Postprint: Wind Tunnel Simulation of Sand Fixation Effects of a Square-Loop Sand Barrier System

Authors: Qu Jianjun, Zhu Zhihua, Shen Baoshou, Gao Yongping, Li Hong

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Abstract

Based on stable-state straw checkerboard sand fixation dimensions (height-to-length ratio of 0.1~0.2), this study proposes a novel sand checkerboard barrier technology that utilizes local sand to construct barriers measuring 20 cm in height and 100 cm in length. Although this technology offers advantages of convenient construction and low cost, its standalone application is vulnerable to wind erosion damage. To address this limitation, an innovative concentric (回-shaped) protection pattern is established by installing fiber mesh barriers or brush-type straw checkerboard barriers around the sand checkerboard periphery. To elucidate the sand fixation mechanism of sand checkerboard barriers and enhance the efficacy of the concentric sand fixation system, wind tunnel simulation experiments were conducted with three configurations: standalone sand checkerboard barriers, fiber mesh barrier combined with sand checkerboard barrier, and brush-type straw checkerboard barrier combined with sand checkerboard barrier, measuring sediment transport rates and sand surface erosion-deposition patterns. Functional fitting was employed to model the vertical distribution of sediment transport rates, and the protective effects of fiber mesh barriers or brush-type straw checkerboard barriers on sand checkerboard barriers were analyzed. The results indicate: (1) Standalone sand checkerboard barriers significantly reduce sediment transport rates at 0~10 cm height, but slightly increase rates above 10 cm. (2) Upstream flexible barriers (fiber mesh barriers or brush-type straw checkerboard barriers) effectively attenuate wind-sand flow energy, further reducing sediment transport rates, with brush-type straw checkerboard barriers demonstrating superior sand-blocking performance compared to fiber mesh barriers (84.6% > 80.6%). (3) With increasing wind velocity, erosion-deposition phenomena within sand checkerboard barriers become increasingly pronounced, with accumulated sand height rising. At 10 $\mathrm{m \cdot s^{-1}}$ wind speed, upstream flexible barriers effectively protect sand checkerboard barriers from height reduction; at higher wind speeds, brush-type straw checkerboard barriers exhibit better protective performance than fiber mesh barriers (sand checkerboard height reductions of 2~8 cm versus 3~9 cm, respectively). (4) The combined application of sand checkerboard barriers with upstream flexible barriers significantly enhances sand fixation effectiveness and service life. Brush-type straw checkerboard barriers are recommended for priority consideration in practical applications due to their complex three-dimensional brush structure, superior protective performance, and lower comprehensive cost. This study provides a novel pattern for optimized sand barrier design in desertification control and offers scientific basis and technical support for local material utilization, sand-to-sand treatment, and concentric sand control systems.

Full Text

Wind Tunnel Simulation Test on Sand-Fixing Effect of the Nested-Square Sand-Fixing System

QU Jianjun[1,2], **ZHU Zhihao**[1,2], **SHEN Baoshou**[1], **GAO Yongping**[3], **LI Hong**[4]

[1]College of Urban and Environmental Sciences, Northwest University, Xi' an 710127, Shaanxi, China
[2]Guangdong Provincial Laboratory of Southern Marine Science and Engineering, Guangzhou 511458, Guangdong, China
[3]Shapotou Desert Research and Experiment Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, Gansu, China
[4]Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, Gansu, China

Abstract

This study proposes a novel sand-checkerboard barrier technology based on steady-state dimensions for straw checkerboard sand fixation (height-to-length ratio of 0.1–0.2), utilizing locally sourced sand to construct barriers measuring 20 cm in height and 100 cm in length. While this approach offers advantages in construction convenience and cost efficiency, standalone application remains vulnerable to wind erosion. To address this limitation, we developed an innovative nested-square protection mode by installing fiber net barriers or brush straw checkerboard barriers around the perimeter of the sand checkerboards. To clarify the sand-fixing mechanism of sand-checkerboard barriers and enhance the effectiveness of the nested-square sand-fixing system, wind tunnel simulation experiments were conducted comparing standalone sand-checkerboard barriers with two combined configurations: fiber net + sand-checkerboard and brush straw checkerboard + sand-checkerboard. Sediment transport rates and surface erosion-deposition patterns were measured, and functional relationships between sediment flux density and height were established through curve fitting. The protective effects of front-mounted flexible barriers (fiber net or brush straw checkerboard) on sand-checkerboard barriers were also analyzed.

The results demonstrate that: (1) Standalone sand-checkerboard barriers significantly reduce sediment flux density within the 0–10 cm height range, while causing a slight increase in transport rates above 10 cm. (2) Front-mounted flexible barriers effectively attenuate wind-sand flow energy, further reducing sediment transport rates, with brush straw checkerboard barriers exhibiting superior sand-blocking performance compared to fiber net barriers (84.6% > 80.6%). (3) As wind velocity increases, erosion and deposition patterns within sand-checkerboard barriers become increasingly pronounced, with accumulated sand heights rising accordingly. At 10 $\mathrm{m \cdot s^{-1}}$ wind speed, front-mounted flexible barriers effectively protect sand-checkerboard barriers from height reduction; at higher wind speeds, brush straw checkerboard barriers demonstrate better protective performance than fiber net barriers (sand-checkerboard height reductions of 2–8 cm vs. 3–9 cm, respectively). (4) The combined application of sand-checkerboard barriers with front-mounted flexible barriers significantly improves both sand-fixing effectiveness and service life. Due to its complex three-dimensional brush structure, superior protective performance, and lower comprehensive cost, brush straw checkerboard barriers are recommended as the preferred option for practical applications. This study provides a novel optimization model for sand barrier design in desertification control and offers scientific evidence and technical support for strategies of local material utilization and sand-combating-sand approaches.

Keywords: nested-square sand-fixing system; sand-checkerboard barrier; fiber net barrier; brush straw checkerboard barrier; wind tunnel simulation test

1. Materials and Methods

1.1 Experimental Design

Wind tunnel simulation tests were conducted at the Shapotou Field Wind Tunnel Laboratory of the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. The wind tunnel features a direct-current closed-circuit blowing system with adjustable wind speeds ranging from 1 to 40 $\mathrm{m \cdot s^{-1}}$ and measurement accuracy of $±0.3±$0.5%. The test section measures 1.2 m × 1.2 m, with a maximum boundary layer thickness of 0.5 m. The facility is equipped with a wind speed measurement and control platform, multi-channel automatic wind speed and pressure data acquisition system, digital camera, desktop computer, and stopwatch.

Sand-checkerboard barriers were constructed by stacking sand particles into ridges with a triangular cross-section (40 cm base width, 20 cm height). Each checkerboard consists of four such ridges, with 20 cm spacing at the ridge tops and 100 cm spacing at the bottoms, forming a novel "local-material, sand-combating-sand" barrier system that is convenient to construct and cost-effective. To enhance the sand-fixing benefits, two fiber net checkerboards or brush straw checkerboards were installed immediately in front of the sand-checkerboard barriers, creating nested-square protection systems [Figure 1: see original paper][Figure 2: see original paper]. The fiber net checkerboards were formed using 20 cm-wide fiber nets, while the brush straw checkerboards were constructed from 20 cm-diameter brush straw ropes with internal grid dimensions of 20 cm × 20 cm.

1.2 Data Collection

Sand barriers were installed on a 10 cm-thick sand surface. Before each test, sand was replenished and the surface was leveled using tools to ensure consistent sand bed thickness, length, and morphology. A vertical sand sampler was employed to collect sediment transport data at heights from 0 to 60 cm, featuring 20 collection ports at 0.5 cm intervals [Figure 3: see original paper]. Four test wind speeds were applied (6, 10, 14, and 18 $\mathrm{m \cdot s^{-1}}$) with erosion durations of 1 minute for standalone sand-checkerboard barriers and 5 minutes for combined barrier systems. After each erosion event, collected sand from each height interval was weighed using a precision balance (0.001 g accuracy).

Total sediment flux density (qz) was calculated as the sum of transport rates across all height intervals. The total sediment flux reduction rate (Rs) was determined using the equation:

$$R_s = \frac{q_{tf} - q_{tg}}{q_{tf}} \times 100\%$$

where qtg represents total sediment flux density after barrier installation ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$) and qtf represents total flux density without barriers ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$).

Erosion and deposition patterns within barriers were monitored using the pin method [Figure 3: see original paper]. Eighteen pins were installed in each sand-checkerboard barrier (three checkerboards with six pins each). Four wind speeds were tested with varying erosion durations: 1 minute for standalone barriers and 5 minutes for combined systems. After each erosion event, pin scale readings were used to determine internal erosion and deposition conditions. For combined systems, 30 pins were installed across two protective barriers and three sand-checkerboard barriers, with four wind speeds tested at 5-minute erosion durations.

2. Results

2.1 Sediment Flux Density Characteristics

At 6 $\mathrm{m \cdot s^{-1}}$ wind speed, no sand particles were collected by the sampler in the absence of barriers, yielding zero sediment flux density. Figure 4 illustrates sediment flux density distributions for conditions without barriers, with standalone sand-checkerboard barriers, with fiber net + sand-checkerboard combinations, and with brush straw checkerboard + sand-checkerboard combinations across the remaining wind speeds. Without barriers, sediment flux density decreases exponentially with height, with maximum transport occurring nearest the sand surface. Compared to the no-barrier condition, sand-checkerboard barriers significantly reduce sediment flux density in the 0–10 cm layer (52.6% average reduction), while causing a slight increase in transport rates above 10 cm.

Installing fiber net or brush straw checkerboard barriers in front of sand-checkerboard barriers further reduces sediment flux density. Nonlinear regression analysis of sediment flux density profiles above the sand surface reveals that transport rates follow an exponential decay function:

$$q(z) = a \cdot e^{-bz} + c$$

where q(z) represents sediment flux density at height z ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$), z is height (cm), and a, b, and c are regression coefficients. Table 1 presents the regression results, with R^2 values exceeding 0.94 for no-barrier conditions and 0.98 for barrier conditions, all statistically significant ($P < 0.001$).

Total sediment flux reduction rates (Rs) under different wind speeds are summarized in Table 2. For standalone sand-checkerboard barriers, Rs values range from 29.6% to 31.7% across wind speeds, with an average of 22.7–28.0%. The fiber net + sand-checkerboard combination achieves Rs values of 70.9–82.7% (average 80.6%), while the brush straw + sand-checkerboard combination yields Rs values of 76.5–88.1% (average 84.6%). The brush straw checkerboard barrier thus provides superior sand-blocking performance compared to the fiber net barrier.

2.2 Erosion-Deposition Dynamics

At 10 $\mathrm{m \cdot s^{-1}}$ wind speed, sand particles remained immobile and no erosion-deposition patterns developed. Figure 6 illustrates erosion-deposition changes within standalone sand-checkerboard barriers at other wind speeds. At 14 $\mathrm{m \cdot s^{-1}}$, accumulation occurs at the front and sides of the first checkerboard cell (0.0–0.8 cm), the second cell shows relatively stable conditions (0.0–0.4 cm), and the third cell exhibits accumulation at the rear (0.0–0.8 cm). At 18 $\mathrm{m \cdot s^{-1}}$, the first and second cells show accumulation at their front portions (0.0–1.4 cm), while the third cell demonstrates overall accumulation (0.1–1.8 cm). As wind speed increases, accumulated sand heights gradually increase, with the third checkerboard cell generally maintaining the most stable surface across all velocities due to progressive energy dissipation.

Under protection from fiber net or brush straw checkerboard barriers, sand-checkerboard barriers show no erosion-deposition changes at 10 $\mathrm{m \cdot s^{-1}}$. Figure 7 presents erosion-deposition patterns for the fiber net + sand-checkerboard combination. At 14 $\mathrm{m \cdot s^{-1}}$, accumulation concentrates in the first fiber net cell (maximum height 1.6 cm) and at the front of the second fiber net cell (0.0-0.5 cm). Within the sand-checkerboards, accumulation occurs at the sides of the first two cells (0.0-0.8 cm), while the third cell shows erosion at the center (-0.1 to 0.0 cm). At 18 $\mathrm{m \cdot s^{-1}}$, accumulation remains concentrated in the first fiber net cell (maximum 2.0 cm), with the first sand-checkerboard showing more stable surface conditions compared to the more variable third cell.

Figure 8 shows erosion-deposition effects of brush straw checkerboard + sand-checkerboard combinations. Accumulation primarily occurs in the first brush straw cell, reaching maximum heights of 1.9 cm at 14 $\mathrm{m \cdot s^{-1}}$ and 2.8 cm at 18 $\mathrm{m \cdot s^{-1}}$. The second brush straw cell shows minimal accumulation (0.5-0.8 cm). The first sand-checkerboard maintains a relatively stable surface, while the second and third checkerboards exhibit central erosion with maximum depths of -0.2 cm and -0.3 cm, respectively. This indicates that brush straw checkerboard barriers provide superior surface protection compared to fiber net barriers.

Table 3 quantifies sand-checkerboard height changes under different conditions. Without protection, barrier heights decrease from 18-19 cm to 10-12 cm after 1 minute of erosion at 18 $\mathrm{m \cdot s^{-1}}$. With fiber net protection, heights decrease from 15-18 cm to 12-15 cm after 5 minutes at the same wind speed. With brush straw protection, heights decrease from 15-17 cm to 11-15 cm. The data demonstrate that brush straw checkerboard barriers offer better protective performance, reducing height loss to 2-5 cm compared to 3-5 cm with fiber net protection.

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3. Discussion

Sand-checkerboard barriers represent a double-edged sword in sand fixation: while they effectively intercept wind-sand flows, their sand-based construction makes them vulnerable to aeolian erosion and potentially transforms them into secondary sand sources. Therefore, strategic application of these barriers requires complementary protective measures. This study employed fiber net and brush straw checkerboard barriers—both demonstrating excellent windbreak and sand-fixing performance—to assist sand-checkerboard barriers by attenuating wind-sand flow kinetic energy, thereby enhancing service life and sand-fixing effectiveness.

3.1 Differences in Sediment Flux Density

Sand-checkerboard barriers significantly reduce sediment flux density in the 0–10 cm layer, demonstrating pronounced blocking and stabilization effects near the surface—similar to traditional straw checkerboard barriers [19]. However, unlike permeable straw barriers, sand-checkerboard barriers lack porosity, forcing near-surface airflow to compress and jet upward over the barriers [22], resulting in slightly increased sediment transport rates above 10 cm. Installing fiber net or brush straw checkerboard barriers in front of sand-checkerboard barriers attenuates wind-sand kinetic energy, causing sand particles to deposit in front barrier cells [25] and reducing destructive effects on the sand-checkerboards, which further decreases overall sediment flux density.

Previous research indicates that sediment flux density above sand surfaces follows an exponential decay model when barrier height is below approximately 10 cm ($R^2 > 0.94$), transitioning to a Gaussian distribution above this threshold [20]. In this study, both no-barrier and sand-checkerboard barrier conditions follow exponential decay models ($R^2 > 0.98$), enabling clear characterization of barrier effects on wind-sand flow structure. Front-mounted flexible layers (fiber net or brush straw) primarily reduce wind-sand kinetic energy through elastic deformation and small-scale turbulence generation, while rear-positioned sand-checkerboard barriers dissipate remaining energy through large-scale turbulence created by their rigid structure. Among all configurations, the brush straw + sand-checkerboard combination achieves the optimal reduction effect.

Wind tunnel simulations by Qu et al. [8] revealed reverse airflow and vortex formation within brush straw checkerboard barriers, whereas Deng et al. [24] observed no reverse airflow in fiber net barriers, with wind speeds exceeding $0\ \mathrm{m \cdot s^{-1}}$ throughout the flow field. The complex three-dimensional brush structure of straw barriers, combining flexible deformation with rope-based consolidation, more readily generates turbulence that reduces wind-sand kinetic energy [8], resulting in superior sand-blocking performance compared to fiber net barriers.

3.2 Erosion-Deposition Patterns Under Combined Barrier Systems

As wind velocity increases, sand-checkerboard barrier tops become progressively damaged, with heights decreasing substantially as sand particles fall into barrier cells. Interference from the checkerboards weakens wind-sand flow kinetic energy and carrying capacity, causing sand deposition within cells. Vortex formation within cells further shifts sand particles, ultimately creating stable concave surfaces similar to straw checkerboard barriers [19]. With increasing wind speed, erosion-deposition phenomena become more pronounced and accumulation heights increase—consistent with previous findings [21]. At lower wind speeds ($10\ \mathrm{m \cdot s^{-1}}$), sand particles are primarily intercepted at cell fronts, while higher velocities enable accumulation zones to expand rearward. Progressive energy dissipation across three sand-checkerboard barriers achieves stepwise sand particle settlement, with the third cell maintaining relatively stable surface conditions across all wind speeds—similar to magnesium cement board barriers [31].

Under protection from fiber net or brush straw barriers, wind-sand destructive capacity is attenuated, preventing erosion-deposition changes in sand-checkerboard barriers at 10 $\mathrm{m \cdot s^{-1}}$. At higher wind speeds, accumulation zones shift rearward in fiber net systems, distributing across two cells, whereas brush straw systems maintain accumulation primarily in the first cell —demonstrating superior adaptability and stable windproof performance under high-velocity conditions [8]. The three-dimensional brush structure of straw barriers induces small-scale turbulence that more effectively weakens wind-sand kinetic energy, reducing destructive effects and yielding maximum erosion depths of only -0.2 cm in protected sand-checkerboards compared to -0.3 cm with fiber net protection.

Without protection, sand-checkerboard barrier height decreases with increasing wind speed, with damage severity escalating accordingly. At 10 $\mathrm{m \cdot s^{-1}}$, fiber net and brush straw barriers effectively protect sand-checkerboards from height reduction. At 18 $\mathrm{m \cdot s^{-1}}$, fiber net-protected barriers lose 5-9 cm in height, while brush straw-protected barriers lose only 3–5 cm, confirming superior protective performance of brush straw barriers.

In practical applications, sand-checkerboard barriers require only labor costs, eliminating material and transportation expenses associated with other barrier types. Workers use shovels to locally stack sand into longitudinal and transverse ridges, forming checkerboard patterns at approximately 2 yuan/$\mathrm{m^2}$. Brush straw checkerboard barriers have achieved mechanized production, integrating bulk wheat or rice straw with universal straw rope through proprietary equipment to create multi-segment brush straw ropes [8]. During installation, these ropes are simply transported to treatment areas and cross-fixed into checkerboard networks without burial requirements [8], totaling approximately 2 yuan/$\mathrm{m^2}$ for materials, transport, and labor—25.7% lower than fiber net barriers. Comprehensive cost analysis indicates brush straw checkerboard barriers offer superior practical applicability.

This study examined sand-checkerboard barriers with a height-to-length ratio of 0.1-0.2. Future research should investigate different aspect ratios to compare sand-fixing benefits, utilizing numerical simulations to calculate windproof effectiveness and combining field observations to identify optimal barrier configurations for nested-square systems.

4. Conclusions

1) Sand-checkerboard barriers demonstrate significant effectiveness in intercepting wind-sand flows, particularly in blocking and stabilizing sand particles near the surface. However, their sand-based, non-permeable construction makes them vulnerable to wind erosion and potential secondary

sand sources, necessitating complementary protective measures for rational application.

2) Front-mounted fiber net or brush straw checkerboard barriers effectively attenuate wind-sand kinetic energy and reduce sediment transport rates. The complex three-dimensional brush structure of straw barriers, combining flexible deformation with rope-based consolidation, generates small-scale turbulence that further reduces kinetic energy, yielding superior performance compared to fiber net barriers.

3) Combined application of sand-checkerboard barriers with front-mounted flexible barriers significantly enhances sand-fixing effectiveness and extends service life. The synergistic interaction between barrier types improves overall sediment retention capacity.

4) With increasing wind speed, erosion-deposition phenomena within sand-checkerboard barriers become increasingly pronounced. At 14–18 $\mathrm{m \cdot s^{-1}}$, accumulation concentrates at cell fronts and sides while central zones experience erosion. The stepwise energy dissipation across multiple cells achieves graded sand particle settlement, with the third cell maintaining relatively stable surface conditions.

5) Fiber net and brush straw checkerboard barriers effectively weaken wind-sand destructive capacity. Brush straw barriers provide superior protection, as evidenced by reduced height loss in protected sand-checkerboards (2–5 cm vs. 3–5 cm) and shallower erosion depths within cells.

6) Brush straw checkerboard barriers are recommended for practical applications due to their mechanized production, lower comprehensive costs (25.7% less than fiber net barriers), and superior protective performance. This study provides a scientifically grounded framework for optimizing barrier design and supports local-material utilization strategies in desertification control.

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