Windbreak and Sand Fixation Characteristics of Vertical Nylon Mesh Sand Barriers and Their Optimal Configuration Postprint

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Abstract

Vertical sand barriers are widely used in wind-sand disaster protection for linear engineering projects, with their layout patterns directly influencing the windbreak and sand-blocking efficiency and cost-effectiveness of the project. On the windward side of a sand-crossing highway in the Ulan Buh Desert, sparse-top-dense-bottom nylon sand-blocking nets were selected to design single-row barriers of four different heights and double-row barriers of four heights with three spacings to simulate a wind-sand disaster prevention observation field. A step-type sand collector and HOBO anemometer were employed to observe windbreak and sand-blocking efficiency parameters under different wind speeds. The results indicate: (1) Under low wind speed (<12 $m \cdot s^{-1}$) conditions, the effective protection distance behind high-standing nylon sand-blocking net barriers is within 3H (distance equivalent to the barrier height) for single-row barriers and 12H for double-row barriers. (2) For single-row high-standing nylon sand-blocking net barriers, the average sand interception rate is 85.14% at 3H leeward and 91.23% at 5H leeward; for double-row barriers, the average rate at 3H leeward is 93.53%. (3) When configuring nylon sand-blocking nets for linear engineering protection in medium-low wind energy areas, barriers with heights of 0.6 m and below are not recommended; for wind speeds of 8 $m \cdot s^{-1}$ and below, single-row nylon sand-blocking net barriers with a height of 1 m are recommended; for wind speeds of 8–12 $m \cdot s^{-1}$, double-row nylon sand-blocking nets with a spacing of 8H and heights of 0.8–1.0 m are recommended; in high wind speed areas (>12 $m \cdot s^{-1}$), multi-strip compound configuration of nylon net barriers with expanded spacing to 10H and height of 1.2 m should be selected. This pattern can optimize sand control engineering design and improve the sand damage prevention system for linear projects.

Full Text

Abstract

High vertical sand barriers are widely employed in wind-sand disaster protection for linear engineering projects. The layout configuration directly influences both the efficiency and cost-effectiveness of wind and sand control engineering. On the windward side of the Dengkou-Ustai sand-crossing highway in the Ulan Buh Desert, we established an observation field to simulate wind-sand disaster prevention and control using upper-sparse-lower-dense nylon sand-blocking nets. Ladder-type sand collectors and HOBO anemometers were deployed to observe windproof and sand-blocking efficiency parameters under various wind speeds. The experiment designed four heights of single-row barriers and four heights with three spacings of double-row barriers.

The results demonstrate that under low wind speed conditions ($<12\ m \cdot s^{-1}$), the effective protection distance behind high vertical nylon sand barriers is within 3H for single-row configuration and 12H for double-row configuration (where H represents the barrier height). The average sand interception rate is 85.14% at 3H behind single-row barriers and 91.23% at 5H behind single-row barriers. For double-row barriers, the average interception rate reaches 93.53% at 3H behind the barrier. In medium-low wind energy regions, sand barriers with heights of 0.6 m or less are not recommended for linear engineering protection. At wind speeds of 8 $m \cdot s^{-1}$ and below, single-row nylon sand barriers with a height of 1.0 m can be deployed. At wind speeds of 8–12 $m \cdot s^{-1}$, double-row nylon sand barriers with 8H spacing and 0.8–1.0 m height are appropriate. In high wind speed areas ($>12\ m \cdot s^{-1}$), a multi-strip compound configuration of nylon mesh sand barriers with spacing widened to 10H and height of 1.2 m should be selected. This configuration model can optimize sand control engineering design and improve the sand disaster prevention system for linear projects.

Keywords: high vertical sand barrier; windproof benefit; sand blocking interception rate; configuration optimization

Introduction

High vertical sand barriers represent a common technical measure for wind-sand disaster prevention, reducing losses from wind erosion and sand burial in linear engineering projects. The barrier layout directly affects prevention efficiency and cost-effectiveness. Previous research has explored different barrier types through field observations, wind tunnel experiments, and numerical simulations, establishing that single-row nylon mesh barriers and high white nylon mesh barriers have protection ranges of specific values. Wind tunnel studies indicate that 1.1 m and 1.2 m high nylon mesh barriers can achieve protection ranges of certain distances, demonstrating a relationship between barrier height and protection distance. However, wind tunnel simulations involve specific backgrounds, model materials, scale ratios, and geometric similarity issues that may not reflect real-world double-row barrier performance. Numerical simulations also employ simplified boundary conditions and parameters.

Field studies reveal that complex wind conditions and diverse barrier parameters create compound effects in double-row configurations, making comparative experiments with different height and spacing combinations essential. Researchers have established experimental patterns with barriers on the windward side of wind-sand flow activity, concluding that the optimal spacing for double-row barriers is 1.5 times the barrier height, with maximum sand accumulation between barriers. Corresponding wind tunnel experiments with 20–30 m spacing and numerical simulations have validated these findings. However, these configurations lack diverse gradient trials and multi-parameter comparisons under unified backgrounds.

Nylon mesh has been widely applied in wind-sand prevention due to its strong aging resistance, wind-sand durability, and convenient production, transportation, and construction. This study employs nylon sand-blocking nets in controlled field experiments to observe actual windproof characteristics, sand-blocking capacity, and effective protection distances under various row spacings, heights, and combinations. The research aims to clarify wind speed variation patterns on windward and leeward sides, sand-blocking characteristics under height and spacing influences, and provide field data for optimizing sand control engineering design with material-efficient, low-cost configurations.

1.1 Study Area Overview

The study area is located north of the Dengkou-Ustai sand-crossing highway in Bayannur City, at 40°10 21 -40°10 23 N, 106°48 17 -106°48 19 E. The region features abundant sand sources and frequent wind-sand activity, with northwesterly winds as the primary sand-driving wind. The multi-year average wind speed is 3.7 $m \cdot s^{-1}$, average strong wind speed is 10.5 $m \cdot s^{-1}$, with 75–79 strong wind days, 19–22 sand-raising days, and 10–32 sandstorm days annually. Lattice dunes and dune chains are widely distributed, with interspersed mobile, semi-fixed, and fixed dunes.

The area has a typical mid-temperate continental monsoon climate with dry conditions, average annual rainfall of 142.7 mm, and evaporation of 2380.6 mm. The soil is typical aeolian sandy soil, with vegetation dominated by *Nitraria tangutorum* and *Haloxylon ammodendron*. The experimental site was mechanically leveled prior to the experiment, providing flat, open terrain ideal for observing protection benefits of sand control measures.

1.2.1 Material Selection and Experimental Design

Material Selection: Previous studies indicate that porosity of 0.3–0.6 produces maximum effective protection distance. For nylon mesh, comparative analyses of uniform, upper-dense-lower-sparse, and upper-sparse-lower-dense structures show the upper-sparse-lower-dense configuration performs best. Therefore, this experiment exclusively used upper-sparse-lower-dense nylon mesh.

Experimental Layout: The experiment was conducted north of the Dengkou-Ustai sand-crossing highway in the Ulan Buh Desert. Four heights were tested for single-row barriers (0.6 m, 0.8 m, 1.0 m, 1.2 m) and double-row barriers with three spacings (8H, 10H, 12H). The double-row barriers had first and second row spacings of 8H, 10H, and 12H respectively. All barriers were laid perpendicular to the prevailing wind direction on the same horizontal line, with disconnected sections to avoid interference. Control open-field measurements were taken on unaffected flat bare sand upwind. The experimental layout schematic is shown in [Figure 1: see original paper].

Observation points for single-row barriers were set at -10H, -5H, -3H, -1H, 0H, 1H, 3H, 5H, 10H, 15H, and 20H (negative values indicate windward side, positive values leeward side; 0H is the barrier position). Double-row barriers had additional measurement points between the two rows. The specific point layout is shown in [Figure 2: see original paper].

1.2.2 Wind Speed Measurement

Wind speed was measured using Onset HOBO anemometers with a 1-second collection interval. Measurements commenced when wind direction was perpendicular to the high vertical sand barriers, with each observation point measured for no less than 30 minutes. Anemometers were deployed at vertical heights of 0.2 m, 0.5 m, 1.0 m, and 1.5 m.

1.2.3 Sand Accumulation Measurement

Sand accumulation was measured using ladder-type sand collectors with ten height layers: 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, 25–30 cm, 30–35 cm, 35–40 cm, 40–45 cm, and 45–50 cm. For single-row barriers, measurement points were at windward, leeward, and 3H, 5H, 10H, 15H, 20H positions. For double-row barriers, additional points were between the two rows. The layout schematic is shown in [Figure 2: see original paper]. Observations began when sand-driving wind speeds were reached, with timing recorded. Samples were sealed immediately after collection and weighed using a 0.001 g precision electronic balance.

1.2.4 Calculation Methods

Effective Protection Distance: Based on field observations and wind tunnel results, effective protection distance is defined as the distance from the barrier to the point downwind where wind speed recovers to 20–50% of the open-field speed at the same height. This study adopts the widely used criterion of 20% reduction (i.e., wind speed reduced to 80% of open-field speed) to determine effective protection distance, marked with dashed lines in wind speed diagrams. The calculation formula is:

$$bk_{ij} = \frac{V_{kj} - V_{kij}}{V_{kj}} \times 100$$

where V_{kij} is the wind speed value at coordinate i, j under wind speed environment k; V_{kj} is the open-field wind speed at height j; and bk_{ij} is the wind speed reduction percentage at that position. Larger bk_{ij} values indicate better windproof effects.

Sand Barrier Interception Rate: Assuming ground sand erosion results from pure wind shear stress and sand-laden wind impact, we employ the concept of interception rate as a key parameter to quantitatively evaluate sand barrier effects on sand particle retention. The interception rate is defined as the percentage of sand particles retained by the barrier relative to total eroded sand particles. The calculation formula is:

$$\eta = \frac{W - Q}{W} \times 100$$

where η is the sand barrier interception rate; W is the sand transport flux in the open field at the same height layer under the same wind speed ($g \cdot cm^{-1} \cdot min^{-1}$); and Q is the remaining sand transport flux after barrier influence.

2.1.1 Effect of Sand Barrier Height on Windproof Performance

As shown in [Figure 3: see original paper], at constant barrier height, higher wind speeds result in greater percentages of wind speed reduction. Taking the 1.2 m height barrier as an example, the inflection point of rapid wind speed reduction occurs approximately at -1H windward of the barrier. At the 0.2 m height level, the wind speed reduction percentage is substantial, while the effective protection distance leeward is 12.9H. At the 0.5 m height level, the reduction is moderate, with the barrier effect decreasing at higher positions.

Under the same wind speed, the inflection point for rapid wind speed reduction remains at approximately -1H windward for all three barrier heights. At the 0.2 m height level, the effective protection distances are 11.9H, 12.5H, 12.9H, and 12.9H for 0.6 m, 0.8 m, 1.0 m, and 1.2 m barriers respectively. Lower barriers have shorter effective protection distances, confirming that height is a critical factor constraining windproof performance. Wind speed magnitude does not significantly affect the reduction pattern but influences the effective protection distance.

2.1.2 Effect of Sand Barrier Row Spacing on Windproof Performance

As shown in [Figure 4: see original paper], at constant wind speed, the inflection point remains at -1H windward. Under 12H spacing configuration, the 0.6 m height barrier shows the lowest protection benefit, with wind speed reduction occurring between barriers at -2.4H to -3.0H. The 0.8 m height barrier shows moderate performance, and the 1.0 m and 1.2 m barriers exhibit discontinuous protection effects approaching open-field conditions, indicating excessive spacing.

Under 10H spacing, the 0.6 m and 0.8 m height barriers achieve effective protection distances of 11.9H and 12.5H respectively, while 1.0 m and 1.2 m barriers show continuous protection with distances exceeding 12.9H, representing ideal performance.

Under 8H spacing, all barrier heights demonstrate continuous protection with effective distances of 11.9H, 12.5H, 12.9H, and 12.9H respectively. However, an anomaly occurs where increased height results in reduced protection distance due to overlapping effects from narrow spacing. The overlapping effect intensifies with barrier height, making this spacing relatively narrow.

Comprehensive analysis indicates that 8H–10H spacing is optimal for double-row barriers. Combined with single-row performance, the effective protection distance for 1.2 m height single-row nylon sand barriers is 12.9H at 12 $m \cdot s^{-1}$ wind speed, while double-row barriers achieve 11.9H.

2.2.1 Effect of Sand Barrier Height on Sand Blocking Performance

Wind-sand flow concentrates primarily near the surface, with transport flux proportion decreasing at higher elevations. Taking the 1.2 m height barrier at 10.87 $m \cdot s^{-1}$ wind speed as an example, the sand transport flux proportions in the 0–30 cm height layers are 35.85%, 26.52%, 15.31%, 9.32%, 5.49%, and 3.38% respectively. Compared with open-field conditions at the same layers, the flux reduction ranges from 82.87% to 100%.

As shown in [Figure 5: see original paper], increased wind speed raises sand accumulation in the open field. Under the same barrier height, the interception rate increases gradually with wind speed. Higher barriers show greater interception rates due to increased interception area. The sand transport pattern across different height layers resembles that of the open field, though small wind speeds carry minimal sand that is almost completely intercepted by barriers.

2.2.2 Effect of Sand Barrier Row Spacing on Sand Blocking Performance

Sand particles deposit heavily before the first barrier row. Wind speed magnitude affects transport quantity but not the overall pattern. As shown in [Figure 6: see original paper], at 10.87 $m \cdot s^{-1}$ wind speed, the open-field sand accumulation is 2.57 $g \cdot cm^{-1} \cdot min^{-1}$. The interception rates at 3H leeward are 74.55%, 88.29%, and 89.47% for 0.6 m, 0.8 m, and 1.0 m barriers respectively.

For 0.6 m height barriers at 8H spacing, the sand transport flux between barriers is 0.33 $g \cdot cm^{-1} \cdot min^{-1}$, with interception rates of 88.13% and 95.24% at mid-barrier and leeward positions respectively. At 10H spacing, flux increases to 0.42 $g \cdot cm^{-1} \cdot min^{-1}$ with interception rates of 91.26% and 86.67%. At 12H spacing, flux reaches 1.81 $g \cdot cm^{-1} \cdot min^{-1}$ with interception rates dropping to 42.89% and 79.77%, indicating poor performance.

For 0.8 m barriers, 8H spacing yields mid-barrier flux of 0.28 $g \cdot cm^{-1} \cdot min^{-1}$ with 95.97% interception, while 10H spacing shows 0.33 $g \cdot cm^{-1} \cdot min^{-1}$ with 88.78% interception. The 12H spacing shows significantly higher flux at 3.18 $g \cdot cm^{-1} \cdot min^{-1}$ with only 41.94% interception, demonstrating discontinuous protection.

For 1.0 m barriers, 8H spacing produces mid-barrier flux of 0.33 $g \cdot cm^{-1} \cdot min^{-1}$ with 95.62% and 83.35% interception rates at mid-barrier and leeward positions. At 10H spacing, flux is 0.42 $g \cdot cm^{-1} \cdot min^{-1}$ with 89.47% and 95.21% interception. At 12H spacing, flux increases to 1.2 $g \cdot cm^{-1} \cdot min^{-1}$ with interception rates of 69.44% and 86.81%.

These results confirm that height is the key factor affecting protection benefits for both single and double-row barriers. Double-row barriers demonstrate cumulative effects on wind speed reduction, and reasonable spacing not only prevents wind erosion and sand burial but also expands protection range and enhances benefits.

3.1 Airflow Velocity Characteristics Under Different Barrier Configurations

Single-row nylon sand barriers show no spacing effects, with analysis focusing on height and wind speed impacts. At constant wind speed, the weak wind zone expands with increasing barrier height, improving protection benefits. This aligns with existing research conclusions that height is a critical factor.

The inflection point for single-row barriers occurs at -1H windward, while double-row barriers show the same inflection point. This pattern remains stable regardless of wind speed changes. Wind passing through double-row barriers experiences two stages of weakening, with this effect gradually diminishing as spacing or height changes. Under identical spacing or height conditions, altering either factor affects windproof performance.

3.2 Sand Transport Characteristics Under Different Barrier Configurations

Near-surface sand transport decreases with height, concentrating within 0–20 cm. Under single-row barrier influence, sand transport proportions at 0–10 cm and 10–20 cm heights average 85.14% and 89.47% respectively. The unit time and area sand transport follows: open field > windward side before barrier > between barriers (ignored for single-row) > leeward side after barrier.

Sand transport quantity decreases with increasing height, gradually stabilizing after reaching certain elevations, becoming nearly zero at greater heights. Transport concentrates in the 0–10 cm layer, with minimal transport above 30 cm.

For double-row barriers, sand accumulation between rows varies most significantly with spacing. Smaller spacing yields greater sand interception capacity, while larger spacing reduces it. At 8H spacing, accumulation is minimal; at 10H spacing, it increases; at 12H spacing, it reaches maximum. This aligns with research showing that smaller combination spacing results in more concentrated sand distribution.

3.3 Rational Configuration of Nylon Sand Barriers

Comprehensive consideration of both wind speed reduction and sand transport changes is necessary to identify optimal configurations that balance actual benefits, material efficiency, and low cost. Comparative analysis of four barrier heights reveals that 0.6 m height provides the lowest protection benefits for both single and double-row configurations and is not recommended.

Higher interception rates indicate more significant wind speed weakening. While 1.2 m height barriers show excellent performance, they waste some protection potential and increase costs. Excessively wide spacing allows conditions to revert toward open-field status, failing to control sand erosion and deposition effectively. Therefore, establishing rational height-spacing combinations is crucial.

Considering cost control, for medium-low wind energy regions with similar backgrounds, the recommended configuration is 1.0 m height single-row high vertical nylon sand barriers, or 0.8–1.0 m height double-row barriers with 8–10H spacing. These findings are significant for wind-sand control and linear engineering protection.

4 Conclusions

1) Under rational configuration, the wind speed reduction inflection point for single-row high vertical nylon sand barriers is at -1H windward, with the leeward recovery inflection point extending farther as height increases, unaffected by wind speed magnitude. For double-row barriers, the inflection point is also at -1H windward with 12H effective protection distance,

showing minimal fluctuation with wind speed.

2) Near-surface sand transport decreases with height, concentrating within 20 cm. Under single-row barriers, sand transport proportions at 0–10 cm and 10–20 cm average 85.14% and 89.47% respectively. The average sand barrier interception rate is 85.14% at 3H behind single-row barriers and 91.23% at 5H. For double-row barriers, the average interception rate is 93.53% at 3H.

3) In medium-low wind energy regions for general linear protection projects, prioritizing cost savings and practicality, sand barriers with heights \$ \$0.6 m are not recommended. At wind speeds \$ $8m \cdot s^{\{-1\}, 1.0 m height single-row nylon sand barriers can be deployed. At wind speeds of 8–12 m \cdot s}\{$-1}\$, double-row nylon sand barriers with 8H spacing and 0.8–1.0 m height are suitable. In higher wind speed conditions, multi-strip compound configuration with 1.2 m height and spacing widened to 10H is recommended.

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