Postprint: Vertical Differentiation Characteristics of Aeolian Sand Flow and Sediment Particle Size Under Different Sand Control Measures

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Abstract

To reveal the variation patterns of wind-sand flow structure and its sediment-carrying particle size under the influence of different sand control measures, four types of sand control measure models were constructed using two materials (wood and nylon mesh): checkerboard sand barriers, single-row sand barriers, double-row sand barriers, and sand-blocking walls. Wind tunnel experiments were employed to measure the wind-sand flow structure before and after the implementation of sand control measures, and a Mastersizer3000 laser particle size analyzer was used to conduct particle size composition analysis on sand samples. The results indicate that: (1) The vertical distribution of wind-sand flow on the windward side of different sand control measures is basically similar to that without sand control measures, with sediment transport rate decreasing as height increases, and over 88% of sediment transport concentrated in the 0–10 cm height layer; whereas on the leeward side, sediment transport rate exhibits a pattern of first increasing and then decreasing with height, and as barrier size decreases, height increases, row spacing narrows, and porosity reduces, the concentrated range of sediment transport gradually shifts upward, with the position of the sediment transport peak shifting from lower-height permeable checkerboard sand barriers (7 cm) upward to higher-height impermeable sand-blocking walls (26 cm), and the accumulated sand amount in the near-surface 0–10 cm height layer decreases accordingly. (2) Under the influence of different sand control measures, the particle size characteristics of sand at different height layers differ significantly, overall showing a pattern where the average particle size of sand gradually decreases with increasing height; fine sand and medium sand are mainly distributed in the near-surface 5–25 cm layer, while the near-surface 0–5 cm layer contains fine sand, medium sand, and coarse sand, with a peak appearing near 0.300 mm and an average content of approximately 12.09%; changes in particle size parameters are less affected by variations in sand control measure specifications and are more manifested in differences between height layers; sand particles at various height layers under different sand control measures are well sorted and extremely positively skewed, with kurtosis changing from broad and flat to medium and sharp-narrow with the intensification of sand control measure parameters, transitioning from checkerboard sand barriers (0.990), single-row sand barriers (0.990), and double-row sand barriers (0.996) to sand-blocking walls (1.086), and the aforementioned variation patterns gradually intensify with increasing indicative wind speed.

Full Text

Vertical Distribution Characteristics of Wind-Sand Flow and Its Grain Size Under Different Sand Control Measures

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Abstract

To reveal the structural characteristics of wind-sand flow and the variation patterns of sand-carrying grain size under different sand control measures, we fabricated models of four types of sand control structures using wood and nylon mesh materials: checkered sand barriers, single-row sand barriers, double-row sand barriers, and retaining walls. Wind tunnel experiments were conducted at the Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences to measure the wind-sand flow structure before and after implementing these measures. The particle size composition of sand samples was analyzed using a Mastersizer3000 laser particle size analyzer. The results demonstrate that: (1) The vertical distribution of wind-sand flow on the windward side of different sand control measures was basically similar to that without any measures, with sediment transport decreasing with increasing height, and over 88% of the sediment transport concentrated within the 0–10 cm height layer. On the leeward side, however, sediment transport first increased and then decreased with height, following a Gaussian distribution pattern. As the barrier specifications decreased, height increased, row spacing narrowed, and porosity reduced, the concentrated range of sediment transport gradually shifted upward. The peak sediment transport position moved from lower-height permeable checkered barriers (7 cm) to higher-height impermeable retaining walls (26 cm), with less sediment accumulation in the near-surface 0–10 cm layer. (2) Under the influence of different sand control measures, significant differences in grain size characteristics were observed across various height layers. The overall average grain size of sand particles gradually decreased with increasing height, with fine and medium sand mainly distributed in the near-surface 5–25 cm layer. The near-surface 0–5 cm layer contained fine, medium, and coarse sand, with a peak around 0.300 mm and an average content of approximately 12.09%. Changes in grain size parameters were less affected by variations in barrier specifications and more reflected differences across height layers. The kurtosis value transitioned from wide-flat to medium-narrow with increasing density of barrier parameters, changing from checkered barriers (0.990), to single-row barriers (0.990), double-row barriers (0.996), and retaining walls (1.086). These patterns intensified with increasing wind speed.

Keywords: wind speed profile; wind-sand flow; vertical distribution of grain size; sand prevention technical measures

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1.1 Experimental Equipment

Wind tunnel experiments were completed at the Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. The facility is a direct-current closed-circuit blowing wind tunnel comprising a power section, rectification section, experimental section, and diffusion section. The tunnel has a total length of [value] m, an experimental section length of [value] m, a cross-section of 0.6 m $\times$ 1.0 m, a boundary layer thickness of approximately 120 mm, and an operational wind speed range of 0–40 $m \cdot s^{-1}$. The experimental setup is illustrated in [Figure 1: see original paper].

1.2 Experimental Materials and Similarity Principles

The experimental design considered both simulation accuracy and operational feasibility. Based on Reynolds number values, a model similarity ratio of [value] was determined. According to similarity principles, when the flow reaches a turbulent state and enters a self-similarity regime, the flow field distribution between the model and prototype can be considered similar. The experimental models were constructed using wood and nylon mesh materials. When the simulated flow Reynolds number exceeds the critical value (approximately 1$×10^{7}$), the boundary layer flow characteristic parameters such as mean wind speed profile, turbulence intensity, and surface friction resistance become independent of Reynolds number variations. Therefore, Reynolds number was used to determine the aerodynamic similarity in the wind tunnel and verify whether the experimental models met requirements. The model parameters and similarity calculations confirmed that the design satisfied similarity criteria .

Grain size parameters including mean grain size, sorting coefficient, skewness, and kurtosis were calculated using the following formulas:

1.3 Experimental Methods

Wind speed profile measurement: Wind speed profiles for different sand control measures were measured under clean wind conditions at gradient wind speeds of 8, 10, 12, and 14 $m \cdot s^{-1}$. After the wind flow stabilized, measurements were taken for 2 minutes. Wind speeds were calculated from pitot tube pressure difference system measurements at heights of 0.5, 2, 4, 8, 12, 16, 20, and 24 cm. Measurement positions included: before the model—at 2H, 4H, and 6H (where H represents model height); inside the model—observation points uniformly distributed according to barrier type; and after the model—at multiples of model height.

Wind-sand flow measurement: Wind-sand flow structure was measured under sand-laden wind conditions at wind speeds of 8, 10, 12, and 14 $m \cdot s^{-1}$. After stabilization, blowing durations were 6, 4, 2, and 1 minute respectively for each wind speed. A continuous equal-height step-type sand trap was used to collect sediment at 2 cm intervals from 0 to 30 cm height, with each collection opening having a 2 cm × 2 cm cross-section. Measurement points were located at 2H on both windward and leeward sides.

Grain size analysis: Following the Udden-Wentworth scale, grain size groups were determined and logarithmically transformed using the Kumdein algorithm to convert particle diameters from real numbers to Φ values for convenient plotting and calculation. Formulas proposed by Folk and Ward were used to calculate mean grain size, sorting coefficient, skewness, and kurtosis values.

2.1 Vertical Airflow Velocity Profile Characteristics

The vertical airflow velocity profiles on the windward and leeward sides of different sand control measures (checkered barriers, single-row barriers, double-row barriers, and retaining walls) are shown in [Figure 2: see original paper]. Under various gradient wind speeds (8, 10, 12, and 14 $m \cdot s^{-1}$), the windward side velocity profiles exhibited similar patterns across all measures, with wind speed increasing with height. However, the leeward side showed significant differences due to barrier effects, with notable variations in near-surface wind speed control. Different specifications of checkered barriers had minimal impact on the overall velocity profile but effectively controlled near-surface (0–5 cm) wind speeds, reducing them by an average of 42.52% compared to the windward side. As barrier size decreased, this control effect became more pronounced, with 2 cm × 2 cm checkered barriers demonstrating the best windproof performance. Under high-standing barrier influence, leeward airflow patterns were similar to those of checkered barriers. Single-row barriers showed more pronounced wind speed reduction with increasing height. When combined as double-row barriers, the control effect strengthened further, reducing wind speeds by an average of 19.66% compared to single-row barriers at the same height. As row spacing decreased, the wind speed reduction trend gradually intensified, with double-row barriers having the greatest impact. Near-surface (0–5 cm) wind speed control effectiveness ranked as: checkered barriers > single-row barriers, while at 5–12 cm height, double-row barriers > checkered barriers, and above 12 cm, high-standing barriers showed an uplifting effect. Changes in wind speed were merely reflected in the scale of airflow variation.

2.2 Wind-Sand Flow Structure Characteristics

Under wind speeds of 8, 10, 12, and 14 $m \cdot s^{-1}$, the wind-sand flow structure variations on windward and leeward sides of different measures are presented in [Figure 3: see original paper]. On the windward side, the structure remained basically similar across different wind speeds, with sediment transport concentrated in the 0–10 cm layer. For checkered barriers, single-row barriers, double-row barriers, and retaining walls, sediment transport in this layer accounted for 87.32%, 89.04%, 91.82%, and 84.63% of total transport, respectively. However, different measures affected total sediment flux on the windward side differently, with double-row barriers (16.19 $g \cdot m^{-2}$) > checkered barriers (14.90 $g \cdot m^{-2}$) > single-row barriers (14.44 $g \cdot m^{-2}$) > retaining walls (3.07 $g \cdot m^{-2}$). On the leeward side, affected by barriers, sediment transport no longer followed the standard wind-sand flow structure law. Instead of decreasing with height, transport first increased then decreased, showing a Gaussian distribution pattern. Due to variations in barrier specifications, height, row spacing, and porosity, the position and magnitude of peak sediment transport differed significantly. Generally, larger barrier specifications, lower heights, and wider row spacing produced greater peak values. Double-row barriers had the greatest impact on transport with the smallest peak value, followed by checkered barriers, while single-row barriers had the least effect on leeward sediment transport. Under impermeable retaining walls, near-surface (0–10 cm) sediment transport was nearly zero, with approximately 90.28% of total transport concentrated in the 15–30 cm layer. The uplifting effect was most pronounced at 20–30 cm height, averaging 17.32% higher than the windward side, and this pattern intensified with increasing wind direction angle. Examination of velocity profiles revealed that, except for retaining walls, windward and leeward velocity profiles under different wind speeds were basically similar, with only the near-surface (0–12 cm) wind speed reduction effect becoming more pronounced as wind speed increased. The uplifting effect above 12 cm also became more obvious, further indicating that wind speed changes are merely reflected in the scale of airflow variation.

2.3 Grain Size Frequency Distribution Characteristics in Wind-Sand Flow

The grain size frequency distribution curves for wind-sand flow under different measures [Figure 4: see original paper] show that experimental sand samples ranged from 0.001 to 1.000 mm, with main distribution between 0.100 and 1.000 mm. Fine sand (0.125–0.250 mm) and medium sand (0.250–0.500 mm) dominated, with a peak near 0.300 mm. The frequency distribution curves for each height layer under different measures showed basically similar single-peak patterns. However, affected by different barriers, the peak position and content varied slightly across height layers, with most peak contents ranging between 9% and 14%. As height increased, the grain size frequency distribution curves shifted slightly upward to the right. Regardless of changes in barrier specifications, height, row spacing, or wind direction angle, different measures had minimal impact on the overall particle frequency distribution pattern, only affecting the peak position and content, with this effect intensifying at higher wind speeds. This aligns with the vertical distribution characteristics of sand particles during aeolian transport, proving that under constant wind speed, changes in grain size distribution with height are minimally affected by barrier parameters.

Exponential, logarithmic, power, and normal distribution models were used to fit wind-sand flow flux. The windward side transport flux showed a significant exponential relationship with height (coefficient of determination $R^2 >$ [value]), while the leeward side, influenced by different barrier types and specifications, exhibited a Gaussian distribution model. Although function coefficients and fitting results varied due to different barrier types and specifications, the overall fitting effect was good. The wind-sand flow variation patterns on both sides were basically unaffected by wind speed, though the average sediment transport in each layer increased significantly with wind speed, again indicating that wind speed changes are merely reflected in the scale of transport variation.

2.4 Spatial Variation Characteristics of Grain Size Parameters in Wind-Sand Flow

The spatial variation characteristics of grain size parameters (mean grain size, sorting coefficient, skewness, and kurtosis) in wind-sand flow under different measures are shown in [Figure 5: see original paper]. Within the 0–30 cm height range on the leeward side of different barriers, sediment particle size gradually became finer with increasing height. The mean grain size became progressively finer in the 0–8 cm layer, gradually stabilized in the 8–20 cm layer, and showed some fluctuation in certain layers but overall trended finer. The mean grain size curves for different measures were basically similar, generally showing that as barrier size decreased, height increased, and row spacing narrowed, the mean grain size of sand particles gradually decreased.

The sorting coefficient of sand particles in wind-sand flow under different measures ranged from 0.300 to 1.000, with average values of [value] for retaining walls, [value] for checkered barriers, [value] for single-row barriers, and [value] for double-row barriers, indicating that retaining walls had the greatest influence. The sorting coefficient showed a trend of first increasing then decreasing and gradually stabilizing with height, with greater fluctuation under retaining wall influence but still following this pattern. The variation curves for other measures were basically similar. From checkered barriers to single-row, double-row barriers, and retaining walls, the skewness values of sediment particles in wind-sand flow tended to increase with height, showing an extremely positive skew distribution, indicating that the mean moved toward a finer median direction, consistent with the variation pattern of mean grain size under different measures.

Kurtosis values ranged from 0.887 to 1.209 for checkered barriers (mean: [value]), 0.891–1.189 for single-row barriers (mean: [value]), 0.901–1.150 for double-row barriers (mean: [value]), and 0.897–1.413 for retaining walls (mean: [value]). Kurtosis transitioned from wide-flat to medium-narrow states as barrier parameters became denser. Changes in grain size parameters were less affected by variations in barrier specifications and more reflected differences across height layers. The influence of different measures on grain size parameters at various height layers intensified with increasing wind speed and denser specification parameters.

3 Discussion

Aeolian sand transport is a near-surface process, and implementing different sand control measures to alter near-surface airflow and wind-sand flow can effectively weaken aeolian activity intensity. Previous studies have shown that when wind-sand flow is obstructed, its transport capacity decreases, causing sediment particles to deposit on both windward and leeward sides within certain ranges, thereby affecting sediment transport at different positions and causing changes in wind-sand flow structure and accumulation around obstacles. This study analyzed the vertical distribution characteristics of wind-sand flow before and after permeable checkered barriers, single-row barriers, double-row barriers, and impermeable retaining walls, finding that the windward side structure was basically similar to that without measures, with sediment transport decreasing with height, consistent with Bagnold' s wind-sand flow vertical distribution law. However, the leeward side no longer followed this law due to barrier influence.

Many factors affect wind-sand flow structure, primarily surface conditions, vegetation, soil properties, and aeolian environment, leading to differences in fitting functions. This study employed wind tunnel experiments to control parameter variables, considering the effects of wind speed and barrier parameters. Results showed that total sediment transport and layer-wise variations differed significantly due to different barriers, generally following the pattern that smaller specifications (higher density), greater height, narrower row spacing, lower porosity, and wind direction angles closer to 90° resulted in less total transport. As barrier specifications decreased, height increased, row spacing narrowed, porosity decreased, and wind direction angles approached 90°, the peak sediment transport shifted upward, with less accumulation in the near-surface 0–10 cm layer. Under impermeable retaining walls, near-surface (0–10 cm) accumulation on the leeward side was nearly zero, and these patterns intensified with increasing wind speed.

Various models (exponential, logarithmic, power, and normal distribution) were used to fit wind-sand flow flux, identifying the best-fitting models. The windward side transport flux showed a significant exponential relationship with height, consistent with previous research showing that aeolian flow flux within 60 cm of the desert surface can be expressed by exponential functions, similar to Zhang et al.' s findings. This study further analyzed leeward side transport flux patterns under different barriers, revealing Gaussian distribution models influenced by barrier type and specifications, with varying function coefficients and fitting results.

Grain size is a crucial indicator reflecting wind transport capacity and sorting properties. Under different barrier influences, vertical differentiation occurs to some extent. Previous studies by Wang et al. and Feng et al. demonstrated that mean grain size decreases with height in exponential patterns, with coarse particles having higher entrainment rates than fine particles on non-uniform beds, and coarse particles shielding fine particles. Li et al. found that behind nylon net checkered barriers, mean grain size decreased, sorting became poorer, skewness increased, and kurtosis decreased. This study validates these conclusions and further explores how barrier parameters (specifications, height, row spacing, porosity, wind direction angle) affect these distribution patterns through mean grain size, sorting coefficient, skewness, and kurtosis parameters.

4 Conclusions

This study employed wind tunnel simulation to analyze in detail the wind-sand flow and its vertical grain size distribution characteristics under different sand control measures, reaching the following main conclusions:

1) Sediment transport on the windward side of different sand control measures decreased with height, following an exponential function model, with over 88.20% of total transport concentrated in the 0–10 cm layer. On the leeward side, transport first increased then decreased with height, following a Gaussian distribution pattern. As barrier specifications decreased, height increased, row spacing narrowed, and porosity reduced, the concentrated range of sediment transport gradually shifted upward. The peak position moved from lower-height permeable checkered barriers (7 cm) to higher-height impermeable retaining walls (26 cm), with less sediment accumulation in the near-surface 0–10 cm layer. Under impermeable retaining walls, near-surface (0–10 cm) accumulation on the leeward side was nearly zero. These patterns intensified with increasing wind speed.

2) In wind-sand flow under different measures, the mean grain size gradually decreased with height. Medium sand was mainly distributed in the near-surface 5–25 cm layer, while the near-surface 0–5 cm layer had a broader size distribution (0.100–1.000 mm) containing fine, medium, and coarse sand. Changes in grain size parameters were less affected by barrier specification variations and more reflected differences across height layers. Sorting was generally good and extremely positively skewed at all height layers. Kurtosis transitioned from wide-flat to medium-narrow

states as barrier parameters became denser, changing from checkered barriers (0.990), to single-row barriers (0.990), double-row barriers (0.996), and retaining walls (1.086). The degree of these changes gradually intensified with increasing wind speed.

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