

Unmanned aerial vehicle-assisted evaluation of the effectiveness of sand control engineering along a Gobi desert highway in Ejin Banner, northern China (Preprint)

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Abstract

Sand control engineering plays a pivotal role in ensuring the safe operation of transportation corridors that traverse desertified areas. Evaluating the effectiveness of these interventions provides a crucial scientific basis for mitigating aeolian hazards and guiding the sustainable management of fragile and arid ecosystems. In this study, we investigated a representative section of Highway S315, which is prone to windblown sand hazards, in Ejin Banner, northern China. By integrating segmented measurements with unmanned aerial vehicle (UAV)-based oblique photogrammetry, we quantitatively characterized the spatial and temporal evolution of sand accumulation around multiple sand control structures and assessed their blocking efficiency. Complementary road sand-removal records and meteorological observations were analyzed to evaluate the long-term performance of engineering measures. Our results showed that sand accumulation behind high vertical sand barriers typically exhibited a triangular cross-sectional morphology, with a gently inclined stoss slope and a steep lee slope. The shape and volume of these deposits evolved dynamically in response to variations in the prevailing wind regime, reflecting strong feedback between barrier geometry and local airflow redistribution. In contrast, the low-profile checkerboard sand barriers displayed a three-stage morphological trajectory—initial accumulation, edge intensification, and functional decline—indicating a progressive loss of sand-trapping capacity as burial proceeded. Sand accumulation was markedly greater on the highway's western (upwind) side than on the eastern (downwind) side, with 70.0%–90.0% of the airborne sediment flux intercepted by the upwind structures. From 2015 to 2020, mean annual wind speeds remained stable (2.68 ± 0.04 m/s), while precipitation varied from 22.6 to 103.7 mm. However, the annual sand removal volume from the road decreased

consistently, confirming the enhanced mitigation effect of multi-level protective system. These findings highlight the coupled interactions between engineering design, wind-sand dynamics, and topographic context. Beyond their immediate protective role, well-designed sand control systems also contribute to the prevention of regional desertification by stabilizing mobile dunes and fostering conditions favorable for ecological restoration. The insights gained here provide both theoretical and practical support for optimizing sand control engineering and advancing sustainable hazard mitigation in arid and semi-arid areas.

Full Text

Preamble

J Arid Land (2026) 18(3): 372–386 Unmanned aerial vehicle-assisted evaluation of the effectiveness of sand control engineering along a Gobi desert highway in Ejin Banner, northern China MA Xixi , XIAO Jianhua , YAO Zhengyi , HONG Xuefeng , XUE Xian 1 Department of Geography, Fuyang Normal University, Fuyang 236037, China; State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; Transportation Development Center of Alxa League, Banyanhot 750306, China; 4 Drylands Salinization Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Minqin 733300, China

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These findings highlight the coupled interactions between engineering design, wind-sand dynamics, and topographic context. Beyond their immediate protective role, well-designed sand control systems also contribute to the prevention of regional desertification by stabilizing mobile dunes and fostering conditions favorable for ecological restoration. The insights gained here provide both theoretical and practical support for optimizing sand control engineering and advancing sustainable hazard mitigation in arid and semi-arid areas.

Keywords

sand control engineering; unmanned aerial vehicles (UAV); sand accumulation morphology; sand-blocking © 2026 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, and Science Press. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

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1 Introduction

To support resource development and regional integration in western China, Chinese government has constructed several major transportation arteries, such as Baotou-Lanzhou Railway, Kuqa-Golmud Railway, Tarim Oilfield Highway, etc., across sandy deserts, Gobi (gravel) deserts, and areas with intense aeolian activity. Engineering challenges of infrastructure development in aeolian landscapes of these arteries is inevitable (Bruno et al., 2018). Especially, in vast areas dominated by mobile sand, Gobi deserts, and degraded land, windblown sediment poses persistent threats to transportation infrastructure and the safety of travelers on local transportation arteries.

Therefore, there is an urgent need to establish scientifically grounded and context-specific sand control systems to ensure the long-term functionality of these vital transport corridors.

The design and deployment of sand mitigation systems must consider local environmental factors, including climate, geomorphological settings, sediment grain-size distribution, and regional wind regimes (Xie et al., 2020; Zhang et al., 2023).

In desert areas with relatively abundant water resources, combined biological-engineering approaches, such as checkerboard straw barriers integrated with tree and shrub shelterbelts, have been widely implemented, as exemplified by sections of the Baotou-Lanzhou Railway and the Tarim Oilfield Highway (Zhang et al., 2011). In contrast, in hyper-arid Gobi deserts where vegetation establishment is nearly impossible, mechanical sand barriers are the primary mitigation measure. These sand barriers include stone grids, concrete sand barriers, and high-density polyethylene mesh panels, which have been widely adopted along infrastructures such as the Dunhuang-Golmud Railway (Xie et al., 2017; Qu et al., 2023; Wang et al., 2024).

These large-scale mechanical structures not only serve as effective defenses against aeolian hazards but also are well-suited to environments where biological measures are infeasible.

Despite the growing diversity of mechanical sand control systems that are available to engineers, their site-specific effectiveness and broader applicability require systematic evaluation to enable more precise and efficient deployment. A wide array of techniques—including field monitoring, remote sensing image analysis, wind tunnel experiments, and computational fluid dynamic simulations—has been applied to assess their performance (Wang et al., 2017; Horvat et al., 2020; Lin et al., 2020; Yao et al., 2025). Among the most critical indicators of protective performance is the sand-trapping capacity of the system, which depends heavily on accurate measurement of sand deposition morphology and volume (Liu et al., 2023). A variety of measurement tools have been employed to obtain 3 Dimensions (D) information on sand accumulation. These tools can generally be categorized into two types: contact-based and non-contact methods. Contact instruments—such as measuring tapes, compasses, clinometers, leveling rods, total survey stations, and real-time kinematic (RTK) global positioning system (GPS)—can be cost-effective and easy to operate; however, they often disturb loose surface sediments, potentially compromising data accuracy (Husemann et al., 2024). They are also logistically challenging to implement when they must be used over large areas. In contrast, non-contact approaches, such as terrestrial photogrammetry and 3D laser scanning, preserve surface integrity while generating high-density point cloud datasets with theoretically high precision and spatial fidelity (Solazzo et al., 2018; Vos et al., 2022). However, their application in complex terrain typically requires the use of multiple stations or overlapping viewpoints, which increases operational complexity and workload, presenting a major technical bottleneck (Koci et al., 2017), although they may be a more practical approach for large-area surveys.

Recent advances in unmanned aerial vehicle (UAV) photogrammetry have made aerial surveys more accessible and efficient, with broad applications in topographic mapping, resource-

monitoring, and ecological assessment (Woodget et al., 2017; Chen et al., 2025). Oblique UAV photogrammetry combines vertical and multi-angle imaging with high overlap among images and high spatial resolution, thereby enabling the

rapid generation of high-precision digital elevation model (DEM), digital surface model (DSM), and orthophotos (Kovanic et al., 2023). This technology has enabled researchers to construct 3D models of landslides, quantify geomorphic changes, and enhance the accuracy of dynamic landscape assessments (Eltner et al., 2016). In agriculture and forestry, multispectral UAV imagery has proven effective for monitoring crop vigor, estimating yields, detecting pests, and classifying vegetation based on synthetic indices, such as the normalized difference vegetation index and measurements of canopy structure (Tang and Shao, 2015; Michez et al., 2016). UAV-based thermal infrared sensors have also been successfully used to monitor water pollution, urban heat island effects, and agricultural water stress (Zhang and Kovacs, 2012). Nevertheless, UAV photogrammetry has not been applied to quantitatively assess the sand control effectiveness of linear infrastructure projects, such as highways and railways, in desert and Gobi environments, despite their high vulnerability to aeolian processes.

In the present study, we tested the use of this technology by investigating a sand control system along Highway S315 in Ejin Banner, Inner Mongolia Autonomous Region, a representative Gobi transportation corridor in Northwest China, which is vulnerable to windblown sand. We employed UAV-based oblique photogrammetry to acquire high-resolution surface data and generate a 3D digital model of sand control system. We extracted key geometric parameters to characterize the morphology of sand accumulation around mechanical barriers and used these results to assess patterns and processes of sediment deposition, as well as their spatial and temporal evolution.

Additionally, we integrated road maintenance records with regional meteorological data to evaluate the functional effectiveness of sand mitigation infrastructure and its ability to remain effective over time. This approach not only advances the methodology for evaluating protective systems in desert environments but also contributes to the optimization of sand control strategies for future infrastructure planning in arid areas. 2 Materials and methods

2.1 Study area

Highway S315 is a first-grade highway in Ejin Banner ($41^{\circ}57'-42^{\circ}35'N$, $100^{\circ}57'-101^{\circ}13'E$), Inner Mongolia Autonomous Region, China, which traverses a high-risk aeolian hazard zone known as Heifengkou—literally, the Black Wind Gap—a transportation corridor that is frequently affected by strong winds and sandstorms (Fig. 1a [Figure 1: see original paper]). Geomorphologically, Heifengkou lies at the junction of two major alluvial systems: the Ejin River alluvial fan, which slopes northward (at an average gradient of 0.06°), and the Altay Mountains-derived alluvial fan, which slopes southward (at an average gradient 0.65°) (Fig. 1b). Their convergence forms a localized lowland with elevations that range from approximately 910 to 920 m. In the east-west cross-section, the highway occupies a watershed zone between the dried West Juyanhai Lake and the currently water-filled East Juyanhai Lake (Fig. 1c).

2.2 Climate and aeolian environment

Ejin Banner has a temperate continental desert climate characterized by low precipitation, high evaporation, significant diurnal temperature variations, and frequent aeolian activity. The annual mean temperature is 9.7°C, with monthly mean temperatures ranging from -11.2°C in January to 27.1°C in August (Yao et al., 2025). The mean annual precipitation is 37.9 mm, and 75.0% of precipitation falls from June to August, while the annual potential evaporation exceeds 3700.0 mm, which is approximately 100 times the precipitation (Zhang et al., 2019). The area experiences an average of 44 d per year with winds exceeding 17.20 m/s (Niu et al., 2021). Land cover is diverse, including Gobi desert (5.9%), residual hills (47.2%), desert (15.2%), and oasis zones (27.6%) (Niu et al., 2021).

Location and topography of Highway S315 (a) and the south-north (b) and west-east (c) topographic profiles across the aeolian hazard segments. The north-south and west-east topographic transects are defined by points P1 and P2 and points P3 and P4, respectively.

The Heifengkou section of Highway S315 represents a classic wind corridor, characterized by strong winds, abundant sand sources, and a severe potential hazard. The threshold wind velocity for sand transport is a crucial metric for evaluating aeolian activity (Zhang et al., 2023). A wind speed of 5.00 m/s is widely accepted as the threshold for sand entrainment over mobile sandy surfaces in arid areas (Zhang et al., 2023). Accordingly, winds ≥ 5.00 m/s were defined as sand-driving winds, and their directional frequencies were analyzed across 16 sectors to characterize the wind regime and potential sand transport. Meteorological data from HOBO automatic weather stations (Onset Computer Corporation, Bourne, USA) show that in spring, autumn, and winter, westerly winds dominate sand-moving events, accounting for 63.6%, 68.6%, and 41.3% of occurrences, respectively (Fig. 2a [Figure 2: see original paper]-d), compared with 30.6% in summer. Directional variability increases in summer, with dominant directions shifting to west-north-west, east, and east-north-east, which together account for 41.4% of sand-driving winds (Fig. 2b). Seasonally, 24.0% of recorded wind speeds exceeded the sand-entrainment threshold, and the predominant annual wind directions were from the west, west-north-west, and north-west directions (Fig. 2e).

Regional aeolian transport intensity was assessed using drift potential, a standard metric that reflects the sand-carrying capacity of a given wind direction over time, expressed in vector units (VU) (Zhang et al., 2023). The annual drift potential for the study area totaled 344.91 VU, categorizing it as a "medium wind energy" environment according to Fryberger's classification (Zhang et al., 2023). The resultant drift potential is 152.28 VU, with a dominant transport direction of 129.88°, oriented toward the southeast (Fig. 2f).

2.3 Causes of aeolian hazards

The severity of aeolian hazards along the Heifengkou section of Highway S315 is primarily driven by topographic wind acceleration, abundant sediment sources, hyper-arid climate, and engineering-induced disturbance. The Heifengkou section is in a low-lying corridor between West Juyanhai Lake and East Juyanhai Lake (Fig. 1). This bottleneck induces a Venturi effect that amplifies local wind speeds (Yu, 2018). The western flank of the highway borders the dry bed of West Juyanhai Lake and active dune fields that provide a source of fine mobile sand (Ma, 2021).

Aeolian transport is dominated by westerly winds (Fig. 2f). The area experiences minimal precipitation and extreme evaporation. The Heihe River, the only water source, is heavily exploited in the upstream, resulting in reduced discharge to the lower reaches and terminal basins

Wind regimes across the aeolian hazard segments of Highway S315. (a-d), seasonal frequency of sand-driving winds; (e), annual sand-driving wind frequency; (f), annual drift potential. N, north; S, south; E, east; W, west. (Juyanhai Lake). Although water is occasionally diverted to East Juyanhai Lake for ecological restoration, groundwater levels remain critically low, exacerbating vegetation degradation and leading to reactivation of ancient dune fields (Zhang et al., 2019). Unlike conventional highways, first-grade roads include structural features such as protective guardrails, medians, anti-collision barriers, and elevated embankments, which increase surface roughness and wind turbulence.

These design elements can trap blowing sand, leading to clogged culverts and burial of the road

surface (Yu et al., 2019; Yao et al., 2025).

2.4 Sand control engineering design

Based on a comprehensive analysis of aeolian dynamics and hazard causes along Highway S315, people designed and deployed a dual-component sand control system (Fig. 3 [Figure 3: see original paper]). This system comprises high vertical sand barriers (i.e., fences) and low-profile checkerboard sand barriers (Fig. 3a and b). High vertical sand barriers (1.20-1.50 m tall) are installed along the outermost periphery of the protected corridor and serve as the first line of defense, functioning primarily to reduce wind velocity and intercept incoming sand. The low-profile checkerboard sand barriers (20-30 cm tall) are positioned closer to the highway and are entirely embedded within the near-surface flow layer. These structures primarily function to trap residual sand that passes Sand control engineering along Highway S315. (a), view of the sequence of protective measures. Points labeled " West' ' and " East' ' represent the sampling locations; (b), spatial distribution of survey points along the highway corridor, where "K" denotes kilometers from northern terminus and "+" indicates additional meters; (c-h), photographs of the evolution of sand accumulation for

the two main protective structures.

through the vertical barriers and to stabilize surface sediments, thereby preventing entrainment of sand that has been deposited inside the corridor. Figure 3c-h illustrates the stages of the evolution of these measures.

According to road maintenance patrol records, we found that aeolian hazards are most concentrated between positions between K9+000 and K30+600 (Fig. 3b). Within this 21.60 km stretch, approximately 6.00 km stretch is categorized as severely affected and 9.10 km stretch is categorized as moderately affected. These stretches were subdivided into 3 and 7 engineering segments, respectively, for targeted intervention and quantitative assessment of sand retention capacity. The remaining 6.50 km of the road is classified as only slightly affected.

The implementation of protective measures followed a phased strategy (Table 1). Phase I of the project was launched in September 2016, prioritizing highway segments most severely impacted by windblown sand hazards. Phase II was commenced in October 2017, extending the mitigation measures to areas subject to moderate aeolian activity. In response to sand saturation of protective structures and reduced efficiency in specific segments along western edge of the highway, the high vertical sand barriers were increased in height by 1.50 m in October 2019 to restore the interception capacity of the structures and prolong their protective lifespan.

Timing of construction	of sand control engineering structures	Project phase	Sand hazard severity	Implementation date	Treated length (km)	Sand control measure
Phase I	Severe	September 2016	High vertical sand barriers+ sand-fixing checkerboard grids			
Phase II	Moderately severe	October 2017	High vertical sand barriers+ sand-fixing checkerboard grids			
Phase III	Severe	October 2019	Heightened high vertical sand barriers on western side			

2.5 Profiling of sand accumulation

To characterize the morphology of sand accumulation associated with the elevated sand barriers, we conducted detailed field measurements along the severely affected section of the road from K23+000 to K26+500 (Fig. 3). Using the highway as a spatial reference, we established eight measurement points between K24+000 and K24+500, symmetrically distributed on both eastern and western sides of the road (points labeled "East" and "West", respectively, in Fig. 3a). On western side, points West 1-1 and West 1-2 were located at the first (outermost) and second (innermost) high vertical sand barriers, respectively, and points West 2-1 and West 2-2 were set up similarly in the next segment of the road. On eastern side, East 1-1 and East 1-2 were positioned at the first (innermost) and second (outermost) sand barriers, with East 2-1 and East 2-2 completing the symmetric layout (Fig. 3a and b).

In September 2019 and January 2021, sand slopes were profiled using a digital clinometer at 30 cm intervals along each transect. The slope data were in-

egrated in AutoCAD software morphological parameters—including windward and leeward slope lengths, maximum dune height, and sand volume per unit width—were extracted from these profiles.

2.6 UAV-based oblique photogrammetry

High-resolution remote sensing data were acquired using a DJI Phantom 4 RTK UAV (Shenzhen Dajiang Innovation Technology Co., Ltd., Shenzhen, China) equipped with an imaging system that has an effective resolution of 20.48 megapixels. The flights were executed at an altitude of 50 m, with a forward overlap of 70.0% between passes and a side overlap of 30.0%, at a constant speed of 10.00 m/s. The UAV surveys covered all sand-prone segments (severe and moderately severe sand hazard sections, 15.1 km) along Highway S315 (Fig. 3b; Table 1). Image processing

of dense point cloud data, digital orthophotography maps, and a DSM. The final orthomosaics achieved a spatial resolution of 2.80–3.30 cm/pixel.

To estimate sand accumulation volumes and maximum dune heights, we analyzed the 3D global-mapper/). Due to the lack of a pre-engineering DSM and of digital orthophotography map datasets, it was not possible to directly compare the pre- and post-construction topography. Given the relatively flat terrain of the Gobi desert around the road, we estimated the sand volume indirectly from single-period DSM using a cross-sectional profiling approach. For each road segment, we randomly selected 3–5 representative transects and averaged their characteristics to estimate dune volume and height for both high vertical sand barriers and low-profile checkerboard sand barriers. 2.7 Roadway sand removal records and meteorological data integration Roads situated in arid windblown areas often traverse low-lying or open terrain, where wind-driven sand tends to accumulate rapidly. As such, the extent of burial of the road surface (thus, the necessity for sand removal) offers a direct and practical indicator of the effectiveness of adjacent sand control structures. We collected routine maintenance records from the local highway operation and maintenance center, which cover road surface sand removal operations from 2015 to 2020, and used the data to assess the cumulative impact of sand control measures.

These data were further analyzed in conjunction with concurrent meteorological observations, including precipitation and wind speed obtained from monitoring sites along the road segments affected by sand accumulation.

3 Results

3.1 Morphology of sand accumulations associated with sand control structures

3.1.1 Morphological evolution at low-profile checkerboard sand barriers The morphology of sand accumulations within the low-profile checkerboard sand barriers typically progressed through three distinct phases: (1) in initial stage, sand deposition was minimal, with the thickness generally less than a few centimeters,

and in some areas, no significant accumulation was observed (Fig. 3c); (2) in middle stage, a morphological pattern with a low center and high periphery emerged, with sand depth at the center reaching 13.00–17.00 cm, and depth in the edge zones exceeding 20.00 cm, when selecting 30 grids for measurement on each section of the western side of Highway S315 (Fig. 3d); and (3) in late stage, sand levels rose to match the height of grid edges, and the difference in sand elevation between the center and the periphery became harder to see (Fig. 3e). The grid gradually transformed into a sand transport surface, indicating a notable decline in its sediment-trapping efficiency.

Under the prevailing winds shown in Figure 2, sand accumulation exhibited a west-to-east transport trend, with significantly greater deposition on the western side of the road. Although we did not determine when sand deposition began in each part of the protective structure, it appeared that the sand grids on the east only began to trap sand effectively once the western grids became saturated. This spatial pattern reflects prevailing west-to-east aeolian transport and the corresponding response of the engineered structures.

Morphological evolution of sand accumulations around high vertical sand barriers The high vertical sand barriers deployed along Highway S315 exhibited morphological evolution of the sand accumulation. In initial stage (Fig. 3f), minor sand deposition occurred on the windward side of the structures, forming low mounds that partially buried the lower sections of the sand barriers. Despite partial burial, the structures retained a substantial capacity to disrupt near-surface airflow and modulated sediment transport dynamics. As the accumulation process progressed (Fig. 3g and h), the dune body increased in height and extended upwind. Once the barrier became fully buried by windblown sand, its ability to reduce wind velocity and intercept

sediment diminished significantly, ultimately resulting in the near-complete loss of sand control functionality.

The cross-sectional morphology of the sand deposits near high vertical sand barriers was roughly triangular (Fig. 4 [Figure 4: see original paper]). On the road's western side, the windward slopes were gentle, while the leeward slopes were steep, with notable sand heights and volumes. In some cases, sand accumulation surpassed the fence height, thereby compromising its protective function (Fig. 4a–c). In contrast, the eastern side of the highway exhibited steeper windward slopes and gentler leeward slopes, with smaller sand volumes and sand barriers that mainly remained exposed and continued to function effectively (Fig. 4a, d, and e).

Sedimentation dynamics near high vertical sand barriers, documented via two-phase measurements of pattern evolution (a) and a series of current field photographs (b–e) Profiles West 1-1 and West 1-2 represented typical cross-sections near the outermost western sand barriers (Fig. 4a and b). Both sand barriers were 1.50 m high, with peak sand heights of 1.32 and 1.30 m, respectively. Windward slopes extended 14.00 and 13.10 m upwind, respectively, and lee-

ward slopes spanned 8.93 and 7.84 m. The corresponding sand volumes per unit width were 9.48 and 8.47 m /m, indicating high morphological consistency and sand-trapping pattern on the windward face.

In October 2019, the heights of the outermost western sand barriers were increased from 1.50 to 3.00 m in height (Fig. 4a). In January 2021, measurements showed sand heights reaching 1.85 and 1.93 m at the fence line—an increase of 0.53 and 0.63 m, respectively—notably, little additional sand accumulated at the windward toe. Dune crests migrated 1.00–1.50 m downwind, and leeward slopes extended 4.00–5.00 m downwind. The sand volumes in dune crests and leeward slopes per unit width increased dramatically, to 21.50 and 18.50 m /m, respectively, marking 127.0% and 118.0% gains. Given that these volumes accumulated over about 14 months after the barriers were raised (November 2019–January 2021), compared with about 34 months before the barriers were raised (November 2016–September 2019), these results suggested that raising the fence markedly improved both sand capture capacity and efficiency.

Conversely, the West-2 sand barriers exhibited relatively minor morphological changes (Fig. 4a and c). Between October 2019 and January 2021, crest positions migrated downwind by 0.70 and 0.60 m, respectively, whereas maximum heights decreased by 0.20 and 0.15 m. Sand volumes per unit width differed between locations. At West 2-1, they increased by 0.38 m /m, whereas at West 2-2, they decreased by 2.20 m /m. The overall decrease in accumulation was likely due to the raising of the upwind fence, which allowed the fence to capture more sand and reduced the downwind sediment supply, despite sustained wind velocities. This result created conditions with a strong wind but a low sand flux, resulting in local erosion and a net decrease in deposition.

On the eastern side of the road, both sand barriers displayed marked morphological changes, with crest positions advancing downwind and sand volumes increasing significantly. At East-1,

crests shifted downwind by 1.80 and 2.00 m, respectively, with corresponding volume gains per unit width of 1.00 and 1.30 m /m, respectively (Fig. 4a and d). At East-2, crest migration reached 2.80 and 2.85 m, respectively, with increases of 0.60 and 0.90 m /m (Fig. 4a and e). Compared with East-2, East-1 consistently exhibited greater slope lengths, crest heights, and volumes (Fig. 4a), which again supports the existence of a dominant west-to-east sand transport pathway. These morphological transitions confirmed the prevailing aeolian direction and highlighted the role of the eastern sand barriers in prolonging the structure's wind attenuation effect. 3.2 Sand retention capacity and its spatial distribution /m. In contrast, the central segments, which were also moderately affected, exhibited larger accumulations of 4.36–7.95 m /m. Severely impacted areas had the highest accumulations, ranging from 11.60 to 20.49 m /m. These patterns indicated that the primary function of the sand control system was to intercept eastward-moving sand fluxes by encouraging deposition on the western side of the highway and minimizing transport across the road surface. Comparisons between the western and eastern sides of the road showed that

approximately 70.0%-90.0% of the aeolian material was intercepted by western protective structures. This result highlights their crucial role in mitigating sand transport and reducing the severity of sand encroachment.

Sand accumulation in the high-density polyethylene (HDPE) barrier system Road segment Distance Sand hazard level Sand volume (m Contribution of western side (%) Total volume Note: road segment indicates distance from the northern highway terminus; K means kilometers; ' +' means additional meters. 3.3 Protective effectiveness of sand control engineering From 2015 to 2020, the amount of sand removed from the road surface decreased remarkably, from more than $12 \times 10^4 \text{ m}^3$ in 2015 to less than $1 \times 10^4 \text{ m}^3$ by 2020, which highlights the cumulative success of sand control measures (Fig. 5a [Figure 5: see original paper]). The intervention timeline (Table 1) comprises three construction phases: Phase I (September 2016), Phase II (October 2017), and Phase III (October 2019). Each successive phase corresponded to a substantial reduction in sand accumulation, with the most pronounced decline observed after Phase II.

During this period, meteorological conditions remained relatively stable. Annual mean wind speeds averaged $2.68 (\pm 0.04) \text{ m/s}$. However, precipitation fluctuated wildly, reaching a minimum of 22.6 mm in 2020 and a peak of 103.7 mm in 2018 (Fig. 5b). These fluctuations in climatic variables did not align with the consistent downward trend in sand accumulation, which suggests that the improvements can be predominantly attributed to the engineering interventions rather than to the climate change. Consequently, our results suggest that the sand control structures played a decisive role in enhancing road safety and environmental stability in this hyper-arid desert area.

Amount of sand removed (a) and meteorological conditions (b)

4 Discussion

Understanding how engineering interventions reshape wind-sand interactions in hyper-arid transportation corridors remains a central challenge for sustaining road functionality and ensuring long-term hazard mitigation. In this study, we addressed this problem by combining field clinometric profiles, high-resolution UAV oblique photogrammetry, road maintenance (sand- removed) records, and meteorological observations to evaluate how a multi-level sand-barrier system alters sediment transport pathways and the spatial organization of deposition over multi-year timescales.

Field observations revealed that the cross-sectional profile of the sand accumulations around elevated sand barriers consistently exhibited a roughly triangular morphology, with a gently sloping stoss (windward) face and a steep lee slope (Fig. 4a), which is consistent with classical dune formation dynamics (Pächtz et al., 2020; Dlużewski et al., 2023). This morphological evolution can be explained as follows: during the early stages of aeolian activity, localized sediment deposition increases surface roughness, which in turn reduces the near-surface wind velocity and promotes further sand accumulation. This result initiates a

positive feedback loop that accelerates dune initiation (Lee et al., 2002; San et al., 2019; Yu et al., 2020). As dune height increases, wind speeds intensify near the crest of the stoss slope, enhancing the kinetic energy of saltating grains and promoting their downwind transport. This process limits vertical dune growth and drives sediment toward the lee slope. In the active zone on the leeward side, airflow decelerates due to obstruction by the deposit structure, further reducing shear stress and increasing deposition, which in turn shapes the overall morphology and controls lateral dune expansion (Wang et al., 2024). As sand accumulation progressively buries the vertical barriers, their capacity to modify the near-surface airflow diminishes, allowing wind-sand interactions to increasingly resemble natural dune-building processes. This transition explains the morphological differences observed between the West 1 and West 2 transects, where barrier-induced control

weakens as burial progresses. The sand forms therefore record not only the effectiveness of the engineered structures but also the feedback adjustment between protective measures and aeolian sediment dynamics (Lima et al., 2020; Dun et al., 2021; Luo et al., 2023; Yao et al., 2025).

Increasing the height of the vertical sand barriers markedly improved their sand retention performance. The rapid increases in dune height and volume following this structural augmentation demonstrated a strong relationship between barrier height and sand storage efficiency (Lima et al., 2020; Ning et al., 2020; Liu et al., 2023; Yao et al., 2025). This result offers theoretical guidance for the future optimization of design parameters in aeolian engineering.

However, monitoring will be necessary to determine whether the taller barriers will also be buried, which could result in a reduction in their effectiveness.

Beyond the recurrent triangular morphology, a notable asymmetry was observed between the western (upwind) and eastern (downwind) sides of the sand barriers (Fig. 4a). The western side consistently developed a more extended and gently inclined stoss slope and a steeper lee slope. In contrast, the eastern side exhibited a comparatively steeper stoss slope and a gentler lee slope.

This contrast can be explained by the interplay between asymmetric sediment supply and the restructuring of airflow induced by barriers. The western side is directly exposed to abundant aeolian sediment sourced from the dry lakebed and mobile sand surfaces, resulting in sustained sediment influx (Ma, 2021; Yao et al., 2025). Under such supply-rich conditions, the elevated barriers gradually reduce near-surface wind velocity, allowing sand to accumulate progressively along the stoss slope and produce a steep lee slope through rapid deposition in the recirculation zone. In contrast, the eastern side receives only the residual sand that has passed through or diffracted around the barriers, resulting in supply-limited deposition concentrated near the fence, which promotes the formation of a steeper stoss slope and a more diffuse leeward tail.

Accordingly, we infer that sediment supply-structure-wind-field coupling, rather than static terrain differences alone, governs the observed morphological asym-

metry.

The effectiveness of sand barriers is fundamentally rooted in their ability to modify prevailing sediment transport pathways and local wind field structures, thereby inducing the spatial redistribution of aeolian deposits (Li and Sherman, 2015; Cheng et al., 2016; Liu et al., 2023).

Our calculation of the contributions from the western and eastern sides of the system revealed that 70.0%-90.0% of the incoming sand flux was intercepted on the windward side of the structures, resulting in a significant reduction in overall sand transport intensity (Table 2). This finding aligns causally with the observed decrease in annual sand removal volumes from 2015 to 2020, thereby validating the functional success of the sand control system (Fig. 5). Moreover, the integration of multi-source data underscores the value of high-resolution monitoring in evaluating the effectiveness of aeolian mitigation strategies (Wu and Liu, 2022; Wu et al., 2024).

In addition, the staged morphological evolution of sand accumulation within the low-standing checkerboard barriers underscores a gradual loss of function as the structures become buried (Fig. 3c-h). These structures exhibit a strong short-term trapping capacity, but are prone to functional degradation over time, necessitating timely reinforcement or replacement (Yao et al., 2006).

Quantifying their effective service life through systematic monitoring of morphological transitions would provide valuable empirical support for optimizing barrier design and establishing data-based cycles (Fig. 3c-e). From the perspective of desertification prevention and control, the early-stage efficacy of checkerboard barriers remains vital for stabilizing mobile dunes, reducing surface wind erosion, and fostering the initial recovery of vegetation cover.

However, to achieve sustainable mitigation of desertification, these short-lived mechanical measures should be coupled with ecological restoration practices, such as shrub planting or biological crust cultivation, which enhance the resilience of surface systems once the engineered barriers lose their function. This integrated approach has been shown to significantly improve land surface stability and prolong the effectiveness of sand control measures in arid environments (Zhang et al., 2004; Li et al., 2009; Akito et al., 2025).

Despite the clear insights gained into the geomorphic response and protective efficacy of the multi-level sand barrier system, several limitations remain. Spatial variability in barrier

configuration, differences in construction quality, and the uneven service lifetimes of structures installed across multiple phases may influence local sand-trapping performance in ways that are not fully captured in our analysis. Moreover, the UAV-based oblique photogrammetry approach used to reconstruct surface morphology is sensitive to high-reflectance Gobi surfaces and strong illumination contrasts, which can introduce uncertainties in DSM accuracy (Gindraux et al., 2017; Nesbit and Hugenholtz, 2019). Future work should therefore inte-

grate UAV imagery with Light Detection and Ranging (LiDAR) point clouds and real-time kinematic (RTK) to improve the precision and consistency of topographic reconstructions, and combine these observations with event-scale monitoring of aeolian transport during storm conditions. Coupling such empirical observations with numerical simulations would further clarify how engineered interventions regulate wind-sand dynamics under specific meteorological regimes, while long-term monitoring of structural integrity will be essential for assessing performance longevity and guiding adaptive maintenance. Nevertheless, this study provides a robust empirical basis for evaluating the sustainability of barrier-based sand control systems and informs the optimization of protective strategies in transportation corridors of hyper-arid desert areas.

5 Conclusions

This study evaluated the performance of multi-level sand control systems along Highway S315 in Ejin Banner, northern China using field measurements, UAV-based 3D reconstructions, sand removal records, and meteorological data. High vertical barriers produced triangular dune profiles, but with apparent asymmetry: the western (upwind) side developed a long, gently inclined stoss slope and steep lee slope under abundant sediment supply and barrier-induced flow deceleration, whereas the eastern (downwind) side formed a steeper stoss slope and diffuse lee tail under supply-limited conditions. Thus, dune morphology reflects a dynamic coupling among sediment supply, barrier geometry, and airflow restructuring rather than terrain alone. Low-surface checkerboard sand barriers showed progressive functional decline and profile flattening over time.

Windward structures intercepted 70.0%-90.0% of the sediment flux, and increasing the barrier height enhanced sand storage capacity and prolonged the effective service life. The marked reduction in sand removal volumes since 2015 demonstrates that staged improvements to the engineering system significantly mitigated sand encroachment. These findings provide a mechanistic basis for optimizing sand barrier configurations to sustain long-term protection in the transportation corridors of hyper-arid desert areas.

Conflict of interest XIAO Jianhua is a Young Editorial Board member of Journal of Arid Land and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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