Wind tunnel test on the effect of metal net fences on sand flux in a Gobi Desert, China (Postprint)

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Abstract

The Lanzhou-Xinjiang High-speed Railway runs through an expansive windy area in a Gobi Desert, and sand-blocking fences were built to protect the railway from destruction by wind-blown sand.

Full Text

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Abstract: The Lanzhou-Xinjiang High-speed Railway traverses an expansive windy area in the Gobi Desert, where sand-blocking fences have been constructed to protect the railway from wind-blown sand damage. However, the shielding effectiveness of these fences has fallen below expectations. This study investigated the performance of metal net fences with porosities of 0.5 and 0.7 through wind tunnel experiments to evaluate their effectiveness in reducing wind velocity and controlling sand transport. Specifically, horizontal wind velocities and sediment flux densities above the gravel surface were measured under different free-stream wind velocities for the following configurations: no fence, single fence with porosity 0.5, single fence with porosity 0.7, double fences with porosity 0.5, and double fences with porosity 0.7. Experimental results demonstrated that fences with 0.5 porosity were more effective at reducing horizontal wind velocity, particularly for double fence configurations. Wind velocity decreased by approximately 65% at a distance of 3.25 m (13H, where H denotes fence height) downwind of the double fences, with no reverse flow or vortex observed on the leeward side. Sediment flux density decreased exponentially with height above the gravel surface downwind of all tested fences. The reduction percentage of total sediment flux density was higher for fences with 0.5 porosity than for those with 0.7 porosity, especially in double fence arrangements. Furthermore, the reduction percentage of total sediment flux density decreased with increasing free-stream wind velocity. These results suggest that metal net fences with 0.5 porosity are more effective for controlling wind-blown sand in the windy areas traversed by the Lanzhou-Xinjiang High-speed Railway compared to fences with 0.7 porosity.

Keywords: wind-blown sand; wind tunnel experiment; porous fence; flow field; sediment flux density; Lanzhou-Xinjiang High-speed Railway; Gobi Desert

1 Introduction

Sand-blocking fences constitute a critical component of blown-sand disaster shelter systems. Positioned at the leading edge of shelter systems, these structures reduce wind velocity and restrain wind-blown sand particles. Fences can be constructed in various configurations—including upright, horizontal, gridded, holed-plank, and wind-screened designs—depending on locally available materials. For instance, upright fences made of reed bunches have been deployed along highways crossing the Taklimakan Desert in Northwest China, while nylon net fences protect the Qinghai-Tibet Railway and the Mogao Grottoes. The aerodynamic characteristics and sheltering effectiveness of sand-blocking fences depend on their geometric design parameters, including height, length, width, porosity, opening size, distribution pattern, and geometry. Porosity, defined as the ratio of open area to total fence area, is widely considered the most important structural feature controlling fence performance. Field observations in the Shapotou area have shown that fences with porosities of 0.3–0.4 effectively prevent sand accumulation on the windward side, while wind tunnel measurements indicate that porosities of 0.3–0.5 yield optimal shelter system effectiveness. Although low-porosity fences generally exhibit better wind velocity reduction, very low porosity can generate excessive downwind turbulence. The widely accepted principle is that increasing porosity leads to higher wake velocities but lower turbulence intensity. Consequently, the optimal porosity for sand-blocking fences depends on pore distribution and fence material.

The Lanzhou-Xinjiang High-speed Railway, China' s first high-speed railway traversing a vast windy area (462.41 km from east to west), faces persistent blown-sand disasters with instantaneous wind velocities reaching 60.2 m/s. These windy areas are predominantly located in the Gobi Desert, where natural surfaces have been extensively disturbed by large-scale construction projects, particularly railway development. Loose materials (primarily sand and silt) are readily available near railway corridors for wind transport. Rocky checkerboard sand barriers and sand-blocking fences have been installed on the windward side of railways for protection. However, the sheltering effectiveness has proven unsatisfactory, as wind-blown sand frequently accumulates around railway tracks. The relatively low porosity (0.3) and uneven opening distribution of existing fences cause massive sand accumulation on the downwind side. Therefore, designing more effective sand-blocking fences to improve existing shelter systems remains an urgent priority.

This study simulated the sheltering effects of metal net fences with porosities of 0.5 and 0.7 using wind tunnel experiments, comparing single and double fence configurations. Wind velocities, airflow fields, and sediment flux densities downwind of the fences were measured to evaluate their sheltering effectiveness. The results aim to provide guidance for improving the sand-blocking systems protecting the Lanzhou-Xinjiang High-speed Railway.

2.1 Experiment Design and Set-up

Experiments were conducted in May 2016 at the State Key Laboratory of Desertification and Aeolian Sand Disaster Combating, Gansu Desert Control Research Institute. The blow-type non-circulating wind tunnel measured 38.9 m in total length with a test section 16.0 m long. The test section had a cross-sectional area of 1.2 m × 1.2 m and a boundary layer thickness of 0.5 m. Free-stream wind velocities ranged from 4 to 35 m/s.

Fence models were constructed using rigid stainless steel wires with a diameter of 1 mm. Since 90% of wind-blown sand occurs within 3 m above ground in Gobi Desert windy areas, full-scale fences along the Lanzhou-Xinjiang High-speed Railway were designed with heights of approximately 2.5–3.0 m. Correspondingly, model fence height was set at 0.25 m (25 cm), yielding a geometric scale of approximately 1:10 with a scale height to boundary layer height ratio of 0.5. Fence length was 1.2 m, spanning the entire test section width. Two fence models with porosities of 0.5 and 0.7 were fabricated with pore sizes of 3 mm and 8 mm, respectively. Both single and double fence configurations were tested.

As illustrated in Figure 3, the first fence was positioned 10 m from the test section entrance, with the second fence located 1.5 m downwind (11.5 m from the entrance). A gravel surface layer (1.2 m wide and 10.0 m long) was installed level with the tunnel floor to simulate Gobi Desert conditions. This layer consisted of natural Gobi gravels with diameters ranging from 0.5 to 3.0 cm. Based on previous observations, wind-blown sand movement in the Gobi Desert occurs when wind velocity exceeds 10 m/s (10-minute mean velocity). Therefore, four free-stream wind velocities above this threshold—10, 17, 22, and 27 m/s—were used to measure wind velocity and sediment flux density profiles at 60 cm above the tunnel floor at the test section entrance.

2.2 Data Collection and Analysis

Wind velocities were measured using an array of pitot-static tubes at heights of 1, 2, 3, 5, 8, 13, 20, 30, 40, and 60 cm above the gravel surface, and at distances of 1H, 2H, 3H, 5H, 7H, 9H, 11H, and 13H downwind from single and double fences. The effectiveness of metal net fences in reducing wind velocity at specific heights and distances was quantified using the reduction coefficient of horizontal wind velocity ($R_c(x, z)$) as defined by Cornelis and Gabriels (2005):

$$R_c(x, z) = 1 - \frac{u(x, z)}{u_0(x, z)}$$

where x is the distance downwind from the fence (m), z is the height above the gravel surface (cm), $u(x, z)$ is the wind velocity with fences present (m/s), and $u_0(x, z)$ is the wind velocity without fences (m/s).

To determine sand transport rates (mass per unit time and area) above the gravel surface with and without fences, a sand bed (particle diameters 0.1–0.5 mm, width 1.2 m, depth 0.1 m, length 4.0 m) was placed 1 m downwind from the test section entrance. This length ensured full development of the saltating sand cloud. A vertical segmented sand sampler with a total height of 50 cm and 2 cm sampling intervals measured sand transport above the gravel surface. During experiments, the sampler was positioned 15 m downwind from the test section entrance.

The sediment flux density profile describes how sand transport rate varies with height above ground. To obtain sediment flux density, the mass of transported sand collected at each height was converted to units of kg/(m²·s). Sediment flux densities above the gravel surface were then calculated for configurations with and without fences. SigmaPlot version 12.5 was used for linear regression analysis and graph generation, while AutoCAD version 2007 was used for schematic diagrams of fence models and experimental set-up.

3.1.1 Wind Velocity

Baseline measurements without fences revealed that horizontal wind velocity above the gravel surface followed a logarithmic relationship with height across all free-stream wind velocities (Figure 5). Regression analyses yielded excellent fits to the logarithmic curve (R^2 0.89), indicating that wind tunnel simulations accurately represented field conditions.

Wind velocity profiles above fenced surfaces were similar to those without fences, suggesting minimal influence on airflow far downwind. However, horizontal wind velocities decreased significantly below the fence top downwind of both single and double fences, particularly at approximately 20 cm above the gravel surface, while velocities increased above the fence top. Double fences produced substantially greater velocity reductions below the fence top compared to single fences, with slightly greater velocity increases above the fence top. Fences with 0.5 porosity were more effective at reducing horizontal wind velocity than those with 0.7 porosity.

Figure 7 illustrates the reduction coefficient of horizontal wind velocity at various heights and distances downwind under a free-stream wind velocity of 22 m/s. For single fences, the maximum reduction coefficient was approximately 0.4 at 9H downwind for 0.5 porosity and 0.2 at 7H downwind for 0.7 porosity. For double fences, maximum reduction coefficients reached approximately 0.65 at 13H downwind for 0.5 porosity and 0.4 at 13H downwind for 0.7 porosity.

3.1.2 Flow Field Downwind the Fences

Figure 8 presents isovelocity patterns downwind of single and double fences (0.5 and 0.7 porosities) under a free-stream wind velocity of 22 m/s. As air approached the fences, flow was deflected upward, creating a high-velocity region (over-flow) above the fences and a low-velocity region (bleed flow) below. The bleed flow downwind of 0.5 porosity fences was weaker than that of 0.7 porosity fences, while the over-flow was stronger. Double fences, particularly those with 0.5 porosity, produced much weaker bleed flow and much stronger over-flow compared to single fences.

3.2.1 Sediment Flux Density Profiles

Sediment flux density decreased exponentially with increasing height above the gravel surface for all tested fences and wind velocities (Figure 9). The relationship was well described by an exponential decay equation (R^2 0.92). Notably, for surfaces without fences, maximum sediment transport occurred at 2–4 cm heights when free-stream wind velocity exceeded 10 m/s.

Total sediment flux density increased with free-stream wind velocity for all configurations (Figure 10), following a power relationship (R^2 0.82). The correlation coefficient between total sediment flux density and wind velocity was highest for surfaces without fences, with decreasing values in the following order: single fence (0.7 porosity), double fences (0.7 porosity), single fence (0.5 porosity), and double fences (0.5 porosity).

3.2.2 Effects of Fences on Total Sediment Flux Density

Sediment flux density decreased significantly downwind of all tested fences with increasing height. Compared to surfaces without fences, the highest reduction percentage of total sediment flux density occurred downwind of double fences with 0.5 porosity, followed by single fence (0.5 porosity), double fences (0.7 porosity), and single fence (0.7 porosity) across all wind velocities (Table 1).

4 Discussion

The Lanzhou-Xinjiang High-speed Railway traverses a vast windy Gobi Desert region where wind-blown sand movement is characterized by high velocity and stable flow directions. The dynamics of aeolian transport above Gobi surfaces are complex, particularly in strong wind regimes. For surfaces without fences, wind velocity profiles generally follow logarithmic laws, consistent with previous research. In this study, maximum sand transport occurred at 2–4 cm heights under high wind velocities, with sediment flux density following an exponential decay function above this level, agreeing with field observations. This confirms that the simulated gravel surface accurately represented natural Gobi Desert conditions.

The existing shelter system along the railway employs sand-blocking fences with low porosity (0.3) and uneven opening distribution. While these fences reduce strong winds, they generate high turbulence downwind, which may increase near-fence horizontal wind velocity and decrease sheltering effectiveness, leading to sand accumulation around tracks. Airflow downwind of fences can be divided into several regions based on aerodynamic behavior: over-flow region, wake region, internal boundary layer, reverse cell region (with negative velocity), and small vortex region. While low-porosity or solid fences may exhibit all these regions, highly porous fences may lack some features. As shown in Figure 8, streamline patterns downwind of all tested fences were smooth with no reverse cells or only small vortices, indicating dominant bleed flow and negligible turbulence intensity. Consistent with Lee and Mim (1999), fences with 0.5 porosity substantially reduced horizontal wind velocity, with maximum reduction coefficients reaching 0.65 for double fences.

Compared to surfaces without fences, sediment flux density decreased significantly downwind of all tested fences. Double fences with 0.5 porosity achieved the highest reduction percentage of total sediment flux density (84.44%), demonstrating superior effectiveness in trapping sand particles and protecting railways from wind-blown sand damage. Additionally, since no reverse cells or only small vortices formed downwind of the metal net fences, sand particles settled evenly on the leeward side during experiments. This even deposition pattern prevents fence burial, offering a significant advantage over existing fences that frequently become buried by accumulated sand.

5 Conclusions

This study measured horizontal wind velocity and sediment flux density downwind of metal net fences with porosities of 0.5 and 0.7 using wind tunnel experiments. Fences with 0.5 porosity reduced horizontal wind velocity more effectively than those with 0.7 porosity, and achieved higher reduction percentages of total sediment flux density. This indicates that 0.5 porosity fences are more effective at restraining wind-blown sand particles. Metal net fences with 0.5 porosity are therefore recommended for controlling wind-blown sand in the vast windy areas traversed by the Lanzhou-Xinjiang High-speed Railway, and can be deployed at shelter system front edges to improve overall effectiveness. Furthermore, double fences outperform single fences in reducing wind velocity and restraining sand transport. It should be noted that this study only tested two porosities (0.5 and 0.7) under single and double fence conditions; additional porosities (e.g., 0.2, 0.3, 0.4, and 0.6) warrant future investigation.

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Note: Figure translations are in progress. See original paper for figures.