

Article

Track Sand Deposition and Prevention Measures Under Railway Windbreak Walls in Strong Wind–Sand Areas

Guowei Xin ^{1,*}, Jiaxing Xu ¹, Youchun Ding ¹ and Chao Zhang ²

¹ School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China; 15962891197@163.com (J.X.); dyc3432128477@163.com (Y.D.)

² Department of Mechanics, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China; zhangchao@lzu.edu.cn

* Correspondence: xingw@mail.lzjtu.cn

Abstract

This study investigates track sand deposition on the leeward side of subgrade windbreak walls along the Xinjiang section of the Lanzhou–Xinjiang High-Speed Railway. Numerical simulations and wind tunnel tests were conducted to compare flow-field reconstruction, sand transport, and track sand deposition under three structural configurations. The results show that a strong shear layer and a large-scale recirculation vortex form behind a single windbreak wall. The local reverse velocity reaches approximately -10 m/s, which can entrain sand particles back toward the track area. Adding a second wall at the leeward slope toe reduces near-surface wind speed to some extent, but local vortices and high-shear zones remain. In contrast, placing checkerboard sand barriers at the leeward slope toe effectively weakens near-surface recirculation and bed shear. This configuration maintains surface shear stress near the track below 0.5 Pa and reduces sand concentration by approximately 60–80% compared with the single-wall structure. At wind speeds of 15–30 m/s, the checkerboard sand barrier maintains strong sand-reduction performance. Near-surface peak sand concentration decreases by about 38–75%, and track sand deposition decreases by about 42–43% relative to the single-wall structure. These findings indicate that checkerboard sand barriers on the leeward side of windbreak walls can substantially reduce the risk of secondary sand deposition induced by the walls. The proposed leeward-side protection measure can effectively mitigate sand accumulation on railway infrastructure, thereby improving the long-term operational safety, resilience, and sustainability of high-speed railways in desert environments under increasing wind–sand hazards.

Keywords: Lanzhou–Xinjiang High-Speed Railway; windbreak wall; strong wind; sand deposition; checkerboard sand barrier

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1. Introduction

The Lanzhou–Xinjiang High-Speed Railway is an important high-speed rail corridor in Northwest China and the world's first high-speed railway to traverse extensive Gobi and desert regions [1,2]. It crosses several strong-wind zones in Xinjiang, including the Baili, Sanshili, Dabancheng, and Yandun wind zones [3,4]. In these areas, the ground surface is predominantly bare, vegetation is sparse, sand sources are abundant, and wind-blown sand activity is frequent [5]. Owing to the region's distinctive terrain and climate,

some wind zones along the Lanzhou–Xinjiang High-Speed Railway have recorded instantaneous extreme gusts of up to 64 m/s (in the Baili wind zone). Strong winds often entrain large quantities of sand particles, creating a typical strong wind-blown sand environment. As a result, the Xinjiang section faces not only sand deposition and track burial, but also operational risks to trains under strong crosswind conditions.

Strong wind-blown sand affects railway systems in two main ways. First, strong crosswinds alter the aerodynamic loads on trains, increasing lateral force, overturning moment, and wheel–rail instability, particularly on high embankments, in open Gobi terrain, and in mountain-pass wind zones [6–10]. Second, strong winds transport sand particles through saltation, creep, and short-duration suspension near the ground [11]. When airflow encounters subgrades, windbreak walls, power facilities, and track structures, local flow separation, deceleration, and reattachment occur [12,13], causing sand to accumulate on track slabs, fasteners, ballast shoulders, and subgrade platforms. Sand accumulation near the rails increases the demand for track inspection and sand removal, may affect track-structure performance and the operating environment, and poses long-term risks to railway operation and maintenance in sandy regions [14]. Field observations along the Lanzhou–Xinjiang High-Speed Railway indicate that sand accumulates on track slabs, near the rails, and on subgrade platforms on the leeward side of windbreak walls, as shown in Figure 1 [15,16]. These observations suggest that leeward-side sand deposition behind windbreak walls is not an isolated local phenomenon, but rather a secondary wind-blown sand problem associated with railway protection structures.



Figure 1. Sand deposition on the leeward side of windbreak walls along the Lanzhou–Xinjiang High-Speed Railway. (a) track sand deposition; (b) railway line sand deposition; (c) track sand deposition; (d) track sand deposition.

To ensure the safe operation of high-speed trains in strong-wind regions, subgrade windbreak walls have been installed along certain sections of the Xinjiang segment of the Lanzhou–Xinjiang High-Speed Railway. These walls reduce near-surface crosswind velocity and weaken the direct impact of strong winds on train bodies, thereby improving aerodynamic stability and operational safety. However, in areas with abundant sand sources and strong winds, windbreak walls also alter sand transport pathways. When sand-laden airflow passes over a windbreak wall, flow acceleration and a strong shear layer form above the wall, while a low-speed recirculation zone develops on the leeward side [17,18]. Under the combined effects of inertial transport, gravitational settling, and

recirculation-induced entrainment, sand particles may move toward the track area and deposit there, creating a secondary sand-deposition hazard induced by the windbreak facility.

This issue has received limited attention because previous studies have primarily treated windbreak walls as crosswind protection facilities or windward-side sand-blocking structures. Accordingly, their effects on train aerodynamic safety and incoming sand interception have been examined more extensively than their leeward-side influence on sand transport. With increasing train operating speeds and stricter requirements for track cleanliness and maintenance, leeward-side sand accumulation has become more prominent in engineering practice. From a flow-mechanism perspective, sand deposition on the leeward side of windbreak walls is mainly governed by flow separation, recirculation-induced entrainment, and low-speed near-surface settling. When the recirculation zone interacts with the subgrade platform, track slab, and leeward slope toe, the kinetic energy of sand particles decreases rapidly, promoting deposition. Some deposited particles may also be re-entrained by reattachment flow and local vortices. In the strong wind-blown sand environment of the Lanzhou–Xinjiang High-Speed Railway, high wind speed, intense sand transport, and the elevated subgrade structure further intensify wake recirculation, making continuous sand deposition more likely near the track [19].

In recent years, numerous studies have investigated railway wind-blown sand hazards, with a focus on mechanical sand barriers, checkerboard barriers, sand fences, shelterbelts, subgrade optimization, and flow fields around bridges and subgrades [20–23]. Previous findings indicate that sand-control measures can reduce railway sand deposition by lowering near-surface wind speed, increasing surface roughness, and redirecting sand transport pathways. Wind tunnel experiments and numerical simulations have also become important tools for revealing flow fields, sand transport, and deposition patterns along railways [24,25]. Recent studies on high vertical sand fences, porous fences, double-wall systems, and roughness-based energy-dissipation measures further demonstrate that wake-flow regulation can strongly influence sand transport and deposition. Erosion and deposition patterns behind high vertical sand fences, as well as the flow-control effects of porous fences and shelterbelt-like structures in agricultural wind engineering, provide useful references for leeward-side flow regulation behind railway protection structures [4,26–28].

However, most existing studies still focus on incoming sand interception by conventional sand-control measures or on the crosswind protection function of windbreak walls for trains [4,29]. Systematic research on track sand deposition induced by leeward-side recirculation behind windbreak walls remains limited. In particular, the effects of wake-structure evolution, vortex development, surface shear stress, and particle concentration on deposition are not yet fully understood, and the layout and mechanisms of leeward-side mitigation structures require further clarification. Therefore, this study compares a single windbreak wall, an additional solid wall, and checkerboard sand barriers to quantify the secondary deposition effect induced by windbreak walls and to clarify the relationships among wake flow structure, shear stress, particle concentration, and track sand deposition. The results provide a basis for balancing crosswind protection and leeward-side sand accumulation control along sandy high-speed railway corridors.

Based on these issues, this study focuses on sand deposition on the leeward side of subgrade windbreak walls in the Yandun wind zone along the Xinjiang section of the Lanzhou–Xinjiang High-Speed Railway. Numerical simulations and wind tunnel tests are combined to examine the effects of different leeward-side protective structures on wake-flow reconstruction, sand transport, and deposition patterns. By comparing the wind-speed field, velocity vectors, vorticity, Q criterion, surface shear stress, sand concentration, and track sand deposition under three structural configurations, this study reveals the

formation mechanism of sand deposition behind windbreak walls and evaluates the sand-reduction performance of different protective structures. The results provide preliminary guidance for the design of leeward-side sand-deposition mitigation measures. From a sustainability perspective, optimizing leeward-side sand-control measures can reduce maintenance demands, enhance the resilience of railway infrastructure in sandy regions, and support the long-term safe operation of high-speed railways under strong wind–sand conditions.

2. Materials and Methods

2.1. Wind Tunnel Tests

The wind tunnel tests were conducted in the multifunctional environmental wind tunnel at the Key Laboratory of Mechanics on Disaster and Environment in Western China, Ministry of Education, Lanzhou University. This facility is a direct-flow, blow-down, low-speed wind tunnel with a total length of 85 m. The test section is 22 m long and has a cross-sectional area of 1.3 m × 1.45 m. The wind speed can be continuously adjusted from 4 to 40 m/s. To reproduce near-surface flow conditions in strong wind–sand regions along the Lanzhou–Xinjiang High-Speed Railway, spires and roughness elements were installed at the inlet of the test section. After adjustment, a stable turbulent boundary layer with a thickness of approximately 0.3–0.5 m was formed, and the velocity profile followed a near-surface logarithmic distribution. The model height was smaller than the boundary-layer thickness.

The experimental layout is shown in Figure 2. Pitot tubes were used to measure the incoming wind velocity and vertical velocity profiles, and a reference point was placed upstream of the model to monitor flow stability. Wind velocity at each measurement point was recorded continuously for more than 3 min. A uniform sand bed was placed downstream of the roughness elements to provide a stable sand source. The sand bed was 1.3 m wide, 3 m long, and 0.1 m thick. Before each test, the sand bed was leveled to ensure a consistent initial sand supply. Driven by the incoming flow, sand particles were entrained from the sand bed and transported through the subgrade windbreak wall model area, thereby simulating sand transport and deposition behind a windbreak wall under strong sand-laden winds. Sand collectors were arranged downstream of the model to collect transported particles and determine the sand transport rate and deposition patterns under different structural configurations [28].

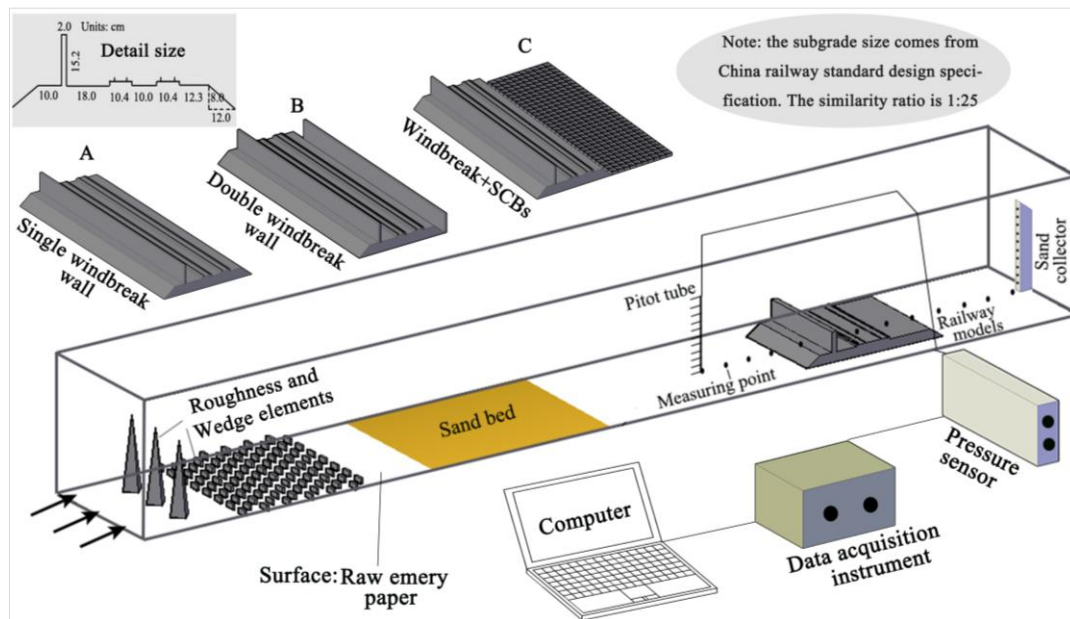


Figure 2. The wind tunnel layout. The windbreak-wall dimensions are indicated in the figure, and the second solid wall is 2 m high. In Case C, the checkerboard barriers were arranged from the leeward slope toe and consisted of 10 rows of solid cells. Each cell had a side length of 0.1 m, an above-ground height of 0.02 m, and a porosity of 0. Unlike traditional straw checkerboards for desertification control, these barriers were concrete or stone engineering structures suitable for Gobi surfaces. A: Single windbreak wall; B: Double windbreak wall; C: Windbreak + Straw checkerboard barriers (SCBs).

Three configurations were tested. Case A consisted of a single subgrade windbreak wall. Case B comprised a windbreak wall with an additional solid wall installed at the leeward slope toe. Case C comprised a windbreak wall with checkerboard sand barriers installed at the leeward slope toe. Case A represented the existing windbreak wall condition. Case B was used to examine whether an additional rigid wall could regulate the leeward recirculation flow. Case C was used to evaluate the extent to which checkerboard sand barriers could reduce near-surface wind speed, suppress sand transport, and mitigate sand deposition on the track. All models were designed according to geometric similarity with a scale ratio of 1:25 to ensure comparability of the flow and sand-transport behavior among the three configurations.

The checkerboard sand barriers considered in this study are not straw checkerboards, but concrete or stone checkerboard structures designed for railway protection in strong wind–sand environments. Their sustainability primarily lies in reducing maintenance demands, extending protection effectiveness, and enhancing the resilience of railway infrastructure in sandy regions. However, concrete or stone checkerboards inevitably require material consumption and generate associated carbon emissions.

Wind velocity was measured using Pitot tubes mounted on a vertical frame at heights of 2.0, 4.0, 7.0, 10.0, 15.0, 20.0, 30.0, and 45.0 cm. A sand collection system was installed downstream of the model to capture transported particles and calculate sand flux. In addition, deposited sand was collected and weighed from the track area, subgrade platform, leeward slope, and slope toe to determine the spatial distribution of sand deposition. Before the formal experiments, baseline tests were conducted under empty-field conditions to obtain reference wind profiles and sand-transport characteristics. These tests were used to verify the stability of the incoming flow and sand supply. Comparative experiments were then performed for Cases A, B, and C. The incoming wind velocities were set to 15 and 30 m/s.

The experimental sand was natural aeolian sand with particle sizes ranging from 40 to 500 μm , a mean particle size of approximately 200 μm , and a particle density of 2650 kg/m^3 . The median particle size, d_{50} , was approximately 0.20 mm, the characteristic coarse particle size, d_{84} , was approximately 0.32 mm, and the uniformity coefficient was about 2.1. The particle-size distribution was approximately normal. According to the empty-field wind tunnel tests, the threshold wind velocity of the sand particles was approximately 5–6 m/s, corresponding to a threshold friction velocity of about 0.22–0.25 m/s. To assess experimental repeatability, each test condition was repeated three times under identical operating conditions. The reported sand deposition values are mean values, and the corresponding standard deviations were used to quantify experimental uncertainty. The sand-blowing duration in the wind tunnel was 5 min.

The wind tunnel tests primarily satisfied geometric similarity, whereas strict similarity in Reynolds number, particle motion, and deposition time could not be achieved simultaneously. At a scale of 1:25, the prototype mean particle diameter of 200 μm would be reduced to approximately 8 μm , which would substantially alter particle entrainment, suspension, settling, and adhesion behavior and therefore could not realistically represent wind-blown sand motion. Based on the model height of 0.232 m and a wind speed of 15 m/s, the Reynolds number is approximately 2.38×10^5 , which is sufficiently high to capture relative differences in sand deposition behind the windbreak wall. However, owing to the geometric scaling between the wind tunnel model and the full-scale numerical model, the wind tunnel deposition results were not used to quantitatively extrapolate prototype deposition rates or time scales. Instead, they served as physical comparative tests to verify whether the deposition patterns and sand-reduction rankings of the different structures were consistent with the full-scale numerical results. Quantitative analyses of flow structure, reattachment length, surface shear stress, and particle transport were mainly based on the full-scale numerical simulations.

2.2. Numerical Simulation Design

Large-eddy simulation (LES) was employed to solve the unsteady turbulent flow around the windbreak wall and the leeward protective structures. This method was used to capture shear-layer separation, recirculation vortex development, and near-surface turbulence behind the wall. Based on the transient flow field, a Lagrangian particle-tracking method was further applied to calculate sand particle trajectories, spatial concentration, and deposition patterns under different structural configurations. This approach helped reveal how flow-field variations influence sand transport and deposition.

2.2.1. Geometric Model

A three-dimensional computational model was established based on the subgrade windbreak wall and track structure of the Lanzhou–Xinjiang High-Speed Railway. The numerical model was consistent with the wind tunnel model. The computational domain measured 20 m $\times$ 6 m $\times$ 5 m, and the geometric scale ratio was 1:25. Three structural configurations were considered: a single subgrade windbreak wall, an additional solid wall at the leeward slope toe, and a combined structure comprising the windbreak wall and an optimized protective measure. The computational domain is shown in Figure 3.

2.2.2. Mesh Generation

The computational domain was discretized using structured hexahedral grids. Local refinement was applied in regions with strong velocity gradients and particle deposition, including the top of the windbreak wall, the wake region, the subgrade surface, the track area, and the leeward slope toe. Near-wall inflation layers were generated to improve

boundary-layer resolution, with 18 layers and a growth rate of 1.2. The final mesh contained approximately 42 million cells. Mesh quality was checked before calculation to ensure numerical stability and adequate spatial resolution.

Near-wall resolution was evaluated using the y^+ value. The area-weighted average y^+ was approximately 20.1; more than 90% of the wall surfaces had y^+ values between 5 and 30, and the maximum y^+ was 74. The wall-adjacent cell-center distance was approximately 0.5 mm, corresponding to a first cell height of about 1.0 mm. The maximum value occurred only in limited regions near sharp edges or strong flow separation, whereas most wall regions remained suitable for WALE-based LES calculations. Therefore, the mesh resolution was considered sufficient to capture the main separated shear layer, wake recirculation, near-surface velocity gradients, and wall shear stress around the windbreak wall system, providing a basis for analyzing vorticity, the Q criterion, surface shear stress, and particle transport.

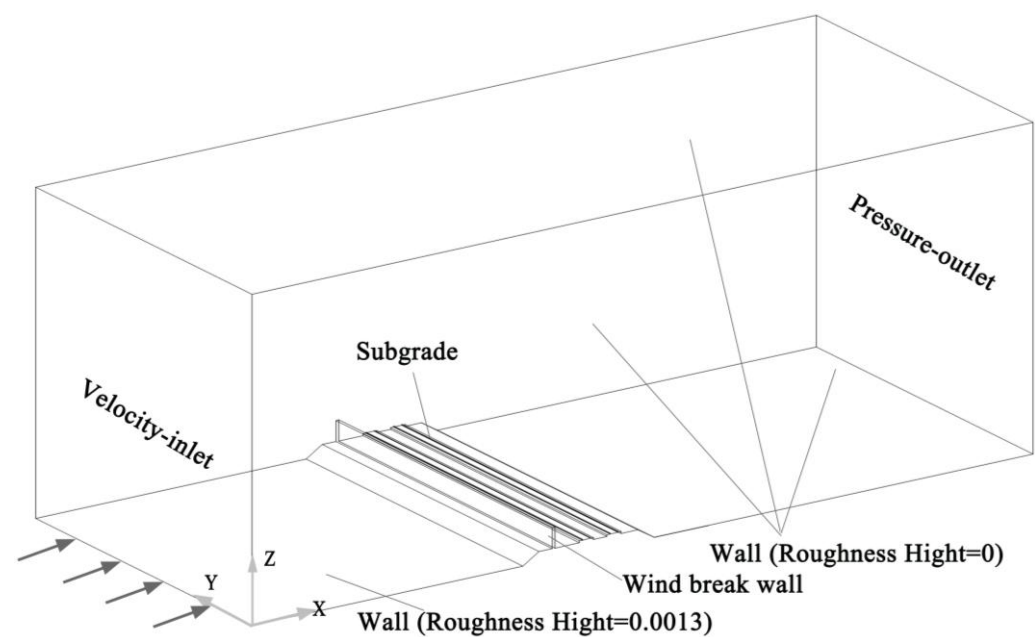


Figure 3. Computational domain for the numerical simulation.

2.2.3. Boundary Conditions

For the air phase, a velocity-inlet boundary condition was applied at the inlet of the computational domain. The inlet wind speed followed a near-surface logarithmic profile to represent the wind field characteristics in actual wind–sand areas. A free-outflow boundary condition was used at the outlet, allowing the airflow to leave the computational domain naturally and reducing the influence of the outlet boundary on the recirculation structure behind the windbreak wall. The subgrade surface, windbreak wall, track structure, and leeward-side protective structures were all defined as no-slip walls. The surface roughness length was set to $z_0 = 0.0013$ m to represent the roughness characteristics of the Gobi desert surface. The surface roughness z_0 affects the near-surface velocity profile and bed shear stress. However, because the same Gobi roughness was used in all cases, small variations in z_0 would mainly change the absolute values of wind speed and shear stress, while having limited influence on the relative trends among different protection structures.

For the sand phase, sand particles were described using the discrete phase model (DPM) and tracked by the Lagrangian method. Particles were released near the inlet to

simulate the transport process of sand-laden flow entering the computational domain under strong wind conditions. In the discrete phase model, the inlet boundary was set as an escape boundary to avoid particle rebound near the inlet and its disturbance to the incoming flow. The outlet boundary was also set as an escape boundary, so that particles transported downstream could leave the computational domain naturally. For the subgrade surface, track, windbreak wall, and leeward-side protective structures, particle-wall interactions were treated as trapping or rebound according to the particle motion state, to represent sand deposition, collision, and re-transport. This boundary setting can reasonably reflect sand transport, deposition, and backflow behind the windbreak wall.

2.2.4. Computational Parameters

The incoming wind speeds were set to 15 m/s and 30 m/s. The air phase was treated as an incompressible fluid, with a density of 1.225 kg/m³ and a dynamic viscosity of 1.789×10^{-5} Pa·s. The sand phase was modeled using the discrete phase model. The particle diameter ranged from 40 to 500 µm, with a mean diameter of 200 µm and a particle density of 2650 kg/m³. This limitation remains because sensitivity to particle-size discretization and distribution tails was not further examined. Real wind-blown sand may deviate from the assumed normal particle-size distribution. More fine particles would enhance suspension and long-distance transport, while more coarse particles would increase inertia and settling, causing deposition closer to the leeward slope toe and low-speed zones. Therefore, the 200 µm normal distribution was used mainly for relative comparison among structures. Based on the mean particle diameter of 200 µm, a characteristic length of 5.8 m, and a wind speed of 15 m/s, the particle relaxation time was approximately 0.33 s, giving a Stokes number of about 0.85, which indicates a certain inertial response of the sand particles. The particle-size distribution was assumed to follow a normal distribution and was divided into 20 size groups. Sand particles were released from the inlet of the computational domain using a uniform area injection method. For the particle boundary conditions, the inlet and outlet were defined as escape boundaries, while the other solid walls were treated as reflective boundaries.

The inlet wind speed followed the logarithmic law:

$$u_{(z)} = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \quad (1)$$

where $u_{(z)}$ is the wind speed at height z , u_* is the friction velocity, κ is the von Kármán constant, taken as 0.4, and z_0 is the surface roughness length.

2.2.5. Solution Mode

The flow field was solved using large eddy simulation (LES) to capture the shear layer, recirculation vortices, and unsteady turbulent structures behind the windbreak wall. Sand particle motion was described using the discrete phase model (DPM). Particles were released near the inlet to simulate the transport of sand-laden flow entering the computational domain under strong wind conditions. The particle phase was tracked using the Lagrangian method. An escape condition was imposed at the inlet boundary to prevent particle rebound and its influence on the results.

The transient LES used a fixed time step of 1×10^{-4} s, and the CFL number was maintained below 1 in most regions. Before particle release, the flow was simulated for approximately eight flow-through times. The first four flow-through times were used for flow development, and the remaining period was used for statistical averaging. The DPM was solved using one-way coupling, with particle-wall interactions modeled by rebound and trapping conditions. This approach was adopted because the study focused on the relative deposition differences among the three structures under the same inlet particle conditions,

whereas two-way coupling would have significantly increased the computational cost due to the large LES domain and dense grid system. This simplification neglects particle feedback on the airflow and may underestimate local feedback effects in regions with dense sand-laden flow.

2.2.6. Governing Equations

The gas phase was treated as incompressible and described by the continuity and momentum equations. Turbulence was resolved using the filtered LES equations. The particle phase was calculated using the Lagrangian equation of motion, in which drag force, gravity, and particle-wall interactions were considered.

The continuity and momentum equations are expressed as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = F_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (3)$$

where u_i denotes the velocity component in direction i ; p is the pressure; ρ and ν are the fluid density and kinematic viscosity, respectively; and F_i represents the additional body force, expressed as follows:

$$F_i = \frac{1}{V_{cell}} \sum_{n=1}^{n_{cell}} \frac{1}{2} C_{dp} A_p |u - u_p| (u_i - u_{pi}) \quad (4)$$

where u and u_p are the air and particle velocities, respectively; A_p is the particle cross-sectional area; C_{dp} is the particle drag coefficient; N_{pcell} is the number of particles in each cell; and V_{cell} is the cell volume.

The LES method decomposes the flow variables into large-scale resolved components and small-scale subgrid-scale components through spatial filtering.

$$\frac{\partial}{\partial t} (\rho \tilde{u}_i) + \frac{\partial}{\partial x_j} (\rho \tilde{u}_i \tilde{u}_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (\mu \frac{\partial \tilde{u}_i}{\partial x_j}) - \frac{\partial \tau_{ij}}{\partial x_j} \quad (5)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \tilde{u}_i) = 0 \quad (6)$$

where τ_{ij} is defined as:

$$\tau_{ij} = \rho \overline{\tilde{u}_i \tilde{u}_j} - \rho \tilde{u}_i \tilde{u}_j \quad (7)$$

where τ_{ij} denotes the subgrid-scale stress. It represents the effect of unresolved small-scale eddies on the resolved large-scale turbulent motion in the filtered momentum Equation (6). In this study, the WALE model was used as the subgrid-scale closure model.

The net force acting on a sand particle is given by:

$$m_p \frac{du_p}{dt} = F_D + F_g \quad (8)$$

$$F_D = \frac{1}{8} C_D \pi D^2 \rho |u - u_p| (u_i - u_{pi}) \quad (9)$$

$$F_g = \frac{1}{6} \pi (\rho_p - \rho_{air}) D^3 g \quad (10)$$

where u_p is the particle velocity; D is the particle diameter; and ρ_p is the particle density.

2.2.7. Computational Procedure and Accuracy Control

The simulation was performed in two steps. First, a clean-air simulation was conducted to obtain the wind speed field, velocity vectors, vorticity, Q criterion, and surface shear stress. After the flow field reached a statistically stable state, sand particles were released to simulate sand-laden flow. During the calculation, the main flow parameters fluctuated regularly around stable mean values after the initial development stage, indicating that statistical stationarity had been achieved. Convergence was evaluated using both numerical residuals and physical monitoring parameters. The residual criterion was set to 10^{-6} , and the wind speed, shear stress, and particle concentration at key monitoring points were required to remain stable. The reported mean flow fields and particle concentration results were obtained by time-averaging over the statistically stable period.

3. Results and Discussion

In this work, the full-scale numerical model was adopted as the main approach for evaluating the wake-flow pattern, flow reattachment distance, vortex distribution, ground shear stress, and sand-particle transport process. The wind tunnel tests were conducted mainly to confirm the reliability of the simulated wind-speed profiles and depositional tendencies, instead of deriving reattachment lengths that could be quantitatively scaled up to the prototype.

3.1. Validation of Numerical Simulation Results

Figure 4 presents the validation of the numerical simulation results by comparing the wind-speed variation around the windbreak wall and the vertical distribution of the sand transport rate. As shown in Figure 4a, the simulation accurately reproduces the wind-speed reduction and subsequent recovery observed in the wind tunnel tests, with both results exhibiting a similar trend. The main discrepancy occurs in the near-wall, high-shear region of the windbreak wall. This is primarily because flow separation, local recirculation, and intense unsteady turbulence occur in this region. These flow features are highly sensitive to mesh resolution, wall boundary conditions, and the turbulence model. Figure 4b shows that the sand transport rate initially changes gradually and then increases rapidly with height. The peak occurs at a height of 0.48–0.52 m. The experimental peak is approximately 14–15%, whereas the simulated peak is approximately 18–19%. The peak height is nearly identical in both cases. Overall, the numerical model captures the low-velocity zone behind the windbreak wall, the wind-speed recovery process, and the vertical distribution of the sand transport rate. Therefore, the model can be used to analyze the sand-deposition mitigation effects of different structures.

For the grid-independence analysis, the checkerboard-barrier model was selected as the representative case, and meshes with approximately 30, 42, and 48 million cells were compared. The wind speed at the center of the first track line on the leeward side of the windbreak wall, 0.5 m above the ground, was 1.521, 0.969, and 0.947 m/s, respectively. The small change from 42 to 48 million cells indicates that the solution was nearly grid independent. Therefore, considering both accuracy and computational cost, the 42-million-cell mesh was used for the subsequent simulations.

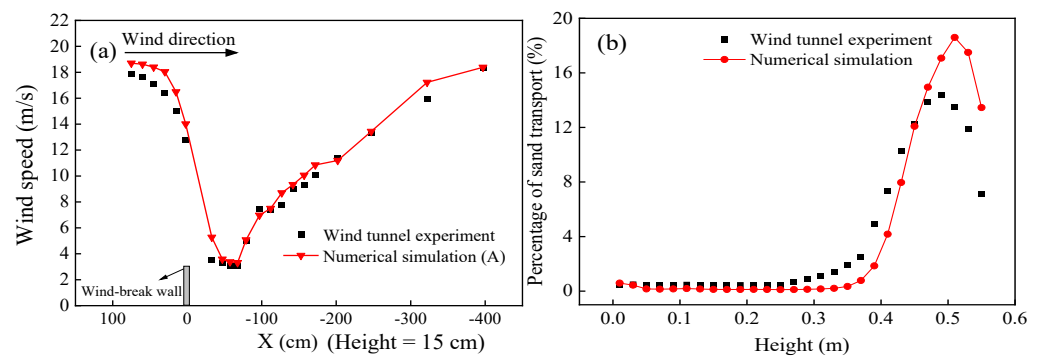


Figure 4. Validation of the numerical simulation results: (a) wind speed; (b) percentage of sand transport.

Based on the validated numerical results, the flow-field characteristics and sand transport variations under the three structural configurations were further analyzed.

3.2. Simulated Flow Fields Under Three Structural Configurations

Figure 5 presents the velocity distributions of the three structures in the x - z plane. The incoming wind speed was 15 m/s, as indicated by the arrow in the figure. As shown in Figure 5, Case A, which includes a single windbreak wall, forms a large low-speed zone behind the wall. The blue low-speed region extends along the subgrade crest and the leeward side, and the near-surface wind speed decreases downstream. However, a continuous high-speed shear layer develops above the low-speed zone, with a maximum wind speed of nearly 20 m/s. This indicates that although the windbreak wall reduces near-surface wind speed, it also induces strong flow acceleration at higher elevations. In Case B, after a solid wall is added at the toe of the leeward slope, the low-speed region near the slope toe expands further. The near-surface wind speed is generally maintained within 0–5 m/s. However, a local high-speed recirculation zone still appears downstream. In Case C, the low-speed zone exhibits the most extensive coverage. The wind speed on the leeward side of the subgrade and near the slope toe is generally controlled within 0–5 m/s. The high-speed region is primarily confined to the area above the windbreak wall. This indicates that Case C more effectively reduces near-surface airflow momentum and weakens the re-entrainment and transport capacity of sand particles on the subgrade surface. Therefore, it provides a more stable low-speed environment and better limits the migration of leeward sand deposition toward the track area.

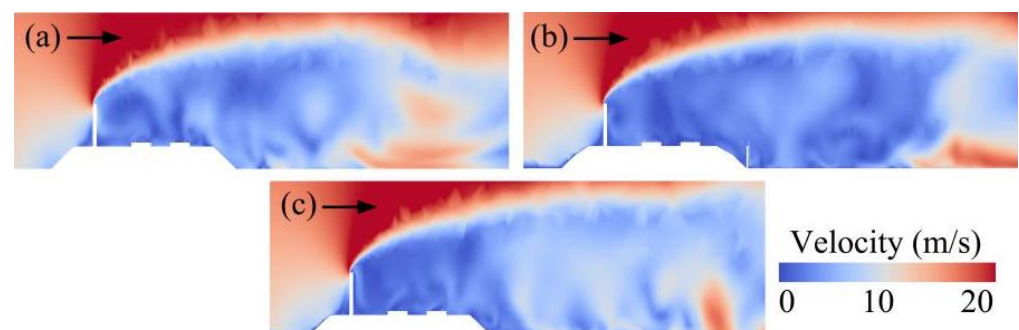


Figure 5. Time-averaged velocity magnitude distribution in the x - z plane (15 m/s). (a) Case A; (b) Case B; (c) Case C.

Figure 6 further presents the velocity vectors of the three structures in the x - z plane, illustrating flow separation, recirculation, and reattachment behind the windbreak wall. As shown in Figure 6, a distinct large-scale recirculation vortex forms on the leeward side

of Case A. The recirculation zone nearly covers the entire subgrade top behind the wall, and the local reverse velocity reaches approximately -10 m/s. This indicates that entrainment by the strong shear layer can drive sand particles back toward the track area. In Case B, the solid wall at the slope toe weakens the near-surface recirculation intensity and shifts the main vortex downstream. However, a continuous vortex structure still persists between the subgrade top and the slope toe, indicating that the blocking effect on recirculation is limited. In contrast, the vortex scale in Case C is significantly reduced. The vector direction becomes smoother, and the extent of reverse velocity decreases. The near-surface airflow is therefore mainly weak and stagnant. These results indicate that Case C blocks the recirculation pathway near the leeward slope toe and weakens the coupled process of “separated shear layer–recirculation vortex–near-surface entrainment.” This is the primary flow-field mechanism by which Case C achieves better sand deposition mitigation than Cases A and B.

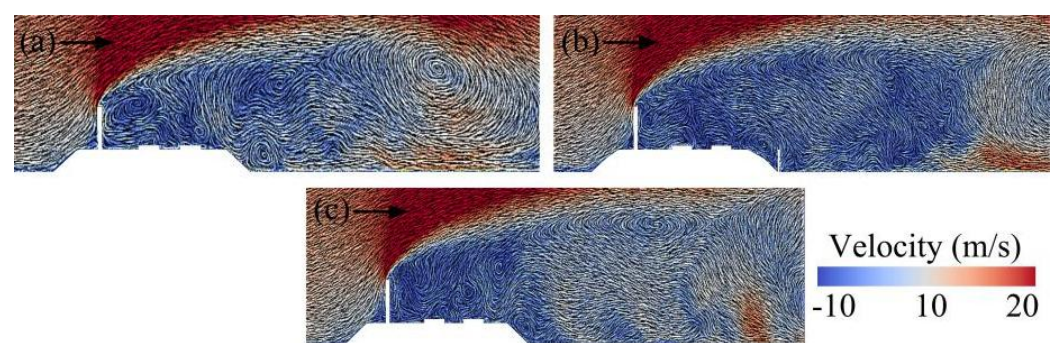


Figure 6. Time-averaged velocity vector and streamwise velocity distribution in the x - z plane (15 m/s). (a) Case A; (b) Case B; (c) Case C.

Figure 7 presents the vertical wind-speed profiles at five streamwise locations, Q1–Q5. These profiles capture the flow development from the windward side, across the windbreak wall, and into the downstream leeward region.

As shown in Figure 7a, the wind-speed profiles for the three cases at Q1 nearly overlap. The near-surface wind speed is approximately 1 – 2 m/s and increases to 16 – 17 m/s at a height of 8 m. This indicates that the additional structures at the slope toe primarily influence the wake flow behind the wall and have little effect on the incoming flow. At Q2, the wind speed within 0 – 2 m decreases to 0 – 6 m/s, whereas the wind speed at 6 – 8 m increases to 16 – 20 m/s. This suggests pronounced flow acceleration above the windbreak wall and the formation of a strong vertical shear layer. Once the flow enters the leeward side, differences among the three cases become more evident at Q3. In Case A, the near-surface wind speed recovers to 0 – 3 m/s, indicating momentum recovery behind the single wall. In Case B, reverse flow of approximately -2 to 0 m/s appears within 0 – 6 m, showing that the solid wall at the slope toe intensifies local recirculation. In Case C, the near-surface wind speed remains close to 0 m/s, while the wind speed at 3 – 6 m is about 1 – 3 m/s. This suggests that Case C suppresses near-surface wind-speed recovery while avoiding strong recirculation-induced entrainment. At Q4 and Q5, Case A still exhibits a near-surface positive velocity of 2 – 3 m/s and an upper-level reverse velocity of -6 to -8 m/s, indicating that the recirculation vortex continues to develop downstream. In Case B, the reverse velocity decreases to about -2 to -5 m/s, but clear backward flow remains. In Case C, the near-surface velocity stays mostly between 0 and -2 m/s, and the main recirculation zone shifts to a higher elevation. Overall, Case C reduces near-surface momentum recovery and shifts the recirculation zone upward. This helps lower the risk of sand re-entrainment and backward transport toward the track area, providing an important flow-field basis for its superior sand-deposition mitigation performance.

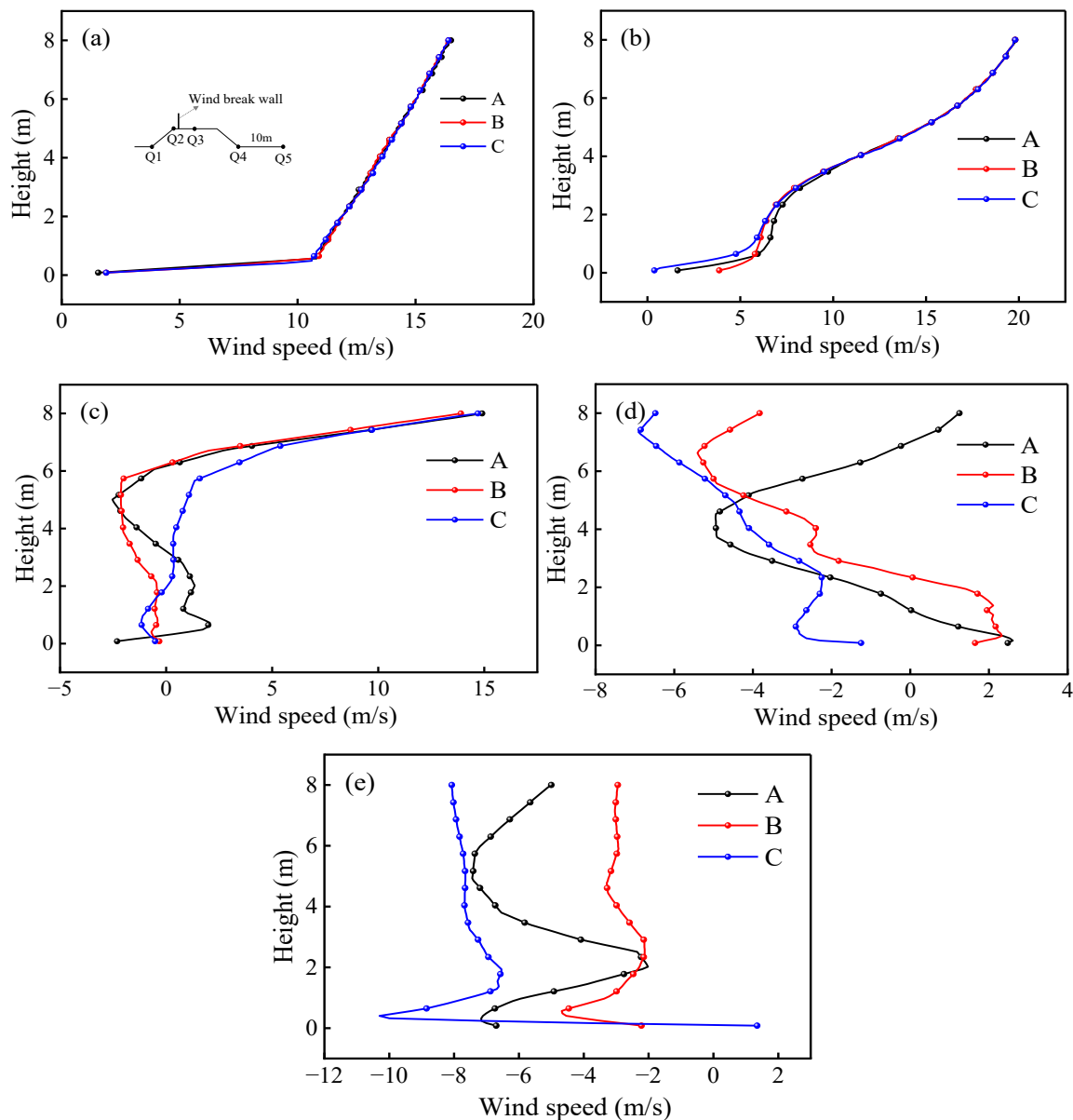


Figure 7. Vertical wind speed profiles at different streamwise positions (15 m/s). (a) Q1; (b) Q2; (c) Q3; (d) Q4; (e) Q5.

Figure 8 shows the streamwise variation in horizontal wind velocity at different heights above the subgrade surface and on the leeward side at a wind speed of 15 m/s. It reflects the near-surface sand transport capacity on the subgrade surface and the downstream leeward side. As shown in Figure 8a, the wind speed in Case A fluctuates markedly over the subgrade crest, with local positive velocities reaching approximately 3 m/s. This indicates pronounced momentum recovery behind the single windbreak wall. In Cases B and C, the wind speed is mainly between -2 and 1.5 m/s, suggesting that the additional structures at the slope toe weaken the positive sand transport capacity on the subgrade surface. Figure 8b shows that the flow velocity above the windbreak wall reaches approximately 18–20 m/s before rapidly decreasing to nearly 0 m/s. Among the three cases, the downstream velocity in Case C is closest to zero, indicating a more stable suppression of flow recovery. After the flow enters the leeward slope, Figure 8c shows that Case A still exhibits positive velocities of about 3–5 m/s at $x = 75$ – 78 m, which can drive sand migration along the slope. In Case B, the velocity is mostly between -6 and -2 m/s, whereas in Case C it remains mainly between -10 and -4 m/s. This indicates stronger

recirculation control in Case C. Figure 8d further shows that, at $H = 5$ m, the downstream velocity in Case B gradually recovers from about -4 m/s to 2 m/s, whereas Cases A and C maintain stronger negative velocities of about -9 to -5 m/s. Overall, Case C substantially reduces the positive wind speed on the subgrade crest and strengthens the low-speed recirculation constraint on the leeward slope. This weakens sand transport and re-suspension toward the track area.

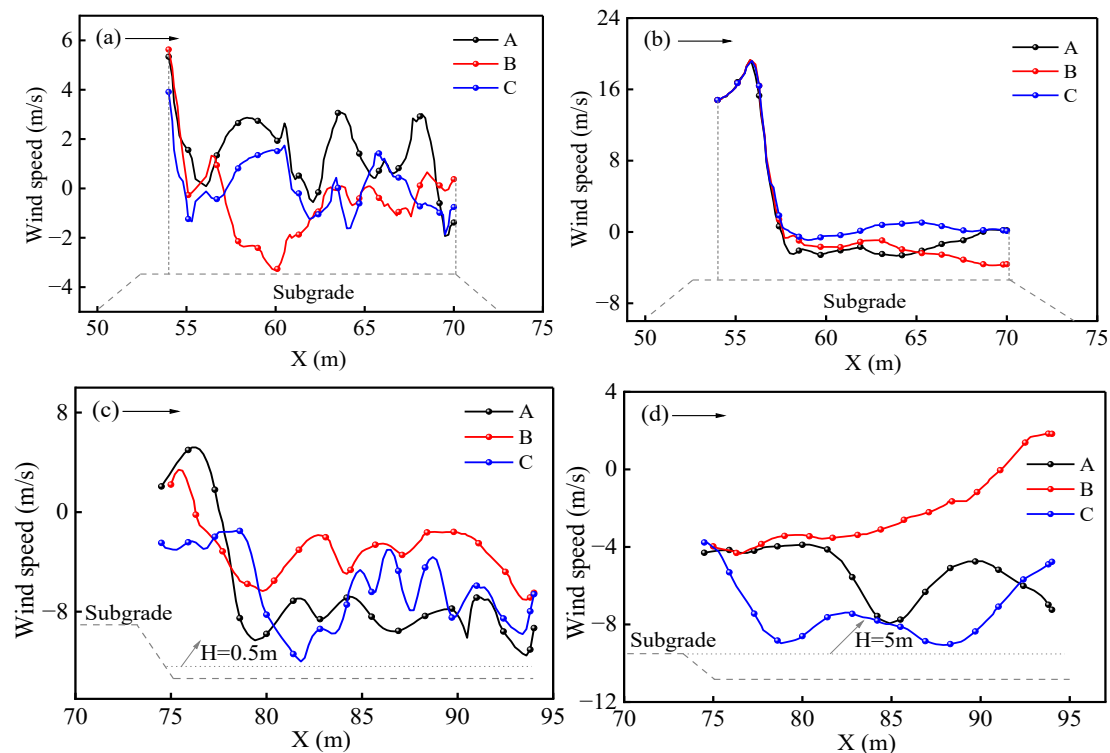


Figure 8. Streamwise variation in horizontal wind speed under different structures at 15 m/s. (a) At a height of 0.5 m above the subgrade surface; (b) at a height of 5 m above the subgrade surface; (c) at a height of 0.5 m on the leeward side; (d) at a height of 5 m on the leeward side.

Figure 9 shows the streamwise vorticity distribution under the three configurations. To reduce the influence of end-wall effects, the discussion mainly focuses on the central leeward region. In Case A, a high-vorticity zone develops near the wall top and extends downstream, indicating strong shear-layer instability and recirculation-induced entrainment behind the single windbreak wall. In Case B, the high-vorticity region becomes concentrated near the additional wall and slope toe, suggesting that the solid wall changes the recirculation path but does not fully suppress turbulent exchange. In Case C, high vorticity is mainly distributed above the wall and away from the near-surface region, while the near-bed vorticity is generally lower. This means that the checkerboard barrier weakens near-surface vortex intensity and reduces the possibility of sand backflow toward the track area.

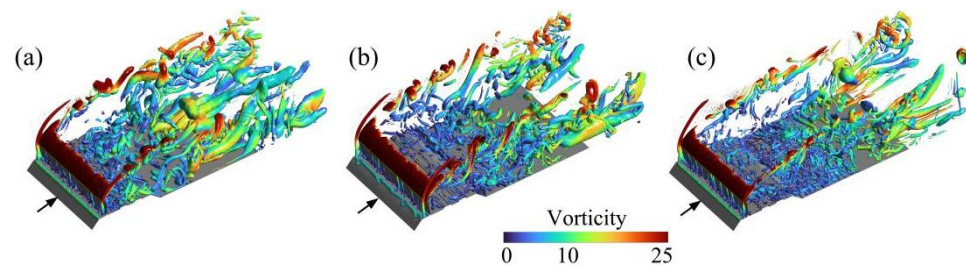


Figure 9. Streamwise variation in vorticity under the three structures (15 m/s). (a) Case A; (b) Case B; (c) Case C.

Figure 10 presents the coherent vortex structures identified by the Q-criterion under the three configurations, and the maximum TKE values provide quantitative support for the comparison of vortex intensity. In Case A, strong alternating positive and negative Q-value regions appear behind the windbreak wall and near the leeward slope toe, with a maximum TKE of $455.385 \text{ m}^2/\text{s}^2$. This pattern indicates intense vortex stretching, vortex breakdown, and strong momentum exchange, which may promote sand backflow and particle re-entrainment toward the track area. In Case B, the maximum TKE decreases to $428.560 \text{ m}^2/\text{s}^2$, suggesting that the additional solid wall partially weakens the overall turbulent fluctuations. However, dense alternating vortex structures remain near the slope toe, indicating persistent local shear, flow separation, and deposition risk. In Case C, although the maximum TKE reaches $464.249 \text{ m}^2/\text{s}^2$, the high-energy region is mainly located above the windbreak wall or farther downstream, away from the track. By contrast, the near-surface vortex structures around the subgrade and track area are clearly weakened. This redistribution of turbulent energy indicates that the checkerboard barriers suppress near-track coherent vortices, reduce momentum transfer to the track surface, and weaken surface sand entrainment.

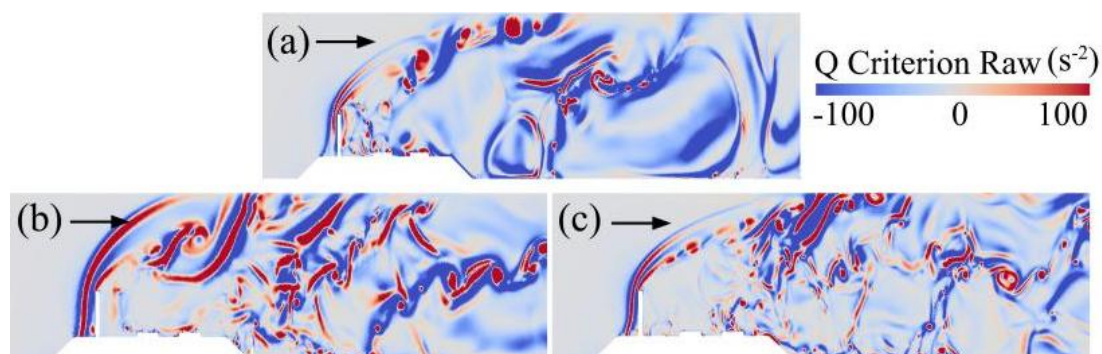


Figure 10. Variation in the Q criterion under the three structures (15 m/s). (a) Case A; (b) Case B; (c) Case C.

Figure 11 shows the surface shear stress distribution on the subgrade under the three structures. It directly reflects the ability of near-surface airflow to initiate and re-transport sand particles. In Case A, several high-shear patches appear behind the windbreak wall and in the downstream region. The local shear stress reaches about $0.5\text{--}1.0 \text{ Pa}$. This shows that the recirculation and reattachment flow induced by the single windbreak wall still have strong near-surface momentum. They can cause secondary sand entrainment and drive particles back toward the track area. In Case B, the high-shear regions are reduced. However, local patches higher than 0.5 Pa still remain near the leeward slope toe and downstream. This suggests that the solid wall weakens part of the near-surface wind speed but cannot fully remove local scouring caused by recirculation reattachment. In contrast, Case C is dominated by low shear stress on the subgrade surface. Most regions

have shear stress below 0.5 Pa, and high-value zones are mainly located at the downstream edge away from the track. This shows that Case C greatly reduces bed shear near the track. It suppresses sand initiation, saltation, and resuspension, thereby reducing the transport risk of leeward sand deposition toward the subgrade surface.

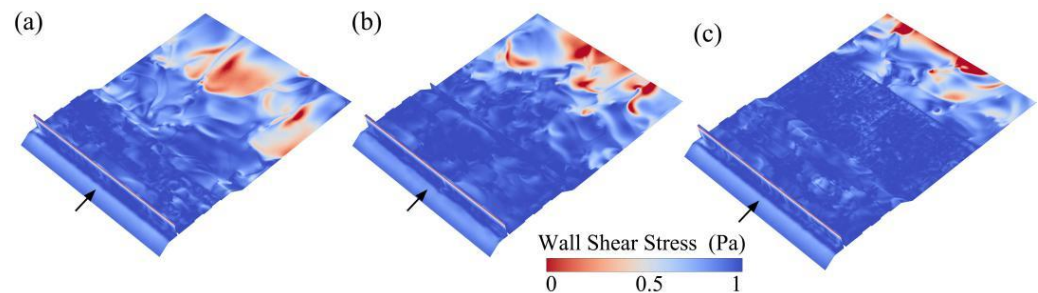


Figure 11. Surface shear stress distribution under the three structures (15 m/s). (a) Case A; (b) Case B; (c) Case C.

3.3. Simulated Sand Deposition Under Three Structural Configurations

Figure 12 shows the sand particle concentration distribution under the three configurations. In Case A, a high-concentration zone of about 12–20 kg/m³ develops behind the windbreak wall and extends toward the subgrade top, indicating strong sand backflow induced by recirculation. In Case B, the additional solid wall reduces part of the near-surface sand transport, but high particle concentration still remains on the leeward side. In Case C, sand particles are mainly retained away from the track area, and the concentration near the subgrade top and leeward slope toe is mostly below 4 kg/m³, which is about 60–80% lower than that in Case A. This indicates that the checkerboard barrier effectively alters sand transport paths and reduces particle backflow toward the track.

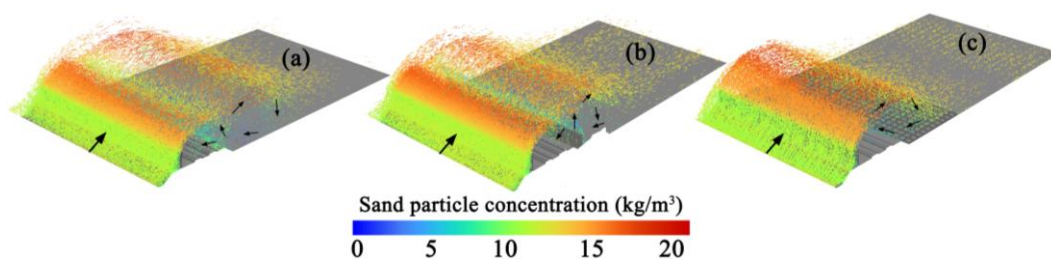


Figure 12. Particle concentration distribution under the three structures (15 m/s). (a) Case A; (b) Case B; (c) Case C.

The flow field, vorticity, shear stress, and particle concentration discussed above were all analyzed under an incoming wind speed of 15 m/s. Figure 13 further compares the vertical sand concentration profiles of the three structures at wind speeds of 15 m/s and 30 m/s to verify the stability of their protective effects under different wind conditions. As shown in Figure 13a, at 15 m/s, sand concentration generally decreases with height. Case A exhibits the highest near-surface concentration, at approximately 0.18 kg/m³. In Case B, the concentration decreases to about 0.11 kg/m³, representing a reduction of approximately 39% relative to Case A. In Case C, the concentration is only about 0.045 kg/m³, or roughly 75% lower than in Case A. The concentration also approaches zero above 2 m, indicating that Case C strongly suppresses near-surface sand transport. Figure 13b shows that when the wind speed increases to 30 m/s, the peak sand concentration shifts upward to a height of 0.8–1.0 m. The peak concentrations of Cases A, B, and C are approximately 0.24, 0.20, and 0.15 kg/m³, respectively. Compared with Case A, the peak values of Cases

B and C decrease by about 17% and 38%, respectively. These results indicate that higher wind speeds enhance sand saltation and suspension, while Case C still maintains the lowest particle concentration. Overall, as the incoming wind speed increases, the peak sand concentration rises and shifts upward, and the differences among the protective structures become less pronounced. Nevertheless, Case C consistently demonstrates the strongest sand-reduction performance at both 15 m/s and 30 m/s, indicating that its sand-deposition mitigation effect has good adaptability to changes in wind speed.

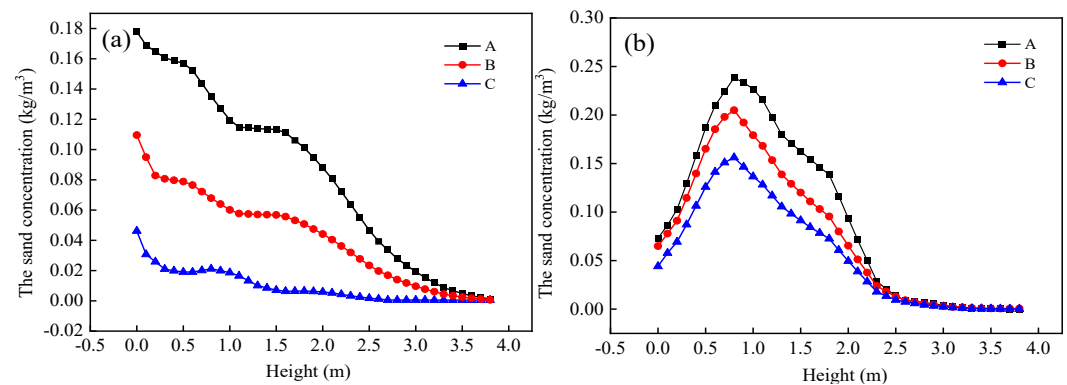


Figure 13. Particle concentration profiles under different wind speeds. (a) 15 m/s; (b) 30 m/s.

3.4. Analysis of Wind Tunnel Test Results

Figure 14 presents the wind tunnel test results for the three structural configurations and was used to validate the sand deposition patterns obtained from the numerical simulations. As shown in the figure, sand deposition is most pronounced on the subgrade surface and near the track in Case A, indicating that the recirculation zone behind a single windbreak wall can readily transport sand particles into the track area. In Case B, the deposition area is reduced; however, local accumulation still occurs near the slope toe and behind the wall. In Case C, sand deposition in the track area is significantly reduced, and most particles are trapped in regions farther from the track. This result is consistent with the numerical findings of lower wind speed, lower shear stress, and lower particle concentration in Case C, confirming its superior sand deposition mitigation performance.



Figure 14. Wind tunnel test results under the three structures at 15 m/s. (a) Case A; (b) Case B; (c) Case C.

Figure 15 presents the quantitative results of sand deposition within the 10 m checkerboard barrier zone on the leeward side and along the track line in the wind tunnel tests. It further confirms the differences in sand-deposition mitigation among the three configurations. As shown in Figure 15a, under upstream sand-supply conditions, the sand deposition rates on the leeward side of Cases A, B, and C are approximately 250, 280, and 290 g/min at a wind speed of 15 m/s, respectively, with only minor differences among them. When the wind speed increases to 30 m/s, the corresponding values rise to approximately

580, 620, and 680 g/min. These results indicate that a higher incoming wind speed substantially increases sand-transport intensity. Figure 15b shows that sand deposition in the track area is most severe in Case A, with deposition rates of approximately 265 and 395 g/min at wind speeds of 15 and 30 m/s, respectively. In Case B, these values decrease to approximately 195 and 320 g/min, representing reductions of about 26% and 19% relative to Case A. Case C exhibits the lowest deposition rates, at only about 150 and 230 g/min, which are approximately 43% and 42% lower than those in Case A. These results indicate that Case C can consistently reduce sand deposition on the track under different wind speeds. This finding is consistent with the lower wind speed, lower shear stress, and lower particle concentration observed in the numerical simulations.

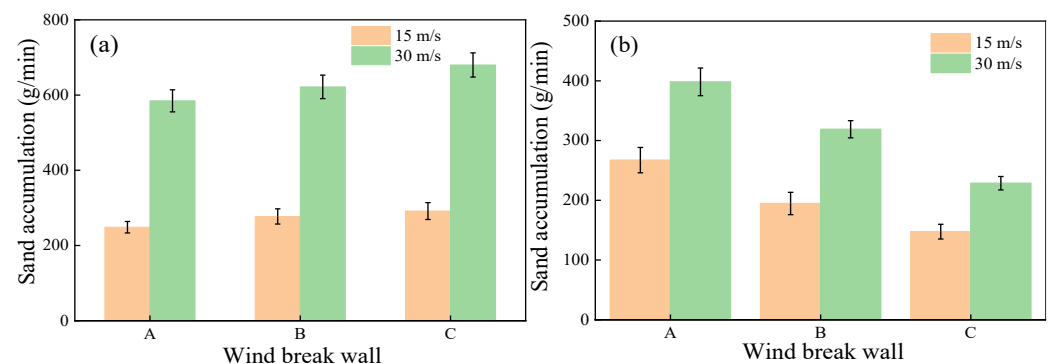


Figure 15. Sand deposition under the three structures at different wind speeds. (a) Sand deposition within the 10 m checkerboard barrier area on the leeward side; (b) sand deposition on the track line.

Although 15 and 30 m/s under the dominant unfavorable wind direction were selected to represent typical and strong-wind conditions, future studies should also consider additional wind speeds, such as 20 and 25 m/s, as well as different wind directions, seasonal variations, and long-term deposition evolution, to better characterize sand-reduction performance across the full operational wind-speed range.

Overall, a single subgrade windbreak wall can reduce the crosswind effect on train operation [15–17]. However, a strong shear layer, large-scale recirculation vortices, and local reattachment flow readily form on its leeward side [13,17]. These flow structures entrain sand particles toward the subgrade crest and track area, thereby increasing the risk of sand deposition on the track. Once leeward-side protective structures are added, near-surface wind speed, surface shear stress, and particle concentration all decrease to varying degrees. Case C performs best. The numerical results show that Case C maintains most areas near the track within a low-speed regime, while also weakening near-surface vortices and bed shear, thereby reducing particle concentration in the track area by approximately 60–80% compared with Case A. Wind tunnel tests further confirm this trend. At 15 m/s and 30 m/s, Case C reduces track sand deposition by approximately 43% and 42%, respectively. This 42–43% reduction mainly reflects the relative sand-reduction effect under identical test conditions. Because all cases used the same scale ratio, inflow conditions, sand supply, and measurement methods, the relative ranking remains reliable, although the absolute deposition amount and reduction percentage may differ at prototype scale.

It should be noted that leeward-side protective structures cannot completely prevent sand particles from entering the track area. Under strong wind conditions, some particles may still reach the subgrade surface through saltation, suspension, and recirculation-induced entrainment. Their role is therefore better described as sand reduction and sand control rather than complete sand blocking. In addition, the conclusions of this study are mainly applicable to high railway embankments in relatively flat desert environments

characterized by strong winds, abundant sand supply, and prevailing winds nearly perpendicular to the railway. The protective performance of these structures may vary under complex terrain, multidirectional wind conditions, different embankment geometries, and long-term field exposure.

From an engineering and sustainability perspective, checkerboard sand barriers may be more practical than rigid walls at the leeward slope toe and other deposition-prone areas [1,29]. They can increase surface roughness, reduce near-surface wind speed, weaken particle re-entrainment, and promote local sand deposition [29]. They are also flexible, low-cost, easy to construct, and relatively easy to maintain and clean. Therefore, checkerboard sand barriers and other flexible energy-dissipation measures are more suitable for mitigating leeward-side sand deposition behind subgrade windbreak walls along the Xinjiang section of the Lanzhou–Xinjiang High-Speed Railway. Under future climate change and more frequent extreme wind events, such flexible sand-control measures may help reduce maintenance demands, improve infrastructure resilience, and support the long-term safe operation of railways in desert regions. Future studies should further optimize the layout, scale, spacing, and maintenance cycle of these measures under different wind directions, sand supply conditions, embankment forms, and long-term field conditions.

4. Conclusions

This study investigated sand deposition on the leeward side of subgrade windbreak walls along the Xinjiang section of the Lanzhou–Xinjiang High-Speed Railway. Numerical simulations and wind tunnel tests were combined to examine the flow field, sand transport, and track sand deposition under three structural configurations. The main conclusions are as follows.

(1) A single subgrade windbreak wall forms a distinct high-speed shear layer, a low-speed zone, and a large-scale recirculation vortex in the leeward wake region. The local reverse velocity reaches approximately -10 m/s. This flow pattern promotes sand back-flow and near-surface re-entrainment, making sand particles more likely to deposit in the track area. These results indicate that although a windbreak wall can reduce the effects of crosswinds, it may also induce secondary sand deposition on the leeward side.

(2) Additional leeward-side protective structures can alter the wake flow pattern behind the windbreak wall and reduce near-surface sand transport capacity. Compared with Case A, Case B weakens the near-surface wind speed and sand concentration to some extent. However, local vortices and high-shear zones still persist behind the wall and near the slope toe, so its sand-reduction effect is limited. Case C more effectively suppresses near-surface recirculation and bed shear. It keeps the surface shear stress near the track mostly below 0.5 Pa and the near-surface vorticity mostly below 10. The sand concentration is reduced by approximately 60–80% relative to Case A.

(3) Both numerical simulations and wind tunnel tests under different wind speeds confirm the stable sand-reduction performance of Case C. At wind speeds of 15–30 m/s, Case C significantly reduces sand transport intensity in the track area. The near-surface or peak sand concentration is approximately 38–75% lower than that in Case A. In the wind tunnel tests, track sand deposition in Case C is reduced by approximately 43% and 42% at 15 m/s and 30 m/s, respectively. These results show that Case C can continuously reduce the risk of track sand deposition by weakening recirculation-induced entrainment and near-surface sand transport. The findings provide a reference for sand-deposition mitigation design along high-speed railways in strong wind–sand environments.

From the perspective of sustainability and engineering applicability, this study is primarily relevant to controlling secondary sand deposition on the leeward side of wind-

break walls along sandy high-speed railway sections. Concrete or stone checkerboard barriers can reduce track sand deposition by increasing surface roughness, weakening near-surface recirculation and bed shear stress, and promoting sand settling away from the track. These structures also require less material, cause less construction disturbance, and facilitate local maintenance, indicating good long-term service potential. However, their service life, cleaning frequency, and maintenance costs depend on local wind–sand intensity, sand supply, and extreme sandstorm events. Routine inspection and timely cleaning are recommended after severe sandstorms or when the cells are nearly filled. Future work should combine long-term field monitoring with railway maintenance records to quantify material consumption, construction costs, life-cycle benefits, service life, cleaning frequency, maintenance cycles, and operating costs.

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