Postprint of Observational Study on Erosion-Deposition Surface Morphology and Its Spatial Patterns Within Two Types of Sand Barriers

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Abstract

Taking the fibermesh sand barrier (FSB) and geotechnical woven bag sand barrier (GSB) deployed on mobile dunes at the western margin of the Tengger Desert as the research objects, three-dimensional laser scanning technology combined with traditional measurement methods was employed to measure and calculate the micro-geomorphological features within the sand barriers. The results indicate that: (1) The erosion depth, erosion volume, and erosion surface area in both sand barrier zones exhibit a gradual increasing trend along the prevailing wind direction. On the windward side of the dune centerline, the erosion depth, erosion volume, and erosion surface area of GSB are all greater than those of FSB, with the erosion depth being 20%~40% greater and the erosion volume being 45%~70% higher than the latter. (2) Both sand barriers show severe damage in the south-central portion of the dunes, which is 30%~50% higher than in other locations. Due to the substantial wind-scouring damage to the geotechnical woven bags, both the damage range and damage degree of GSB exceed those of FSB. (3) Within the sand barrier grids, the maximum erosion depth is mostly not located at the grid center; the north-northeast-east-southeast azimuthal zone constitutes an erosion area (i.e., weak accumulation zone), while the center and west are strong accumulation zones. (4) The erosion depth in the GSB zone is greater than that in the FSB zone, while the damage rate of the latter is significantly lower than that of the former; therefore, the sand-blocking effectiveness of fibermesh barriers is superior to that of geotechnical woven bag barriers. Utilizing three-dimensional laser scanning technology for micro-geomorphological inversion can not only accurately measure erosion depth but also enable the calculation of erosion volume and erosion surface area through software operations, thereby providing a novel tool and methodology for precise microtopographic research in the fields of aeolian geomorphology and sand control.

Full Text

Preamble

Taking fibermesh sand barriers and geotechnical woven bag sand barriers deployed on mobile dunes at the western edge of the Tengger Desert as research objects, three-dimensional laser scanning technology combined with traditional measurement methods were used to calculate the microtopographic morphology within the sand barriers. Results show: (1) The erosion depth, erosion amount, and erosion surface area in both types of sand barrier areas showed a gradually increasing trend along the main wind direction. On the windward side of the dune midline, these values were larger for geotechnical woven bag sand barriers than for fibermesh sand barriers, with erosion depth being 20%-40% deeper and erosion amount 45%-70% higher. (2) Both sand barrier types showed severe damage in the central-southern parts of the dunes, 30%-50% higher than in other areas. Due to greater wind erosion damage to geotechnical woven bags, the damage scope and degree were higher than for fibermesh sand barriers. (3) The maximum erosion depth within sand barrier grids was mostly not located at the grid center; the N-NE-E-SE azimuth zone was an erosion/weak deposition area, while the center and west were strong deposition areas. (4) The erosion depth in geotechnical bag sand barrier areas was greater than in fibermesh sand barrier areas, while the latter' s damage rate was much lower than the former' s, indicating fibermesh sand barriers have better sand-blocking effects.

Using three-dimensional laser scanning technology for microtopographic inversion can not only accurately measure erosion depth but also calculate erosion volume and surface area through software operations, providing new tools and methods for precise microtopographic research in the fields of aeolian geomorphology and sand control.

Keywords: sand barrier; three-dimensional laser scanning technology; erosion and deposition status; microtopography morphology; sand-blocking effect

Desertification is one of the most severe environmental problems currently facing humanity. It is land degradation occurring in arid, semi-arid, and dry sub-humid regions resulting from the interaction of natural variation and human activities. China has 1.72×10^{6} km^2 of desertified land, accounting for 17.93% of its territory, making it one of the countries most severely affected by desertification worldwide. Although desertification has been curbed and reversed overall, the situation remains grave. Wind erosion desertification is a key focus and challenge in desertification control, where sand prevention and control projects are crucial for curbing desertification processes. Mechanical sand barriers are relatively low-cost, highly adaptable, and widely studied, representing one of the most important sand control measures. In northern China' s arid desert regions, numerous sand barriers have been installed for sand prevention and control, with many scholars conducting in-depth research on different sand barrier types. Clarifying the sand control mechanisms is essential for maximizing their effectiveness.

Monitoring of aeolian landforms began in the late 17th century. Since the 1990s, three-dimensional models based on coordinate systems have emerged. Digital elevation models (DEM) provide new methods for extracting dune geomorphological features and numerical simulation. Three-dimensional laser scanning technology, also known as "reality capture technology," is primarily used for high-precision reverse engineering of 3D modeling and reconstruction. It originated in the 1960s as an emerging digital information technology. With its improvement and development, it has gradually expanded from architectural restoration to geoscience applications since the early 21st century, achieving remarkable progress in aeolian geomorphology and sand control research. However, research on three-dimensional laser scanning technology in these fields is still in its infancy, with further investigation needed on scanners and data processing. Unified standards for application protocols and usage patterns are still lacking, necessitating additional research on the technology' s authenticity, reliability, accuracy, and applicability.

To address this, we selected fibermesh sand barriers and geotechnical woven bag sand barriers at the western edge of the Tengger Desert, used laser scanning to obtain point cloud data of internal microtopography, and conducted erosion-deposition morphology analysis to provide a scientific basis for studying sand barriers' sand-fixing and sand-blocking capabilities.

1. Study Area Overview

The study area is located in the Shiguang Corridor scenic spot in Minqin County, Gansu Province, 23.5–29.5 km east of the corridor' s western end. The site is on the windward slope of a dune on the north side, administratively belonging to Nanhu Town, Minqin County, Wuwei City, Gansu Province (103°12 49.51 E, 38°27 56.24 N). The area lies at the junction of the western Tengger Desert and the Minqin Oasis, dominated by mobile and semi-fixed dunes, with fixed and semi-fixed dunes in artificially intervened areas. It belongs to an arid desert region with a temperate continental desert climate—cold winters, hot summers, scarce precipitation, abundant sunlight, and large diurnal temperature variations. The multi-year average temperature is 9.38°C, with annual precipitation of 113.2 mm and potential evaporation of 2,623 mm (23 times the precipitation). Annual sunshine hours total 3,073.5 h, with an average annual wind speed of 2.6 $m \cdot s^{-1}$ and extreme maximum wind speed of 28.5 $m \cdot s^{-1}$ (occurring in 1973). The prevailing wind direction is west-northwest, accounting for 10.71% of sixteen-direction winds; average annual gale days number 25.0, sandstorm days 37.5, blowing sand days 29.7, and floating dust days 28.2. The zonal soil is gray-brown desert soil, with intrazonal soil being aeolian sandy soil. Vegetation consists mainly of xerophytic and super-xerophytic small trees, shrubs, and semi-shrubs.

The dune' s east wing is 113 m long, the west wing 104 m. The windward slope gradient is 15°–25°, the leeward slope 30°–35°. The dune' s west wing was truncated on the south side during desert highway construction, destroying the dune morphology. The windward face has multiple sand barrier types, installed by May 2020. Based on feasibility and rationality, fibermesh sand barriers (FSB) and geotechnical woven bag sand barriers (GSB) on both sides of the dune' s windward slope midline were selected as research objects (Table 1).

2.1 Data Collection

In each sand barrier area, a large grid of 1.5 m × 1.5 m (FSB) or 2 m × 2 m (GSB) was established, totaling 9 zones from north to south and east to west (Figure 1). The FSB area was labeled A1–A9 from north to south and east to west, while the GSB area was labeled B1–B9. The study area' s wind erosion and deposition status was investigated. In each sand barrier zone, three test grids were randomly selected as replicates. Every grid recorded wind erosion/deposition data at 10 cm intervals along the north-south and east-west central lines, noting erosion-deposition degree and barrier height while investigating damage scope and degree.

Surface morphology data were obtained using a RIEGL VZ-2000i 3D laser scanner. First, scanning stations were selected and tripods erected. The scanner and accessories were placed, project names changed, and scanner parameters set (Table 2) before scanning began. After completing one station, equipment was directly dismantled and moved to the next station. The scanner automatically recognized new stations after setup. Starting near the middle of the test area' s east side, stations were set along the sand barrier edge in a clockwise direction. After circling, three additional stations were added from west to east in the test area center. Excluding abandoned and terminal stations, 12 stations were used. The scanning method was adjusted by establishing north-south scanning routes, improving efficiency. However, since the route direction was identical, forming a closed loop in later stitching was difficult. To ensure stitching overlap and accuracy, all stations on one route were reversed.

2.2.2 Point Cloud Data Processing

Scanning data were copied from the scanner. Basic point cloud data processing involved: importing data, checking station information, using Registration Selection Mode for automatic stitching, then Multi Station Adjustment for fine manual stitching. Coordinate system conversion used CGCS2000 Geodetic coordinates imported into RiSCAN PRO software. After displaying point clouds, Polydata tools removed noise and thinned data. The Terrain Filter created digital elevation models (DEM) through triangulation, exported to Geomagic Wrap. Using Mesh Doctor, the model was optimized by smoothing and removing spikes, then reimported into RiSCAN PRO. DEM data were displayed in Change View Type with +60°/-40° height angles. The Min/Max tool obtained erosion-deposition depth data. In Planes files, new planes were created and adjusted to completely cover the model. Flipping the plane face downward allowed direct volume and surface area calculation using Measure Volume &

Surface Area.

3.1 Surface Erosion-Deposition Morphology Characteristics Within Fibermesh Sand Barriers (FSB)

Based on manually measured and fitted surface data (Figure 2), all grids showed a morphology of high peripheries and low centers. The lowest value positions varied by location: A1 appeared in the west-central area (25 cm), A2 in the central-south (10 cm), A3 near the center (27 cm), A4 in the east-central area (46 cm), and A5 basically at the center (10 cm). From the grid erosion depth, erosion intensity was generally strongest in the north, moderate in the south, and weakest in the center. The central A5 area showed the most obvious accumulation, with a minimum value of -4.949 cm. Considering the west side is near the midline leeward side, erosion weakened and accumulation occurred. The north, near the main wind direction area, showed deepening erosion in flat terrain. In the south, erosion gradually deepened with surface uplift, 偏向南和东侵蚀，在北和西堆积。但从图中看出，沿主风向没有明显的变化趋势。

Point cloud data-based erosion-deposition distribution maps (Figure 3) showed the lowest erosion points in A1 and A2 were in the north and northeast. The strongest erosion areas in the dune's central and eastern regions were on the sand barrier' s east side. Erosion depth was relatively small (10–20 cm) in the north and central barrier areas, but relatively large (20–30 cm) in the southern area. Table 3 shows erosion depth was positively correlated with erosion volume and surface area, so the latter two showed similar trends. Overall, southern erosion was strongest while central accumulation was most obvious. The maximum erosion depth mostly appeared in the north-central and east-central areas, while the central-west showed the most obvious accumulation.

Erosion depth showed a gradually increasing trend from north to south. From west to east within the same dune elevation range, erosion depth decreased somewhat, indicating the sand barrier's wind-sand blocking function. Compared with manual measurements, point cloud data showed greater erosion depth and slightly different erosion locations, but generally showed strongest erosion depth in the north-central and eastern areas, with most obvious accumulation in the central-west.

3.2 Surface Erosion-Deposition Morphology Characteristics Within Geotechnical Woven Bag Sand Barriers (GSB)

During manual measurement, the entire GSB area showed a central erosion and peripheral high morphology. According to Figure 4, the lowest value appeared in the northeast-central part of B3 at -12.022 cm. Weaker erosion was in B1 at -5.528 cm. Overall, the lowest erosion values mostly appeared in the central-north and central-east, but B4 appeared at the grid center, B5 in the central-south, and others mostly in the east or north at 20–25 cm. Considering local winds are mainly northwest and southeast, B3 is on the dune' s east side where southeast winds intensify after dune uplift, exacerbating erosion, so eastern areas near the midline had high erosion depths.

Point cloud data-based erosion maps (Figure 5) showed B4 had a small central uplift, possibly from vegetation blocking dust. Other locations showed lowest values in northern grid areas, consistent with manual measurements. Erosion depth was similar to FSB: smaller in the north (20–25 cm) and larger in the south (30–35 cm). Erosion volume and surface area also gradually increased from north to south. The scanning accuracy of 5 mm made errors negligible compared to manual measurements. The scanner uses pulse signals, unaffected by light, realistically restoring surface conditions and greatly reducing human-induced errors. Therefore, for discrepancies, we consider point cloud data more reliable and closer to reality.

4. Discussion

This study used both manual measurement and point cloud data to characterize surface erosion-deposition morphology changes within sand barriers. The two datasets were generally consistent but had errors. Reasons include: (1) Manual measurement errors from tape stability, visual accuracy, reading precision, and optimal route selection reduced data reliability. (2) Fitting errors—since manual measurement is time-consuming, only north-south and east-west routes were measured in each grid. The lack of data was evident in subsequent surface fitting, where peripheral morphology differed from reality. Point cloud data uses new 3D laser scanning technology for precise topographic inversion with high accuracy (5 mm scanning precision), realistically restoring surface states and greatly reducing human error. Therefore, we consider point cloud data more reliable.

Fibermesh sand barriers are permeable structures that reduce wind speed and erosion by altering underlying surface properties and increasing surface roughness, thereby achieving sand fixation. They also create lag effects in soil moisture redistribution, improving habitats and fixing mobile sand. These barriers are simple to install and long-lasting but prone to wind erosion and sand burial. Geotechnical woven bag sand barriers are non-permeable bag-shaped barriers that alter near-surface wind flow fields, reducing wind speed and changing erosion patterns. Their centers easily form stable concave surfaces, creating non-accumulating transport conditions with significant windproof and sand-fixing effects at only 43.7%–53.7% the cost of clay or straw barriers. However, their bag characteristics make them prone to deformation and twisting, increasing maintenance costs.

Both sand barrier types showed severe damage in central-southern areas, 30%–50% higher than other locations. Geotechnical bags experienced wind erosion damage, with damage scope and degree much greater than fibermesh barriers. The maximum erosion depth in grids was mostly not at the center. The N–NE–E–SE azimuth was an erosion/weak deposition zone, while the center and west were strong deposition zones.

Three-dimensional laser scanning for microtopographic inversion can accurately measure erosion depth and calculate erosion volume and surface area, providing important application value for precise microtopographic research in aeolian geomorphology and sand control. However, point cloud data processing has limitations: (1) When calculating erosion volume and surface area, a standard plane must be established. Since grid ranges are small in this experiment, the standard plane must include the sand barrier to reduce error, so these indicators include both sand and barrier volumes/surface areas. As plane positions were consistent, this error was ignored. (2) Errors exist in calculating sand surface height differences because point cloud software cannot distinguish ground objects, requiring visual interpretation that introduces errors. Incomplete removal of dust particles in the air also affects data accuracy. Currently, 3D laser scanning is rarely used in aeolian geomorphology and sand control research, offering new scientific methods that require reasonable integration with traditional approaches. Higher precision and efficiency require deeper research and discussion.

In this study, maximum erosion depth in grids was not at the center but in north or east 偏区. Zhang Dengshan et al. studied straw checkerboard sand barriers, finding lowest erosion depth deviated from grid centers, consistent with our results. They also found the SW–W–NW–N azimuth was a strong deposition zone with the center and south being weak deposition (erosion) zones. Our results show the N–NE–E–SE azimuth as an erosion/weak deposition zone with the center and west as strong deposition zones, differing from other researchers. These differences may stem from inconsistent dune slopes/orientations, main wind directions, sand barrier specifications, and manual intervention levels, causing different wind effects from landform changes and ultimately different lowest erosion depth positions. This erosion-accumulation pattern requires further exploration.

5. Conclusions

(1) On both sides of the midline, erosion depth, erosion amount, and erosion surface area in both sand barrier types showed gradually increasing trends along the main wind direction. The geotechnical bag sand barrier's erosion depth, amount, and surface area were larger than the fibermesh barrier' s, with erosion depth 20%–40% deeper and erosion amount 45%–70% higher.

(2) Both sand barrier types showed severe damage in central-southern dune areas, 30%–50% higher than other locations. Due to wind erosion damage to geotechnical bags, their damage scope and degree were much greater than fibermesh barriers.

(3) Maximum erosion depth in sand barrier grids was mostly not at the center. The N–NE–E–SE azimuth was an erosion/weak deposition zone, while the center and west were strong deposition zones.

(4) Geotechnical bag sand barrier areas had greater erosion depth than fibermesh areas, while the latter' s damage rate was much lower. Therefore, fibermesh sand barriers have better sand-blocking effects.

(5) Three-dimensional laser scanning technology for microtopographic inversion can accurately measure erosion depth and calculate erosion volume and surface area, providing important application value for precise microtopographic research in aeolian geomorphology and sand control.

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