Effects of Different Guardrail Types on Aeolian Sand Transport over Desert Highway Pavement Postprint

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Abstract

Guardrails are essential highway traffic safety facilities designed to prevent vehicles from accidentally leaving the roadway and ensure driving safety. However, desert highway guardrails obstruct wind-blown sand movement, reducing sand transportation across the pavement and causing sand grain deposition that endangers traffic safety. To investigate this phenomenon, we conducted wind tunnel simulations to examine flow fields and sand transport volume distributions around concrete, W-beam, and cable guardrails under varying wind velocities. We assessed pavement sand transportation using wind velocity attenuation coefficients, sand transportation quantity, and sand transportation efficiency. Results demonstrate that pavement sand transportation is closely related to the zoning characteristics of flow fields and wind velocity variations around guardrails. The concrete guardrail created three distinct zones: deceleration, acceleration, and vortex zones. The W-beam guardrail interacted with wind-blown sand similarly to a lower wind deflector, generating vortex and acceleration zones behind and beneath the plates, respectively, with the acceleration zone facilitating sand transport across the pavement. The cable guardrail only caused wind velocity variability within its height range, producing no sand deposition on the highway pavement. Total transportation quantities for cable, W-beam, and concrete guardrails were 423.53, 415.74, and 136.53 g/min, respectively, with sand transportation efficiencies of 99.31%, 91.25%, and 12.84%. From the perspective of effective pavement sand transportation, cable guardrails should be preferred for desert highways, followed by W-beam guardrails, while concrete guardrails are unsuitable. These findings provide a theoretical basis for optimal guardrail design and prevention of wind-blown sand disasters on desert highway pavements.

Full Text

Preamble

Effects of Different Types of Guardrails on Sand Transportation of Desert Highway Pavement

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Keywords: desert highway; wind-blown sand; guardrail; sand transportation capacity; wind tunnel test

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1 Introduction

Wind-blown sand in desert areas poses a serious threat to agriculture, forestry, and transportation infrastructure. The combination of dry climate, strong winds, and abundant sand sources makes highways and railways crossing these regions particularly vulnerable to wind-blown sand disasters. Passing wind-blown sand causes subgrade erosion and pavement deposition, and in severe cases can bury highways, stop trains, and block traffic, seriously impacting driving safety. Currently, China has built over 4,000 km of desert highways, with more than 1,000 km under construction. These desert-crossing highways serve as major transportation arteries, making wind-blown sand prevention a critical engineering and technical challenge for road construction and maintenance. Field investigations reveal that most sand deposition on highways in wind-blown sand activity areas occurs near guardrails [Figure 1: see original paper], indicating that guardrails significantly affect sediment transport and pavement sand transportation.

To prevent vehicles from leaving the roadway due to faults or accidents, concrete guardrails (rigid), W-beam guardrails (semi-rigid), or cable guardrails (flexible) are typically installed along highway subgrades, median separators, and bridges to ensure driving safety. In desert areas, these different guardrail forms become obstacles to wind-blown sand movement, disturbing airflow to varying degrees, reducing wind velocity, and altering flow field distribution, which decreases sand transportation and causes grain deposition. Sand deposition on highway pavement reduces surface friction and skid resistance, causes vehicle slippage, obstructs driver sightlines, and increases road maintenance difficulty and burden, thereby endangering driving safety.

Research on wind-blown sand disaster prevention along highways and railways has a long history, with existing countermeasures generally falling into three categories. First, mechanical sand prevention measures include high vertical reed sand barriers, polyethylene (PE) net sand barriers, and sheet-type sand fences, as well as stabilization measures such as low vertical grass squares, PE grids, and sand fixation boards. Second, biological measures involve planting sand-fixing vegetation like *Haloxylon ammodendron* and *Tamarix* to create natural protective barriers that prevent mobile dunes from invading highways. Third, chemical stabilization involves spraying agents on sand surfaces to form consolidation layers. While these three approaches have been widely applied and play important roles in reducing road sand deposition and ensuring vehicle safety, they target off-road protection systems. Little research has examined how highway structures and accessory facilities themselves influence sediment transport. In desert highway sand prevention practice, the smooth pavement surface can be leveraged for sand transportation when combined with barrier resistance and particle stabilization systems. Therefore, research on effectively utilizing pavement for sand transport is urgently needed.

Wind-blown sand movement is typically studied through field observations, wind tunnel tests, and numerical simulation. Wind tunnel testing is particularly powerful for investigating aerodynamic characteristics of obstacles and sand transport under artificial atmospheric boundary conditions. Previous studies have simulated sand destruction processes on desert highways, evaluated sand prevention performance of concrete barriers along railways, and examined flow fields and deposition patterns around highway subgrades and median separators. However, most research has focused on wind-blown sand field characteristics and prevention performance of various measures, with few studies investigating how different guardrail types affect pavement sand transportation using wind tunnel tests.

This study addresses the urgent need for sand prevention engineering in desert highways by using wind tunnel modulation to measure wind velocities around concrete, W-beam, and cable guardrails, along with pavement sand transportation quantity. We obtained wind velocity isoline maps, attenuation coefficients, sand transportation efficiency, vertical distribution characteristics, and transport patterns along desert highways, comparing pavement sand transportation under the three guardrail types. The results provide a theoretical basis for guardrail type selection, structural design, and parameter optimization for desert highways.

2.1 Materials

The blow-down wind tunnel used in this study consists of five main components: a power section, rectification section, sand supply section, test section, and diffusion section. The total length is 38 m, with a test section length of 21 m and cross-section dimensions of 1.3 m (width) × 1.0 m (height). Wind velocity is continuously adjustable from 0 to 20 m/s. Previous experiments demonstrated a wind turbulence degree of about 1.0%, airflow stability coefficient less than 1.0%, and transverse unevenness less than 2.5%. The wind velocity measurement system included a pitot tube, micro-pressure sensor, and supporting software. Axis wind velocity at the test section entrance was measured using a Hot-Wire Anemometer (HWA), calibrated with a pitot tube and differential pressure meter before testing.

Guardrail height was scaled at 1:10 according to Chinese national standards. The concrete guardrail height (Ha) was 8.1 cm, W-beam guardrail (Hb) 7.5 cm, and cable guardrail (Hc) 11.3 cm. The concrete guardrail was constructed from poured concrete, the W-beam guardrail consisted of a pillar and waveform iron sheet (sheet height 3.1 cm), and the cable guardrail was assembled from pillars and steel cables (5 cables, each 0.18 cm diameter). All three guardrail types were 80 cm long to avoid wind tunnel sidewall effects on the flow field.

2.2 Experimental Design

The wind tunnel test comprised two parts: flow field testing and sediment transport testing. An open-field test (same wind velocity and sand source, but no guardrail model) served as the control treatment. During flow field tests, wind speeds at different monitoring points were measured using a pitot tube fixed on an adjustable frame. Monitoring points were positioned at 1.0H, 2.0H, 5.0H, and 10.0H on the windward side, and 0.0H, 1.0H, 2.0H, 5.0H, 10.0H, 15.0H, and 20.0H on the leeward side of the guardrail [Figure 2: see original paper], where H represents guardrail height. The pitot tube simultaneously monitored speeds at heights of 1, 2, 3, 5, 7, 10, 15, 30, and 50 cm. Measured wind velocity data were processed using Surfer software to generate wind velocity isoline maps around the three guardrail types, with Kriging interpolation selected.

For sediment transport tests, sand was supplied by wind blowing, with consistent sand source quantity and testing time under each wind velocity. Sandpaper was laid flat on the wind tunnel floor to simulate surface roughness, extending from 40.0H before the guardrail to 20.0H after it. The guardrail installation position remained unchanged. Dune sand collected from the Taklimakan Desert was placed at the test section entrance (100 cm length × 80 cm width × 2 cm height). The device operated at 8 m/s wind velocity for 5 minutes, with photographs recording sand deposition near the guardrail.

Pre-testing showed that installing a sand sampler beyond 2.0H on the leeward side avoided influencing sand deposition distribution while effectively collecting sand grains at different heights. Therefore, sand samplers were installed at 2.0H, 5.0H, 10.0H, 15.0H, and 20.0H on the leeward side. At test completion, sand deposition quantities collected at different heights in the sand collecting box were weighed, and deposition distributions around the three guardrail types were observed [Figure 3: see original paper]. Sand samplers had an overall height of 20 cm, with 20 vertically distributed collecting holes (1 cm × 1 cm each). To avoid sand saturation from excessively long tests, test durations for 8, 10, 12, and 14 m/s wind velocities were 15, 7, 4, and 3 minutes, respectively.

Wind velocity profiles of the simulated boundary layer [Figure 4: see original paper] followed a logarithmic distribution. The boundary layer thickness in test sections was about 15.0 cm, with maximum guardrail height of 11.3 cm located within the boundary layer. According to hydrodynamic calculation principles, wind tunnel simulation requires a tunnel section blocking probability below 5% (model area to whole section area ratio) to avoid deformation effects. In this study, blocking probabilities for concrete, W-beam, and cable guardrails were 4.98%, 1.91%, and 0.55%, respectively, meeting all requirements. The lowest test wind velocity was 8 m/s, yielding a Reynolds number (Re) of 6.1×10^{5} based on guardrail height. Previous studies indicate that when $Re \geq 1\times10^{5}$, scale model flow becomes dynamically similar to full-scale conditions. In the wind tunnel test section, the Froude number (Fr) of grain saltation was 20, meeting the minimum Fr criterion proposed by Owen and

Gillette (1985):

$$Fr = \frac{u}{\sqrt{gH}}$$

where u is fluid velocity (m/s), g is gravitational acceleration (m/s^2), and H is characteristic length (m).

2.3 Evaluation Indicators

The wind velocity reduction degree at a certain leeward distance and height above ground is expressed by the wind velocity attenuation coefficient (WVAC):

$$\xi(x, z) = \frac{v_0(x, z) - v(x, z)}{v_0(x, z)}$$

where x is the distance between a test point on the leeward side and the guardrail (H: H is guardrail height); z is test point height from ground (m); $v_0(x, z)$ is wind velocity at point (x, z) without guardrail (m/s); and $v(x, z)$ is wind velocity at point (x, z) with guardrail (m/s). Larger WVAC values indicate more severe wind velocity attenuation and weaker sand transportation capacity (STC) of the airflow. Areas with larger WVAC values may become sand unloading or deposition zones.

To reveal effects of different guardrail types on desert highway pavement sand transportation, we used Equation 3 to calculate sand transportation efficiency (STE) of pavement below 1.0H of the guardrail:

$$\eta_x = \frac{\sum_{i=1}^{10} Q_{hxi}}{\sum_{i=1}^{10} Q_{nxi}} \times 100\%$$

where η_x is STE of pavement at distance x (2.0H, 5.0H, 10.0H, 15.0H, and 20.0H) from the guardrail; Q_{nxi} is sand interception $(\mathrm{g}/(\mathrm{cm}^2 \cdot \mathrm{min}))$ of the ith sand collecting box at x without guardrail; and Q_{hxi} is sand interception $(\mathrm{g}/(\mathrm{cm}^2 \cdot \mathrm{min}))$ of the ith sand collecting box at x with guardrail. Higher STE indicates better STC and less deposited sand when that guardrail type is used.

3.1 Flow Field Distribution Around the Guardrail

Sand transport quantity and deposition trends on highway pavement are controlled by flow field distribution around guardrails. Figure 5 shows wind velocity isoline maps for the three guardrail types at 12 m/s wind velocity, where positive and negative values represent leeward and windward sides, respectively. The flow field around each guardrail changed due to blocking effects, with significantly different velocity isoline patterns. The concrete guardrail flow field divided into three areas: a deceleration zone on the windward side, an upper acceleration zone, and a leeward vortex zone [Figure 5a: see original paper]. The W-beam guardrail surface hindered airflow above and below the corrugated plate, producing detour flow. When upper airflow was raised, its speed increased, forming an acceleration zone. Separated upper and lower airflow generated a vortex zone on the leeward side. When reverse airflow met forward airflow accelerated under the plate, forward wind velocity decreased, forming a deceleration zone [Figure 5b: see original paper]. The cable guardrail had minimal influence on incoming wind velocity, causing only increased airflow pulsation on the windward side with no clear flow field change on the leeward side [Figure 5c: see original paper].

Based on wind tunnel results and velocity isoline maps, streamline evolution and wind patterns around the three guardrail types are shown in Figure 6, where R_u is the clockwise vortex zone on the windward side and R_d is the reversed flow region on the

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

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