behind
wind barriers at different wind incidence angles and concluded that the vertical incident wind angle increase had a greater impact on the flow field characteristics than the horizontal incident angle, because the increase in the vertical wind incident angle caused velocity fluctuations and the average free stream velocities to approach the road surface (Kozmar, 2012). Avila-Sanchez analyzed the turbulence intensity of the catenary region of a double-track bridge and concluded that the wake of the parapet would cause the contact wire to be impinged upon by the edge shear layer. Increasing the wind incident angle or the height of the parapet would increase the turbulence intensity (Avila-Sanchez et al., 2010). Avila-Sanchez further analyzed the flow field of the double-track bridge parapet and the aerodynamic characteristics of the contact wire (Avila-Sanchez et al., 2017), comprehensively comparing their results with those of Scanlon and Oldroyd (2000) to determine that transverse galloping depends both on the aerodynamic coefficient of the contact wire and the incident flow characteristics. However, there are certain differences in the structures of bridge windbreaks and EEWWs, which will cause differences in the flow field behaviors in the catenary area. In addition, catenary wires have elongated structures and non-circular cross sections according to CENELEC standards, which are likely to cause aeroelastic instabilities, such as a galloping phenomenon (Alonso et al., 2007; Carassale et al., 2013; Johnson, 1996; Scanlon & Oldroyd, 2000). Therefore, the wind resistance of the catenary system and the wind-induced displacement of the contact wire have attracted considerable interest (Scanlon & Oldroyd, 2000). Scanlon and Oldroyd suggested that these will cause galloping only when the horizontal wind direction is 7°–14° and the wire is worn. Xie and Zhi found that the wind-induced response under turbulence was stronger than that under uniform flow, and the wind speed would affect the acceleration of the hanging point (Xie & Zhi, 2019).

In this study, the influence of the heightened optimization of the EEWW along the Lanzhou Xinjiang railway on the flow characteristics and wind-induced displacement of the catenary wires was analyzed to ensure the railway’s safe operation. Because of the contact wires under wind load, which will deviate from the center position of the pantograph line and affect the normal sliding contact of the pantograph (Song et al., 2017). The contact force between the pantograph-catenary system significantly affects the quality of the current collection, as the electrical resistance is inversely proportional to the contact force value (Carnevale et al., 2017). The relationships between the height of windbreak, wind speed, and displacement were examined, and the causes of the differences between these were explored based on the flow field.

2. Numerical set-up

2.1. Windbreak wall geometric model

The EEWW model was established in accordance with China’s railway design codes (Zhu, 2009). The core of the paper is focused on the differences of the flow field near the catenary position and the displacement of the contact wires with different windbreak heights, and cases without trains are currently considered. A comprehensive investigation including a train model will be a subject of subsequent research.

The cross section and three-dimensional model at the full scale of the EEWW are shown in Figure 2. The height difference between the top of the original EEWW from the ground level was \( H = 3.5 \) m, which was set as the characteristic height. The width on the top was 1 m, the cross section was an isosceles trapezoid, and the slope ratio was 1:1.5. The thickness of the windshield was 0.1 m (which satisfied the Chinese railway construction specifications), and its height (h) was 0.5 or 1 m. The double-line track included the windward line (Line1) close to the EEWW and the leeward line (Line2). The positions of the catenary wires were 6.3 m directly above the centerline of the tracks level, were denoted as \( C_{\text{Line1}} \) and \( C_{\text{Line2}} \) respectively. The distance between tracks level the ground level is 1 m.

2.2. Flow field computational details

2.2.1. Computation domain and boundary conditions

The domain and corresponding boundary conditions are illustrated in Figure 3, and the calculations used a full-size model. To eliminate the effect of the boundary...
conditions on the flow field around the catenary position and ensure the full development of flow field, the inlet was 17H upstream from the center of the railway lines and the total height of the domain is also 17H. The origin of the coordinate system was set in the middle plane at the center of the double-track railway lines and at the same height level of the track surface. The directions were defined as follows. The positive direction of the y-axis was perpendicular to the windshield direction, which was consistent with the direction of $V_{ref}$. The direction of the x-axis was parallel to the track line direction. The positive direction of the z-axis was perpendicular to the ground and vertically upwards. The windshield was consistent with the length of the domain in the x-direction. A uniform velocity of 40 m/s was set at the inlet in Figure 3. The turbulence kinetic energy, $k$, and the specific dissipation rate, $\omega$, were set through the Turbulence Specification Method of the commercial software STAR-CCM+ to specify the properties of the incoming flow. These parameters were calculated as follows:

$$k = \frac{3}{2}(IV_{ref})^2,$$

$$\omega = k^{\frac{3}{2}} / \left(0.07H \cdot C^2 \right),$$

where the boundary layer is approximately 1% according to wind tunnel test condition (Niu et al., 2018; Zhang et al., 2018) that has been given at the inlet boundary condition, $V_{ref}$ is the incoming flow velocity, and $C$ is the empirical constant whose value is 0.09. A pressure outlet boundary condition of 0 Pa was applied at the outlet. The ground, EEWW, railways, and windshield were set as no-slip walls. The other surfaces of the domain were treated as symmetric walls. In addition, according to the calculation formula of Reynolds number $Re = W f H/\nu$, at the ambient temperature of 20°C, the air kinematic viscosity $\nu = 1.54 \times 10^{-5}$, the $Re$ number of main numerical simulations is $9.09 \times 10^6$.

In order to compare the effect of different inlet velocity profiles on flow distribution around EEWW, a power law is used to describe the vertical distribution of horizontal mean wind speeds, and the wind profile power law relationship can be written as $v = v_{ref}(z/z_{ref})^\alpha$ (Cook, 1997), where $v$ is the wind speed at height $z$, and $v_{ref}$ is the known wind speed consisted with the same value of the uniform wind speed at $z_{ref} = 10$ m above the ground based on the Chinese Standard, the exponent ($\alpha$) took in this paper is 0.15 (ASCE/SEI7-05, 2016). The value of turbulent intensity at distributed regions is 0.05 that set as inlet boundary condition (Zhang et al., 2019).

Three reference lines in the middle plane of the domain are shown in Figure 4. $L_{ref1}$ and $L_{ref2}$ at the center of Line1 and Line2, and $L_{ref3}$ was a horizontal line at the height of contact wires that was 6.3 m from the rail surface level. The distribution of mean speed ratio $V_R = (V/V_{inlet})$ of these three reference lines are shown in Figure 5, where

![Figure 3. Computational domain and boundary condition.](image1)

![Figure 4. Location of three reference lines.](image2)
$V$ is the mean velocity magnitude combined with the Y- and Z-direction components and $V_{inlet}$ is the incoming flow velocity. $V_R$ around the original type of EEWW with different velocity inlet profiles are shown in Figure 5. As it is shown in Figure 5(a,b), the $V_R$ in $L_{ref1}$ and $L_{ref2}$ had a slight difference between the two inlet conditions and the lower value of $V_R$ can be observed above the height $z/H = 1.5$ of Atmospheric Boundary Layer (ABL) inlet condition. As for $L_{ref3}$ showed in Figure 5(c), $V_R$ present similar changes trend along the $L_{ref3}$, especially before passing the EEWW. However, uniform flow contributed to a larger value of $V_R$ than that of ABL flow. This is because inlet velocity profile of ABL below the $z_{ref}$ height follows the relationship of the power law, velocity near the ground and the flow over the EEWW are much less than of the uniform inlet velocity profile. Although using uniform velocity profile may overestimate the risk to train operation safety and limit the train speed (Mao, Xi, & Yang, 2011), it is better to guarantee the catenary operation security and much safer for trains operating in the strong wind regions, especially in complex terrain environment like Baili wind region. Combining the above factors, a uniform velocity profile is used in this paper as the inlet boundary condition to explore the flow characteristic around EEWW and catenary position.

### 2.2.2. Mesh generation

To ensure the accuracy of the simulation and the efficiency of the calculation, an unstructured trimmed cell mesh was used to discretize the calculation area illustrated in Figure 6. The horizontal and vertical mesh sizes near the top of the EEWW are 0.009H. There are 3 cells in the y-direction (wind direction), and 30 cells z-direction (vertical) near the windshield for the coarse size mesh when $h = 1$ m. The flow near the tracks and windbreak may show considerable flow separation and attachment. To capture the details of the flow field around these areas and ensure the accuracy of the calculation results, these regions were contained in refinement boxes. To capture the flow structure near the EEWW and tracks, a prism layer of ten cells was attached to the model surfaces. The thickness of the first layer was approximately 0.6 mm, which corresponded to a value of the dimensionless wall distance ($y^+$) over the EEWW and track surfaces.
is less than 1, which satisfied the calculation requirements (Niu et al., 2018, 2019).

### 2.2.3. Simulation model and solver description

With the improvement and maturity of the computational approaches, Computational Fluid Dynamics (CFD) method is utterly efficient and reliable to solve various engineering problems (Ghalandari et al., 2019; Mou et al., 2017; Ramezanizadeh et al., 2019).

It is acknowledged that there may be separated unstable flows and the presence of tail vortices due to the presence of trains or windbreaks. Although the Reynolds averaged Navier–Stokes (RANS) model has a low mesh density requirement and a small number of required for calculations, it has difficulty accurately simulating the unstable separation flow around the train surface or the back of an obstacle.

The detached eddy simulation (DES) approach, which combines the advantages of the RANS model and large eddy simulation (LES) model, can smoothly switch between the area Reynolds-Averaged equations performed and the area of LES equations solved. The efficiency and accuracy of the DES method at high Reynolds numbers in massively separated flows are adequate, and the DES method is now widely considered to be a promising method for simulating the aerodynamic characteristics of high-speed trains (Chen et al., 2018, 2018; Guo et al., 2020). However, the DES calculation method also has certain shortcomings. For example, if the grid spacing parallel to wall is too small, the simulation may not be able to implement the RANS calculations in areas with thicker boundary layers nor capture the near-wall turbulence through the LES, resulting in incorrect calculation results (Chen et al., 2019; Spalart et al., 2006).

The improved delayed detached eddy simulation (IDDES) formulation based on the shear-stress transport (SST $\kappa$-$\omega$ model) is a hybrid method that integrates the delayed detached eddy simulation (DDES) and wall-modeled LES (WMLES), which can effectively reduce the limit of the Reynolds number near the wall and effectively solve the grid-induced separation problem (GIS) (Shur et al., 2008). This method can accurately simulate the flow field around the train (Chen et al., 2019; Li et al., 2019) and the flow field near the railway embankment (Zhang et al., 2019).

A segregated incompressible finite-volume solver was adopted for the simulations presented in this paper, and the SIMPLE pressure–velocity coupling method was employed. To discretize the convective term, a hybrid scheme that switched between a bounded central-differencing scheme (BCDS) and a second-order upwind scheme (Travin et al., 2002; Xia et al., 2020) was employed. Additionally, a second-order upwind scheme was used for the turbulence equations, and the BCDS was applied in the LES region. The time step was $\Delta t = 1.25 \times 10^{-3}$ s so that the convective Courant–Friedrichs-Lewy (CFL) number is less than 1 for most cells, and only small parts of the cells exceeds 1. Several researches have shown that this minor infringement on the CFL number requirement to the effect of the flow field can be approximately ignored (Flynn et al., 2016; Krajnovic, 2008; Li et al., 2019). Ten iterations for each time step was chosen mainly based on calculation convergence and reduction of residual considerations, which satisfied the computational requirement of this study, according to the monitored history of the aerodynamic quantities and the STAR-CCM+ user guide (SIEMENS, 2017). Meanwhile, the instantaneous flow structure was captured, and the flow field was fully developed after 4000 time steps. Furthermore, 4000 time-step data samples were selected to average the flow field.

### 2.3. Catenary system numerical set-up

#### 2.3.1. Catenary geometric model

The main parts of the catenary system structure, which included the suspension and support structure, are
shown in Figure 7(a). The suspension was composed of contact wires, a dropper, and messenger wires that mainly exists in the form of clues, and a wind load will result in a certain amount of displacement of the suspension. The catenary system model was based on the prototype along the South Xinjiang Railway. It complied with the railway design code and technical parameters of the manufacturing company, and the dimensions agreed with those of the actual observation and measurement. Simplifications were implemented to avoid redundant and unnecessary calculations and improve calculation efficiency and accuracy. Figure 7(b) shows the structural element model of the catenary.

2.3.2. Load conditions

After obtained the wind speed at the contact suspension position, the total wind load in each direction acting on the contact suspension can be calculated based on this results, according to the theoretical study of Zhou (Zhou, 2012) that shown in Equation (3). And the wind load acting on the contact suspension depends on the size, direction, and shape of the windward part, which can be obtained as follows:

\[ F_w = c_w \cdot q \cdot A_w \cdot \sin^2 \alpha_w, \]  

(3)

where \( c_w \) refers to the wind load form factor of the component under a load, \( A_w \) is the projected area on the plane normal to the wind direction (GB50009-2012, 2012), \( \alpha_w \) represents the angle between the wind direction and the line direction, and \( q \) is the theoretical wind pressure on the surface of the catenary structure under constant wind load with the wind direction perpendicular to its surface, which depends on the kinetic energy of air flow. \( q \) is defined as follows:

\[ q = \frac{1}{2} \gamma \cdot v_w^2, \]  

(4)

where the air density, \( \gamma \), was taken to be 1.225 kg/m³, and \( v_w \) is the wind speed. Substituting Equation (4) into Equation (3), the wind load per unit length of the contact suspension and columns can be obtained as follows:

\[ F'_w = \frac{1}{2} \gamma' \cdot c_w \cdot v_w^2 \cdot d, \]  

(5)

where the diameter of the contact wire tube \( d = 0.01 \text{ m} \), \( c_w \) of the suspension was 0.8, the outer diameter of the columns \( D = 0.35 \text{ m} \), and \( c_w \) of the support columns was 0.9 (GB50009-2012, 2012; Zhou, 2012), the Reynolds number of contact wire and columns are \( 2.6 \times 10^4 \), \( 9.1 \times 10^5 \) respectively. After obtaining the wind speeds at the positions of the contact wires and columns for windshields of different heights, Equation (3) was used to calculate the wind load forces at the positions of the contact network and the support columns. Finally, the Finite element analysis software ABAQUS was used to perform the contact network wind-induced displacement calculations and analysis.

As for structure analysis, the finite element simulation software ABAQUS was used to calculate the wind-induced displacement. The type of elements is 8-node hexahedral linear brick C3D8R and the static general analysis method based on reduced integration method was adopted. The wind load is uniformly loaded onto the contact suspension of the finite element model. In a finite-strain formulation the selectively reduced-integration procedure works as follow:

\[ \bar{F} = F \left( \frac{\bar{j}}{j} \right)^n \]  

(6)

\[ \bar{j} = \frac{1}{V_{el}} \int_{V_{el}} J dV_{el} \]  

(7)

where \( F = \partial t / \partial T \) is the deformation gradient; \( n \) is the dimension of the element; \( J = \det(F) \) is the Jacobian at the Gauss point; \( \bar{j} \) is the average Jacobian over the element, and \( n = 3 \) for three-dimensional elements. \( J (\bar{j}) \) are the volume change for three-dimensional elements. The modified rate of deformation tensor, \( \bar{D} \), is obtained from
where $f = 1/3$ for three-dimensional elements, and $I_{ma}$ is the identity matrix in two or three dimensions (ABAQUS/CAE, 2014).

2.3.3. Meshing strategies
The finite element analysis element software Abaqus was used to disperse the catenary model. Additionally, for the uncomplicated geometric model, the quadratic hexahedral element mesh was preferentially divided. The mesh of the contact system is shown in Figure 8. The total number of grids was 0.46 million.

2.4. Algorithm validation
2.4.1. Grid independence
To determine the effect of the mesh resolution in this study, a comparison of the velocity ratio of the reference lines obtained from coarse middle and fine meshes. The details of the grids are presented in Table 1.

Figure 9 shows the $V_R$ of three reference lines with different types of grid. Although slight differences are observed in the wake region at horizontal position $y/H > 2$ between the three cases, which may have been due to the increased turbulence caused by the separation of the air flow through the windbreak, the results on the coarse mesh closely meet these on the middle and fine mesh, especially in the contact suspension area that is the most important research focus. Thus, it can be determined that the results are not a function of mesh resolution and the coarse mesh is sufficient in the analyzed cases. According to the corresponding results, the meshing strategy of the coarse grid chosen for further study and analysis is reasonable.

2.4.2. Program validation
To assess the aerodynamic performance and shielding effect of the windbreak wall, a comprehensive full field test was conducted along with the Baili Wind Region of the Lanzhou-Xinjiang railways in April 2010. The experimental data were used to verify the accuracy of the numerical method. These tests were carried out from April 6th to 21st, lasted for 15 days, the average angle between the windshield and the wind is 40 degrees, the average value of the incoming wind speed ($W_f$) is 24.81 m/s, the gust factor was approximately 1.57–1.63 during the field measurements. The boundary condition setting in the verification simulation case is consistent with of condition the field test. Besides, the test position of the EEWW was selected at the railway mileage of K1483 + 890, and the parameters of the windbreak wall and the distance from the track were the same as those presented in Figure 2. The measurement point that was 10H away from the bottom of the windward side of the windbreak at the height of 6.5 m above the ground level was selected to measure the incoming wind speed and direction, as shown in Figure 10(a), and this point was used as the initial value of the numerical simulations. Figure 10(b,c) show the wind speed distribution measurements behind the windbreak using anemometer masts installed in the middle of Line1 and Line2. Probes and spiral anemometers were installed on the anemometer masts at distances of 1, 2, 3, 4, and 5 m above the track surface, as shown in Figure 10(d).

To intuitively compare the field test data and calculation results, a non-dimensional coefficient $C_u = (W_b/W_f)$ was defined, where $W_b$ is the average wind speed at the measurement points behind the windbreak. The velocity ratios ($C_u$) from the experiment and simulation are presented in Table 2, and Equation (9) defined the error(e) of numerical calculation by using the ratio of the absolute value of the difference between the numerical calculation result and the field test data. The maximum error between them was less than 7%. Additionally, the ratios calculated from the simulation were generally smaller than the values in the field tests, which may have been the reason that the simulations were not completely consistent with the details of the test terrain condition.

Figure 11 shows the field test and numerical simulation of the vertical distribution of the wind speeds on the
Figure 9. Mesh sensitivity of mean $V_R$ along the lines: (a) $V_R$ along $L_{ref1}$, (b) $V_R$ along $L_{ref2}$, and (c) $V_R$ along $L_{ref3}$. The flow was from left to right in these images.

Figure 10. Windbreak walls in aerodynamic field tests: (a) outside wind speed measuring rod, (b) wind speed measuring mast at Line1, (c) wind speed measuring mast at Line2, and (d) wind speed sensor employed for measurements.
Table 2. Comparison of wind speed ratios obtained from the simulations and experiments.

| Height (m) | 1  | 2  | 3  | 4  | 5  |
|------------|----|----|----|----|----|
| Results of Line 1 |     |    |    |    |    |
| $W_f$       | 24.81 |
| Experiment $C_u$ | 0.31 | 0.49 | 0.89 | 1.05 | 1.06 |
| Simulation $C_u$ | 0.29 | 0.50 | 0.85 | 1.04 | 1.10 |
| Error (%) | 6.45 | 2.05 | 5.55 | 1.90 | 4.53 |
| Results of Line 2 |     |    |    |    |    |
| Experiment $C_u$ | 0.33 | 0.61 | 0.80 | 0.98 | 1.02 |
| Simulation $C_u$ | 0.31 | 0.59 | 0.75 | 0.92 | 0.95 |
| Error (%) | 6.06 | 3.27 | 6.25 | 6.12 | 6.86 |

With regard to the validation of the FEM simulation results, a total of four tests conducted since April 25 solstice on May 4, 2019 along China Nanjiang Railway were selected from our previous series of field tests to investigate the characteristics of the catenary under crosswinds. A dynamic target template matching method used to detect the displacement of contact wire, and the anemometer masts used to obtain the local wind-speed during the test process. The relevant filed test layout is shown in Figure 12.

As shown in Table 3, the four average horizontal wind velocities and the corresponding wind-induced displacement are given respectively. Thus, in our supplementary verification, we used the average horizontal wind speed values measured in the field test as the wind speed condition of the finite element numerical simulation, and

![Figure 11. Vertical velocity distributions at centers of Line 1 and Line 2 from the experiments and simulations.](image)

![Figure 12. Wind-induced displacement filed test: (a) catenary system, (b) Installation of monitoring points, (c) displacement monitor point in contact wire (d) anemometer measuring mast.](image)
Table 3. Comparison of horizontal displacement of midpoint obtained from the simulations and experiments.

| Wind-velocity (m/s) | Result of midpoint |
|---------------------|--------------------|
|                      | Experiment (mm)    | Simulation (mm) | Error (%) |
| 26.5                | 46.6               | 45.3            | 2.8       |
| 30.6                | 56.3               | 52.2            | 7.3       |
| 34.9                | 73.4               | 68.4            | 6.8       |
| 39.3                | 86.5               | 78.9            | 8.7       |

Table 4. Wind speed at contact wires positions of different windshield height with $V_{inlet} = 40$ m/s.

| Catenary position | $V_y$ | $V_z$ |
|-------------------|-------|-------|
| Height            | Line 1| Line 2| Line 1| Line 2|
| Original          | 51.04 | 50.65 | 4.88  | 1.94 |
| $h = 0.5$ m       | 35.79 | 12.11 | 6.34  | 0.80 |
| $h = 1$ m         | −2.93 | −2.23 | 1.04  | 2.04 |

got the corresponding simulated wind-induced displacement results. Additionally, the discrepancy error, defined by Equation (9), between the wind-induced displacement data obtained from the field tests and numerical simulations were presented in Table 3.

3. Result and discussion

3.1. Velocity field and flow field analysis

3.1.1. Comparative analysis of wind speed at contact suspension position

The wind speed at the position of the catenary suspension has an important influence on the wind-induced displacement, the reduction of wind load in catenary position and the wind-induced displacement of the contact suspension under strong wind conditions does not exceed the relevant specified value is significant to catenary system operation safety is not affected.

Table 4 shows the specific average wind speed of Line1 and Line2 at the position of the contact wire at a crosswind speed of 40 m/s. $V_y$ gradually decreased as the windshield height increased. For $h = 1$ m, the horizontal wind speeds at the contact wire positions of Line1 and Line2 were 94.26% and 95.60% lower than those of the original type, respectively, and the directions were opposite. However, the values for Line1 and Line2 were significantly different than those for $h = 0.5$ m. Generally speaking, the variation range of $V_z$ at different windshield heights is much smaller than that of $V_y$, and the fluctuation range of $V_z$ is concentrated in 0–10 m/s. Specifically, $V_z$ value in Line1 first increased in the range of h from 0 m to 0.5 m, and reached 6.42 m/s when $h = 0.5$. On the contrary, when $h$ is within the range of 0.5 m to 1 m, the value of $V_z$ gradually decreases. The change trend of $V_z$ value in Line2 showed an opposite way, and had a smaller $V_z$ value when $h = 0.5$ m, 0.8 m/s. In summary, the change in the height of the windshield had a greater effect on $V_y$ than on $V_z$.

3.1.2. Horizontal velocity field distribution

Figure 13 depicts the mean horizontal wind velocity distribution around the windbreak and wake region of the middle plane. The horizontal axis is the non-dimensional horizontal position $y/H$, and the vertical axis is the non-dimensional vertical position. The colors correspond to the non-dimensional velocity $V_y/V_{inlet}$ and the white dots in the figures indicate the positions of the contact wires.

As shown in Figure 13(a), the horizontal velocity slightly changed from the velocity inlet to horizontal position $y/H = −7.5$, and the dimensionless velocity $V_y/V_{inlet} = 1–1.1$. The flow speed gradually increased along the slope on the windward side of the windbreak, reaching a maximum at the top and generating flow separation. On the leeward side, a reverse flow region appeared from the separation point to the horizontal position $y/H = 7.5$ and perpendicular to the ground. The dimensionless velocity $V_y/V_{inlet}$ around the tracks was less than 0. $V_y/V_{inlet}$ was larger than 1.2 From the separation point to the horizontal position $y/H = 7.5$ and the vertical position $z/H = 7.5$, the $V_y/V_{inlet}$ value was larger than 1.2 that inside the black contour line. The position of the contact wire was within the area of the maximum horizontal wind speed.

The horizontal velocity distributions for the windshield heights $h = 0.5$ m and 1.0 m are shown in Figure 13(b,c) respectively. Similar to Figure 13(a) on the windward side, the velocity near the ground gradually increased along the windward slope of the windbreak. The difference was that the separation point was located at the top of the windshield instead of the windbreak. Compared with the original type, after the windshield was heightened, the range of the reverse flow region on the leeward side was wider, and the reverse flow velocity was larger. Furthermore, the region of the reverse flow extended with the increase in the windshield height, and the flow re-attachment point was also farther away in the downstream region, which was located at the horizontal positions near $y/H = 12.5$ and 17.5. The accelerated flow region ($V_y/V_{inlet} > 1$) tended to expand after the windscreen height was increased, and the maximum value of $V_y$ was larger as well. Due to the shielding effect of the windshield on the incoming flow, the accelerated flow region moved upward and gradually moved away from $C_{line 1}$ and $C_{line 2}$. $C_{line 1}$ and $C_{line 2}$ in Figure 13(c) were both in the area of lower $V_y$ compared to those in Figure 13(a,b).

Figure 14 shows the vertical distribution of the $V_y/V_{inlet}$ profile along the horizontal $y/H$ positions
downstream, where the contact wires were at a height $z/H = 1.8$. When $y/H \leq 5$, the vertical trends of $V_y/V_{inlet}$ for the three cases were consistent, including the maximum inflection points (height $z/H \approx 1.5–2.5$), and the inflection points moved upward with the increase in the windshield height. A crosswind acceleration phenomenon occurred at heights approximately equal to those reported by (Dong et al., 2010) and (Avila-Sanchez et al., 2016). When $y/H > 5$, variations of $V_y/V_{inlet}$ in the vertical direction became gentle, and the maximum inflection point no longer appeared. The distance required for flow restoration with uniform shapes was basically the same as that shown in Figure 13.

3.1.3. Vertical velocity field distribution
The distributions of the mean velocity in the vertical direction are presented in Figure 15(a–c) for the different windshield heights, colored based on the non-dimensional vertical velocity $V_z/V_{inlet}$. As shown in Figure 15(a), the incoming flow increased in the vertical direction along the windward slope of the windbreak, generating a strong upward flow and reaching a maximum value at the top. Kamada explained that the steep slope caused an upward flow and accelerated due to flow contraction (Kamada et al., 2019). The $V_z/V_{inlet}$ value inside the white contour line (range of $0 < z/H < 5$, $-7.5 < y/H < 0$) was larger than 0, as represented in the vortex distribution form. Meanwhile, the black lines in Figure 15 represent $V_z/V_{inlet} = 0$, which was the boundary layer between the upward and downward flow. In Figure 15(a), the black line at the horizontal position of $y/H \approx 2.5$, and the reverse flow center was located at $z/H \approx 2$ and $y/H \approx 5$.

A comparison of Figure 15(b,c) shows that after increasing the height of the wind wall, the distributions of the vertical and horizontal velocities differed in that the vertical wind speed formed a maximum area at the top position of the top of the windshield instead
Figure 14. Variations in the mean horizontal wind speed profile in different horizontal positions: (a) $y/H$ = Line 1 center, (b) $y/H$ = Line 2 center; (c) $y/H$ = 3, (d) $y/H$ = 5, (e) $y/H$ = 10, and (f) $y/H$ = 15.

of the contact wire positions above. However, the vortex distribution area extended as the windshield height increased, which can be explained by the role of the windshield, which lifted the flow. The higher the windshield, the more significant the acceleration effect of the flow. In Figure 15(c), the range for $V_z/V_{inlet} > 0.1$ was $0 < z/H < 8$ and $-7.5 < y/H < 4$, which became wider than that of the original type. On the leeward side of the windbreak, compared to the original type, as the height of the windshield increased, the black contour line and the center of the reverse flow area moved backward. The centers of the reverse flow regions of $h = 0.5$ and 1 m were located at horizontal positions of $y/H = 10$ and 15, respectively. After heightening the windshield, the positions of $C_{Line 1}$ and $C_{Line 2}$, which were near the white contour lines, gradually moved away from this region, and their absolute vertical wind speeds ($V_z$) were also close to zero.

Figure 16 shows the vertical distribution of the $V_z/V_{inlet}$ profile along the horizontal $y/H$ positions downstream. The vertical wind speeds at the centerlines of Line 1 and Line 2 for the three cases were all positive values. After raising the windshield, $V_z/V_{inlet}$ reached a maximum value (0.2) at the height $z/H \approx 2$–2.5. The wind speed of Line 1 was greater, but the contact wire position of interest was at a height of $z/H = 1.8$, where the values for Line 2 and Line 1 were both $< 0.1$. In general, the flow separation caused by the shielding effect of the windbreak had little effect on the vertical flow component of the catenary wire position, and similar results were obtained from the wind tunnel test of Dong (Dong et al., 2010). It is speculated that the wind-induced displacement of the contact wire was mainly caused by horizontal wind. Based on the analysis of the variations of the wind speed in the two directions at the catenary wire position, it was inferred that the height of the windshield had a much smaller effect on the vertical wind speed at the position of the contact wire than on the lateral wind speed.

3.1.4. Velocity vector diagram

Figure 17 shows the streamlines distribution projected on the middle-cross section with windshield at different heights, where the background is colored by mean velocity magnitude. There were two main vortices in the field at the leeward side, which were vortex 1 between the slope foot on the leeward side of the windbreak and tracks and vortex 2 located in the far-wake region downstream.
As the height of the windshield increased, the position of vortex 1 did not change much, but the range increased to some extent. However, the position of vortex 2 gradually moved in the downstream direction, and the range increased significantly. In addition, the reverse flow from vortex 2 gradually weakened after encountering the ballast bed, resulting in a generally small velocity between the track and the windbreak. Some flows remained upward along the leeward slope, contributing to an increase in the flow over the windbreak. The red wireframe in the picture shows the reattachment point of the airflow, which was also the position when the airflow began to reverse.

3.2. Catenary wind-induced displacement analysis

3.2.1. Relationship between wind speed and displacement

In order to explore the relationship between the wind-induced displacement of the midpoint of the contact wires and the hanging point under different horizontal and vertical wind speeds. The wind speed was only varied in one direction at a time, and the windspeeds in the other directions were set to zero. The specific values of the contact wire displacement at differentwind speeds are summarized in Tables 5 and 6.

Fit curves based on the wind-induced displacements under different wind speed conditions are shown in Figure 18. When only increasing the horizontal or vertical wind speed, the wind-induced displacement in the corresponding direction increased, and the midpoint was more sensitive to the response of the wind speed than the hanging point was. This was consistent with the conclusions obtained by Xie and Zhi (2019).

However, the increase in wind speed in the same direction had no evident effect on the displacement in the other directions. When the horizontal wind speed was increased from 10 to 60 m/s, the lateral displacement at the midpoint increased from 10.68 to 198.41 mm, while the vertical displacement only increased by 5 mm.
Figure 16. Variations in mean vertical wind speed profile at different horizontal positions: (a) \( y/H = 0 \) at Line1 center, (b) \( y/H = \) Line2 center, (c) \( y/H = 3 \), (d) \( y/H = 5 \), (e) \( y/H = 10 \), and (f) \( y/H = 15 \).

The growing relationship between the wind-induced displacement and wind speed was non-linear.

### 3.2.2. Wind-induced displacement analysis

Based on the response of the midpoint of the contact wire was more sensitive under a wind load than that at the other locations and the consideration of the most dangerous situation, the wind-induced displacement of the midpoint at Line1, where the value of wind speed is larger than that of Line2 in all three cases, was used as the reference displacement for analysis. Because the horizontal displacement of the contact wire due to its deformation is much larger than the wire displacement due to the deformation of the column, the column’s wind load was not be analyzed in the rest of the article.

Figure 19 shows the lateral displacement distribution around the midpoint of the contact wire under the simultaneous application of wind loads in the horizontal and vertical directions. The displacement shown in the figure is the lateral displacement of the catenary system under multiple loads combined with a wind load, assembly prestress, and gravity.

As shown in Figure 19(a–c), the displacement at the origin near the hanging point did not change significantly and was small enough to ignore for the different windshield heights. Meanwhile, the displacement in the midpoint-near region was greatly affected by the wind load. Although all three conditions were in the region with the largest displacement value in the entire system, as the windshield height increased and the wind load decreased, the displacement was also accordingly reduced.

Figure 20 shows the fit curve of the wind speed magnitude and the wind-induced displacement for different windshield heights. The trends of the curves, which indicated the amount of lateral and vertical wind-induced displacement under the action of a crosswind both gradually decreased to nearly zero, especially of lateral direction that sharply decreased from 143.62 mm at original type to 0.47 mm at \( h = 1 \) m, a decrease of 99.67%. Since the special connection and low rigidity, the catenary system is a wind-sensitive structure, and wind-induced displacement increased may cause the strong fluctuation in contact force as well as the increased
occurrence of contact loss that subsequently leads to a significant deterioration of the pantograph-catenary current collection (Pombo et al., 2009; Pombo & Ambrósio, 2013; Song et al., 2016, 2017; Zhou et al., 2018). After the windshield is increased to 1 m giving a smaller value of wind speed and corresponding wind load, it can be effectively ensure the wind-induced displacement within a smaller range.
Figure 18. Relationship between wind speed direction and displacement: (a) wind-induced displacement of horizontal wind and (b) wind-induced displacement of vertical wind.

Figure 19. Lateral displacements of midpoint for the different windshields: (a) original type, (b) $h = 0.5$ m, and (c) $h = 1$ m.

4. Conclusions and future work

For the problem of insufficient wind protection in the earth embankment walls along the Lanzhou-Xinjiang Railway, many researchers have proposed optimization methods to improve the aerodynamic characteristic and enhance the operational speeds of passenger trains. This study was focused on the impact on the wind-induced displacement of a catenary system after adding a thin windshield on the top of the original wind wall. CFD based on the IDDES method was used to analyze the wind speed at the suspension position and flow field structure of the catenary area before and after the
optimization. The finite element analysis method was used to calculate the two-direction displacement of the contact wire and further explore the effect of increasing the height of the wind wall on the catenary displacement. In addition, the data from field tests obtained at a wind speed monitoring front and behind an earth embankment wall were used to validate the calculation method. The results led to the following conclusions.

1. Increasing the height of the earth embankment wind wall had a greater impact on the wind speed in the leeward area. The lateral wind speed at the position of the catenary decreased as the height of the windshield increased, and a case with $h = 1$ m was compared to the original wall. The horizontal wind speeds of Line1 and Line2 were reduced by 94.26% and 95.60%, respectively. However, the vertical wind speed changes were relatively small.

2. In terms of the flow field, the incoming flow separated at the top of the wind wall and reattached in the far region in the downstream direction. The maximum horizontal wind speed area moved upward with the shielding effect of the windshield, and the wind speed in the area where the contact wire was located was relatively small. Meanwhile, the vertical wind speed showed a vortex distribution at the top of the windshield, and the reverse flow area on the leeward side became wider as the height of the windshield increased.

3. The wind-induced response of the midpoint was more intense than that at the hanging point, and the change in the wind speed in a single direction only strongly induced the displacement in the corresponding direction. After the windshield height was increased to 1 m, the lateral-wind-induced displacement of the midpoint was reduced by 99.67% due to the decrease in the wind speed at the back. In addition, the vertical displacement remained small after the height was increased.

As a basic part of the systematic and accurate study of the influence of different windshield types on the safety of the catenary and train operation under crosswind, this paper conducted a basic systematic research of the flow field characteristics and wind-induced displacement of the catenary for the earth embankment type windbreak wall with different heights in the absence of the train. When considering the existence of the trains under the catenary, the results obtained may be different from this paper. After understanding the wind around the specific and actual area in the present work, in further research, we will further study the influence of different windshield configurations such as heights and porosities on the flow field and catenary in consideration of the existence of the static and moving train.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors acknowledge computing resources provided by the High Speed Train Research Centre of Central South University, China. This work was supported by the National Nature Science Foundation of China (U1534210), the Fundamental Research Funds for the Central University of Central South University (No. 1053320183767).

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