Influence of Railway Viaducts on Local Wind Dynamics: A Case Study of Shashangou on the Dunge Railway (Postprint)

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Abstract

This study investigates and analyzes the wind dynamic environmental characteristics on the east and west sides of the Shashangou Grand Bridge on the Dunge Railway through field observations, indoor analytical calculations, and CFD numerical simulation methods. The results indicate that: (1) On both east and west sides of the Shashangou Grand Bridge, sand-entraining winds in spring and summer are predominantly from the NW and WNW directions, while in autumn and winter they are mainly from the SE and S directions; on the west side of the Shashangou Grand Bridge, the annual drift potential is 284.19 VU, belonging to a moderate wind energy environment, the resultant drift potential is 27.4 VU, the resultant drift direction is 124°, the directional variability index is 0.10, belonging to a low ratio, with highly variable wind directions. (2) On the east side of the Shashangou Grand Bridge, the annual drift potential is 31.24 VU, belonging to a low wind energy environment, the resultant drift potential is 8.97 VU, the resultant drift direction is 91°, the directional variability index is 0.29, belonging to a moderate ratio; the west side of the Shashangou Grand Bridge exhibits higher average wind speeds, frequency of sand-entraining winds, drift potential, and resultant drift potential, thus monitoring and prevention of sand hazards on the west side of the elevated bridge should be intensified; based on simulation of the wind dynamic environment characteristics on the west side of the elevated bridge combined with migrating sand dunes, analysis reveals that wind speeds in the bridge-underclearance area and on the bridge deck both exceed the sand-entraining threshold, with strong sediment transport capacity and low probability of sand accumulation. However, as sand dunes migrate forward, the probability of sand accumulation in the bridge-underclearance area and wind-blown sand encroaching onto the bridge increases.

Influences of Railway Viaducts on Local Wind Dynamics: A Case Study of Shashangou Bridge on the Dunge Railway

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Abstract

This study investigated the wind dynamic environment characteristics on the east and west sides of the Shashangou Bridge on the Dunge Railway through field observations, laboratory analysis, and numerical simulation. The results show that: (1) On both sides of Shashangou Bridge, sand-driving winds were mainly from [missing] directions in spring and summer, and [missing] directions in autumn and winter; the resultant sand transport direction was [missing]. The annual sediment transport potential on the west side of Shashangou Bridge was 284.19 VU, indicating a medium wind energy environment, with a resultant sediment transport potential of 27.45 VU. (2) The annual sediment transport potential on the east side was 31.24 VU, indicating a low wind energy environment, with a resultant sediment transport potential of 8.97 VU, a resultant sand transport direction of [missing]°, and a directional variability index of [missing], indicating a medium ratio and variable wind direction. The average wind speed, frequency of sand-driving wind, sediment transport potential, and resultant sediment transport potential were all larger on the west side, suggesting that monitoring and prevention of sand hazards on the west side of the viaduct should be strengthened. Based on the wind dynamic environment characteristics on the west side and simulations incorporating moving dunes, the analysis reveals that wind speeds in the overhead area beneath the bridge and on the bridge deck exceed the sand-driving wind speed, indicating strong sediment transport capacity and limited sand accumulation. However, as dunes migrate forward, the likelihood of sand accumulation in the overhead area and wind-blown sand reaching the tracks increases.

Keywords: Shashangou; wind dynamic environment; sand-driving wind regime; sediment transport potential; numerical simulation

The Dunge Railway (Dunhuang-Golmud) serves as a crucial hub connecting the Qinghai-Tibet Railway to the south, the Lanzhou-Xinjiang High-Speed Railway to the north, and the Korla-Golmud Railway to the west, playing a significant role in expanding and improving the northwestern railway network and promoting economic development and social progress in the region and Tibet. The railway section through Shashangou spans approximately 12.90 km within a total length of 508 km. Shashangou is a flood channel of the Altun Mountains, forming a broad valley with relatively flat terrain. Large areas of low-lying mobile dunes and tall compound dunes are distributed on both sides of the valley, providing abundant sand sources. The main dune types include compound barchan dune chains, chain dunes, grid dunes, and pyramidal dunes, with dune heights generally ranging between [missing] m. The region experiences concurrent dry and windy seasons, with sufficient wind dynamic conditions. To safely traverse the mobile dune section, railway constructors adopted a "bridge instead of road" approach, which is commonly applied in railway and highway construction in northwest desert areas. This approach ensures smooth sediment transport channels while protecting the local ecological environment. However, substantial sand accumulation around the viaduct and continuous forward movement of mobile dunes pose potential risks of wind erosion and sand burial.

Based on field-measured wind conditions and sand collector data from both sides of Shashangou Bridge, this study analyzes the wind-sand dynamic environment characteristics and simulates the influence of moving dune advancement on flow field distribution around the viaduct to reveal wind-sand activity patterns and provide a theoretical basis for railway sand hazard monitoring and prevention.

1. Data Sources and Research Methods

Research data were obtained from wind speed and direction observations by automatic weather instruments and sand accumulation data from sand collectors positioned on both sides of the viaduct between [missing] and [missing]. The automatic weather instruments recorded 10-minute average data at a height of 2.5 m above ground. Based on field measurements, this study employed the Eulerian two-fluid model to simulate flow field distribution around the viaduct when the dune front was positioned at distances of [missing] m, [missing] m, [missing] m, and near the beam bottom on the west side of the viaduct, illustrating the influence of mobile dunes on the flow field and potential sand hazards.

Sediment transport potential is a crucial indicator for measuring wind-sand activity intensity in a region, representing potential sand transport capacity—that is, the ability of winds from a particular direction to transport sand over a certain period. Numerically, it is expressed in vector units (VU). Currently, the most widely used equation for calculating sediment transport potential is the Lettau equation [missing]. The formula is: $\mathrm{DP} = \mathrm{V}^3(\mathrm{V} - \mathrm{Vt})\mathrm{t}$, where DP is sediment transport potential (VU), V is wind speed ($\mathrm{m \cdot s^{-1}}$), Vt is threshold wind speed ($\mathrm{m \cdot s^{-1}}$) uniformly taken as [missing] $\mathrm{m \cdot s^{-1}}$, and t is the duration of sand-driving wind expressed as frequency in statistical tables. The resultant direction obtained by vector superposition of DP from 16 directions is called the resultant sand transport direction (RDD), representing the net sand transport direction. The sediment transport quantity in the resultant direction is called the resultant sediment transport potential (RDP), representing net sediment transport potential under various wind directions. The ratio of RDP to DP is called the directional variability index (RDP/DP), reflecting wind direction combination patterns in a region [missing]. Greater wind direction variability results in smaller directional variability index values.

2.1 Mean Wind Speed and Frequency of Sand-Driving Wind

The monthly variation of mean wind speed and sand-driving wind frequency on both sides of Shashangou Bridge shows that the west side experiences three dominant sand-driving wind directions throughout the year, with frequencies of [missing]%, [missing]%, and [missing]%, respectively. The east side shows dominant sand-driving winds from [missing], [missing], and [missing] directions, with combined frequencies of only [missing]%, [missing]%, and [missing]%. Comparison reveals that the annual sand-driving wind frequency on the west side is generally higher than on the east side, indicating greater sand-entraining potential on the west side.

The variation trends of mean wind speed and sand-driving wind frequency are consistent on both sides, showing an initial increase followed by a decrease, with both reaching maximum values in [missing] (Fig. [Figure 2: see original paper]). However, due to the blocking effect of the viaduct, both mean wind speed and sand-driving wind frequency on the east side are lower than on the west side, with attenuation ratios generally exceeding [missing]%. The spring and summer months ([missing]–[missing]) exhibit the strongest attenuation, when sand-driving wind frequency and mean wind speed are also high, demonstrating that stronger winds experience more intense weakening by the viaduct and that wind erosion on the west side is further enhanced.

2.2 Sand-Driving Wind Regime

Understanding sand-driving wind directions helps characterize the spatial directionality of wind-sand movement on both sides of the viaduct. The west side shows variable sand-driving wind directions, particularly in summer. In contrast, both sides exhibit SE and S winds in autumn and winter, but differ in spring and summer. In spring, the west side shows a higher proportion of [missing] winds, while the east side is dominated by [missing] winds. In summer, the west side displays variable directions with a significantly increased proportion of [missing] winds, while the east side remains dominated by [missing] winds.

Seasonal variations reveal that both sides experience SE and S winds in autumn and winter, but show differences in spring and summer. The west side's variable wind directions, especially the high proportion of [missing] winds in spring, result in a smaller directional variability index (more variable winds). The autumn and winter directional variability index indicates a medium ratio with relatively uniform winds, mainly from [missing] directions. Although [missing] direction shows strong transport capacity in autumn and winter, the [missing] direction becomes increasingly dominant, particularly reaching maximum transport at [missing]–[missing] $\mathrm{m \cdot s^{-1}}$ wind speeds.

2.3 Sediment Transport Potential

The annual sediment transport potential on the west side of Shashangou Bridge is [missing] VU, indicating a medium wind energy environment, with a resultant sediment transport potential of 27.45 VU and a resultant sand transport direction of [missing]°. The directional variability index is [missing], indicating a small ratio with variable wind directions. Seasonally, the west side reaches maximum sediment transport potential in summer, attaining [missing] VU. In the multi-directional wind energy environment, winds from the [missing] direction account for [missing]%, while [missing] direction winds account for [missing]%. The [missing] direction shows the strongest transport capacity, particularly at [missing]–[missing] $\mathrm{m \cdot s^{-1}}$ wind speeds in spring (Fig. [Figure 5: see original paper]).

The annual sediment transport potential on the east side is 31.24 VU, indicating a low wind energy environment, with a resultant sediment transport potential of 8.97 VU, a resultant sand transport direction of [missing]°, and a directional variability index of [missing], indicating a medium ratio. Seasonally, the east side also reaches maximum sediment transport potential in summer at [missing] VU. In the multi-directional wind energy environment, winds from the [missing] direction account for [missing]%, while [missing] direction winds account for [missing]%. The northeast direction shows the strongest transport capacity, particularly at [missing]–[missing] $\mathrm{m \cdot s^{-1}}$ wind speeds in spring (Fig. [Figure 6: see original paper]).

The annual resultant sand transport direction on both sides is primarily [missing], consistent with actual wind-sand flow movement directions, though slight differences exist. The west side's resultant direction is [missing] in spring and approximately [missing] in other seasons. The east side's resultant direction is [missing] in winter and approximately [missing] in spring, summer, and autumn.

3. Flow Field Distribution Characteristics on Both Sides of the Viaduct

The study area has a bridge clearance height of approximately [missing] m, a deck width of [missing] m, a deck thickness of about 0.5 m, and a bottom width of [missing] m, with a [missing]-type beam structure. Mobile dunes are widely distributed around the viaduct, with dune fronts positioned approximately [missing] m horizontally from the viaduct, dune heights near [missing] m, and dune base widths of about [missing] m. Based on previous research on wind speed profiles in this area [missing], the friction velocity u* is 0.37 $\mathrm{m \cdot s^{-1}}$ and the Karman constant k is 0.095 cm.

According to the wind dynamic environment characteristics on both sides of

Shashangou Bridge, this study selected a single orthogonal wind direction condition to numerically investigate flow field distribution characteristics on the leeward side of mobile dunes, i.e., on both sides of the viaduct [missing]. Since wind-sand flow is primarily affected by horizontal and vertical forces, a two-dimensional model was adopted. To better match actual flow fields and sand accumulation conditions around the viaduct, geometric modeling was conducted at a 1:1 scale with a computational domain of 195.5 m × 30 m to ensure fully developed turbulence (Fig. [Figure 7: see original paper]). The left boundary served as the wind-sand flow inlet with velocity inlet boundary conditions (VELOCITY_{INLET}); the right boundary served as the outlet with fully developed outflow conditions (OUT_{FLOW}); dune surfaces and ground were defined as no-slip walls; and the domain top employed symmetric boundary conditions (SYMMETRY). The medium type was FLUID, with a mixed quadrilateral and triangular mesh. Inlet wind speed followed a logarithmic distribution: $u = (u/k) ln(Z/Z_0)$, *where u is wind speed at height Z* ($m \cdot s^{-1}$), *u* is friction velocity ($0.37\ m \cdot s^{-1}$), k is the Karman constant (0.4), Z is vertical height above ground (m), and Z_0 is roughness length (0.095 cm). Inlet sand phase volume fraction was [missing] and turbulence intensity was [missing] [16-18].

As wind-sand flow passes through the viaduct, the bridge opening's 导流作用 (guiding effect) combined with the "venturi effect" at the bridge bottom creates an acceleration zone in the overhead clearance area, with maximum wind speeds reaching approximately [missing] $m \cdot s^{-1}$. Consequently, the overhead area possesses strong sediment transport capacity (Fig. [Figure 14: see original paper]). However, the leeward side of dunes is a wind speed deceleration zone where speeds are far below the threshold, causing substantial sand accumulation at the dune front that can block the bridge opening and affect sediment transport (Fig. [missing]). As dunes migrate forward, bridge deck wind speeds gradually decrease, expanding the low-speed zone and increasing sand accumulation on the deck. Additionally, the viaduct's obstruction creates deceleration zones near both sides, though with different extents. The windward side deceleration range is less affected by dune movement, approximately [missing] m, while the leeward side deceleration zone expands with dune migration, making wind speed reduction more pronounced and increasing the likelihood of wind-blown sand reaching the tracks [missing].

Given the widespread distribution of barchan and chain dunes around Shashangou Bridge, dune migration poses potential threats to wind guidance and sediment transport. Therefore, targeted sand control measures such as sand barriers, sand nets, and checkerboard sand fences should be installed at dune fronts [missing], along with monitoring of dynamic dune changes.

4. Discussion

The Shashangou Bridge section belongs to an arid desert climate zone where relative humidity in autumn and winter exceeds that in spring and summer, leading to higher surface sand moisture content and increased threshold wind speeds. Meanwhile, lower mean wind speeds in autumn and winter result in lower sand-driving wind frequencies. Conversely, higher temperatures and evaporation rates in spring and summer reduce sand moisture content and threshold wind speeds while mean wind speeds are higher, leading to relatively higher sand-driving wind frequencies (Fig. [Figure 9: see original paper]). This aligns with calculated sediment transport potentials that are higher in spring and summer.

Both sides of Shashangou Bridge exhibit large sand fluxes in the [missing] direction, with strong transport capacities and significant potential sand hazards (Fig. [Figure 10: see original paper]). The west side borders the Kumtagh Desert with extensive mobile dunes and extremely abundant sand sources. Additionally, the west side experiences frequent northwest winds in summer with low air humidity ("wind-drought synchronization"), providing sufficient conditions for surface wind erosion and wind-sand activity. The average wind speed, sand-driving wind frequency, sediment transport potential, and resultant sediment transport potential on the west side all exceed those on the east side, making the west side more prone to sand entrainment and posing greater sand hazard threats.

Based on the wind dynamic environment and flow field distribution characteristics around Shashangou Bridge, numerical simulation analysis reveals that over time, sand will accumulate massively at dune fronts and gradually approach the viaduct. Advancing mobile dunes can cause poor ventilation through bridge openings and wind-blown sand reaching the tracks. Therefore, sand control measures such as checkerboard sand fences and sand barriers should be installed around mobile dunes, sand retaining walls should be constructed along the viaduct, and dynamic dune changes should be monitored.

Increased wind speeds also accelerate dune migration, altering the flow field around the viaduct by expanding low-speed and vortex zones, which can cause sand deposition under the bridge and wind-blown sand on the track, seriously affecting traffic safety. According to the spatiotemporal distribution characteristics of wind-sand flow, summer represents the high-incidence period for sand hazards on the west side of the viaduct.

5. Conclusions

(1) On both sides of Shashangou Bridge, sand-driving winds are mainly from [missing] directions in spring and summer, and SE and S directions in autumn and winter. The wind season is concentrated in summer, when both sides exhibit strong sediment transport potential and sand flux. Since the west side borders the Kumtagh Desert with extremely abundant sand sources, and its average wind speed, sand-driving wind frequency, sediment transport potential, and resultant sediment transport potential all exceed those on the east side, the west side shows greater sand-entraining potential and sand hazard threats.

(2) Based on the wind dynamic environment characteristics on the west side of

Shashangou Bridge and numerical simulations of moving dunes, analysis shows that wind speeds in the overhead area beneath the bridge and on the bridge deck exceed the sand-driving wind speed, providing strong sediment transport capacity and limiting sand accumulation. However, as dunes migrate forward, the likelihood of sand accumulation in the overhead area and wind-blown sand reaching the tracks increases.

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