Study on Aeolian Sand Environment Characteristics and Sand Hazard Prevention and Control Countermeasures Along the Korla-Qiemo Desert Highway (Postprint)

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Date: 2023-11-13T00:00:00+00:00

Abstract

The Yuli-Qiemo Desert Highway traverses the hinterland of the Taklamakan Desert, providing strong transportation support for achieving social stability and long-term peace and order in Xinjiang. Aeolian sand hazards constitute the primary threat to the construction and operation of this highway, necessitating urgent protective measures. Based on ERA5 wind data, the wind energy environment along the Yuli-Qiemo Desert Highway was comprehensively analyzed, dune movement characteristics along the route were examined using remote sensing imagery, aeolian sand hazards suffered along the route were systematically elaborated, and targeted aeolian sand control measures for the desert highway were proposed on this basis. The results indicate: (1) The annual average sand-driving wind speed along the route ranges between 6.03~6.64 m·s-1, and the annual frequency of sand-driving wind ranges between 14.73%~30.44%. (2) Sand-driving winds occur primarily in spring and summer. The predominant directions of sand-driving winds are ENE and E. (3) The annual drift potential along the route ranges between 106.48~293.70 VU, indicating both low and medium wind energy environments. The annual directional variability index ranges between 0.49~0.74, classified as medium ratio. The annual resultant drift direction ranges between 213.48°~255.94°. Seasonal drift potential in each direction exhibits consistent variation characteristics with seasonal sand-driving wind frequency, and the directional variability index shows distinct seasonal variation features. The spatiotemporal variation characteristics of the wind energy environment cause spatial differences in dune movement rates. Under the action of sand-driving winds, the route suffers varying degrees of aeolian sand hazards. Along the route, according to the blocking-fixing principle, targeted control measures combining engineering and biological approaches are established. The research results comprehensively summarize the aeolian sand environment characteristics and hazards along the Yuli-Qiemo Desert Highway, providing a theoretical basis for the establishment and subsequent improvement and optimization of control measures along the highway.

Full Text

Preamble

The Yuli-Qiemo Desert Highway (hereinafter referred to as the Yuli-Qiemo Highway) traverses the hinterland of the Taklamakan Desert, providing crucial transportation support for social stability and long-term security in Xinjiang. Wind-sand hazards represent the primary threat to both the construction and operation of this highway, necessitating urgent implementation of protective measures. Based on ERA5 wind data, this study comprehensively analyzed the wind energy environment along the highway, integrated remote sensing imagery to characterize dune movement patterns, systematically documented the wind-sand hazards encountered along the route, and subsequently proposed targeted prevention and control strategies. The results indicate: (1) The annual average sand-driving wind speed ranges from 6.03 to 6.64 $m \cdot s^{-1}$, with annual sand-driving wind frequency between 14.73% and 30.44%, representing a medium ratio. The annual resultant sand transport direction ranges from 213.48° to 255.94°. (2) The annual sand transport potential (DP) along the route varies from 106.48 to 293.70 VU, encompassing both low and medium wind energy environments, with the annual directional variability index (RDP/DP) between 0.49 and 0.74. (3) Sand-driving winds occur predominantly in spring and summer, with ENE and E as the primary directions. The seasonal sand transport potential in each direction aligns with seasonal sand-driving wind frequency variations, while the directional variability index exhibits distinct seasonal patterns. The spatiotemporal variability of the wind energy environment creates spatial differences in dune migration rates. Under the influence of sand-driving winds, the highway experiences varying degrees of wind-sand hazards along its length. Consequently, targeted engineering and biological control measures were established following the blocking-fixing principle. These findings provide a comprehensive overview of the wind-sand environment characteristics and hazards along the Yuli-Qiemo Desert Highway, offering a theoretical foundation for the deployment, improvement, and optimization of control measures.

Keywords: sand-driving wind; sand transport potential; wind-sand hazards; prevention and control measures; desert highway

1 Study Area Overview

The Yuli-Qiemo Desert Highway (38.00°–41.00°N, 85.21°–86.22°E) is located in the Tarim Basin of southern Xinjiang [Figure 85: see original paper]. The route crosses the Taklamakan Desert hinterland with a general north-south orientation, representing the third desert highway across the Taklamakan after the Tazhong and Aral-Hotan desert highways. The highway starts at Yuli County and ends at Qiemo County, with an elevation ranging from 885 to 1157 m and a total length of 332 km. The Taklamakan Desert experiences frequent strong winds, sandstorms, and floating dust in spring; high temperatures and dry conditions in summer; rapid temperature drops in autumn; and cold, dry winters with minimal snowfall. The highway' s average annual temperature is 10.1-10.6°C, with extreme maximum temperatures of 41.5-42.2°C and extreme minimum temperatures of -30.9°C. Annual precipitation averages 18.6-40.8 mm, while annual evaporation reaches 2507-2910.5 mm.

Since most sections (K22+500-K329+000) traverse desert areas, all segments except the starting and ending sections in agricultural and barren lands exhibit varying degrees of wind-sand hazards, primarily sand burial and wind erosion. Severe hazard sections, totaling 305 km, are mainly distributed in mobile dune and compound dune areas characterized by sand burial. Medium hazard sections span approximately 139 km, primarily in semi-fixed/semi-mobile dunes and smaller dune basins, also dominated by sand burial. Minor hazard sections, about 161.3 km, occur in broader basins with mainly blowing sand and wind-accumulated sand on the roadbed.

2 Data and Methods

2.1 Remote Sensing Imagery

Remote sensing imagery along the route was obtained from historical ArcGIS images. To eliminate offset errors, geometric correction was performed to meet accuracy requirements. Dune crest lines were extracted through visual interpretation, with crest line movement serving as the basis for determining dune migration. Feature points were selected uniformly along crest lines at prominent locations such as windward and leeward slope bases [Figure 2: see original paper]. The ratio of the sum of feature point displacement distances to the image time span was calculated as the dune migration rate, while the average displacement angle of feature points on each dune represented its migration direction. The average migration rate of crest lines within a section divided by the year span yielded the section' s dune migration rate, and the average angle of all feature points represented the section' s migration direction.

Five representative sections along the highway were selected based on satellite image quality and update frequency combined with field survey data [Figure 1: see original paper] to analyze wind-sand transport characteristics and provide theoretical support for control measure deployment. Due to inconsistent update frequencies across sections, two-period imagery was obtained for each section to better characterize dune movement (Table 1).

2.2 Wind Data

Wind data along the route were acquired from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset (https://cds.climate.copernicus.eu/) with a spatial resolution of 0.25°$×$0.25° and temporal resolution of 1 hour. This dataset effectively captures the wind environment along the route, enabling precise wind-sand control. The data comprise U (longitude wind speed) and V (latitude wind speed) components at 10 m height. The time range covers the earliest and latest image acquisition periods from 2018 to 2022.

2.3 Dune Movement Characteristics

Investigations reveal that the geomorphology along the highway consists of alternating large compound dunes and basins. Compound dunes feature secondary dunes on their surfaces, all of which are mobile dunes. By tracking mobile dunes in the five representative sections, dune migration rates and directions were calculated (Table 2). Migration rates range from 3.05 to 5.03 $m \cdot a^{-1}$, with the minimum in Section 1 and maximum in Section 3. Migration directions range from 186.78° to 245.59°. The data demonstrate spatial variation in dune migration rates, with lower rates in the northern highway sections and higher rates in the south. While sand-driving wind frequency increases from Yuli to Qiemo, the differences in dune migration rates indicate that wind characteristics alone do not determine dune movement—other factors such as dune volume and density also influence migration, as evidenced by Section 1' s characteristics.

2.4 Wind Energy Environment

Wind speed and direction were calculated from the wind data. Sand-driving wind hours with speeds $ 4.5m · s^{-1}$ were statistically analyzed at annual, seasonal, and monthly scales. Sand-driving wind frequency was expressed as the percentage of sand-driving wind hours relative to total observation hours. The sand transport potential (DP) was calculated using the formula:

$$DP = \sum_{i=1}^{16} V_i^2 (V_i - V_t) t_i$$

where V_i is the sand-driving wind speed, V_t is the threshold wind speed (4.5 $m \cdot s^{-1}$), and t_i is the sand-driving wind duration. Wind speeds were classified into five levels: 4.5-7, 7-9, 9-11, 11-13, and $ 13m · s^{-1}$, with corresponding weight factors calculated to determine DP for each section. The resultant sand transport potential (RDP) and resultant sand transport direction (RDD) were obtained through vector summation of DP from 16 directions. The directional variability index (RDP/DP) characterizes wind direction variability, with RDP/DP $\leq$ 0.3 indicating high variability, 0.3–0.8 moderate variability, and $ $0.8 low variability.

3 Results

3.1 Sand-Driving Wind Characteristics

3.1.1 Annual Characteristics Analysis of annual average sand-driving wind speed and frequency along the Yuli-Qiemo Desert Highway reveals an increasing trend in sand-driving wind frequency from Yuli to Qiemo, rising from 14.73% to 30.44%. The annual average sand-driving wind speed shows a spatial pattern of initial increase followed by decrease, peaking at 6.64 $m \cdot s^{-1}$ in Section 2 and reaching a minimum of 6.03 $m \cdot s^{-1}$ in the Yuli section. The main sand-driving wind directions are ENE and E. Sections 2 through 5 exhibit high-frequency, strong-wind conditions, with Section 2 showing a significant increase in ENE wind frequency. Sections 3 and 4 demonstrate dominant E winds. The wind environment becomes increasingly severe from Yuli to Qiemo, with growing sand hazard threats as sand-driving wind frequency increases. Yuli and Section 1 exhibit low-frequency, weak-wind conditions, while Sections 2–5 show high-frequency, strong-wind trends with concentrated wind directions [Figure 3: see original paper].

3.1.2 Seasonal Characteristics Seasonal sand-driving winds along the highway exhibit distinct spatiotemporal patterns. Temporally, sand-driving wind frequency increases from spring to summer then decreases through autumn to winter, peaking in summer. The seasonal average sand-driving wind speed decreases progressively from spring to winter. Spatially, the average sand-driving wind speed increases from Yuli to Section 2 then decreases, consistent with annual patterns. Sand-driving wind frequency shows an overall increasing trend from Yuli to Qiemo, with Section 3' s summer frequency exceeding Qiemo' s. The main wind directions are NE in Yuli, ENE in Section 1, E in Section 2, and E in Sections 3–4. The frequency of E winds dominates in Sections 3–4, while ENE winds prevail in Section 2. Seasonal average wind speeds show similar patterns across sections, with winter exhibiting greater directional variation [FIGURE:4–6].

3.1.3 Monthly Characteristics Monthly sand-driving wind frequency along the route follows a consistent pattern across sections, showing an inverted V-shape that peaks in May–June and declines to a minimum in December. Monthly average sand-driving wind speed follows the same trend, with the most severe wind conditions occurring in May–June when high-frequency, strong winds significantly increase sand hazard probability. The RDP/DP index ranges from 0.49 to 0.74 annually, indicating moderate directional variability. Yuli and Section 1 show smaller RDP/DP values, suggesting variable wind directions, while Sections 2–5 exhibit larger values indicating stable wind directions that facilitate prediction and targeted control [Figure 7: see original paper].

3.2 Sand Transport Potential Characteristics

3.2.1 Annual DP Characteristics Annual DP along the highway ranges from 106.48 to 293.70 VU, with maximum and minimum values in Sections 3 and 1, respectively. According to wind energy environment classifications, Yuli and Section 1 belong to low wind energy environments (DP < 200 VU), while Sections 2–5 belong to medium wind energy environments (200–400 VU). The RDP/DP index (0.49–0.74) indicates moderate directional variability. The resultant sand transport direction (RDD) ranges from 213.48° to 255.94°, showing good consistency with dune migration directions. Sections 2–5 exhibit single dominant transport directions (ENE in Section 2, E in Sections 3–4), simplifying control complexity despite strong sand transport activity [Figure 8: see original paper].

3.2.2 Seasonal DP Characteristics Seasonal DP shows spatiotemporal variation consistent with annual patterns. Spring and summer are the primary sand transport seasons, with DP values of 46.91–132.91 VU in spring and 46.49–104.01 VU in summer. Autumn DP ranges from 13.61 to 51.87 VU, and winter DP from 12.14 to 51.87 VU. The seasonal RDP/DP index indicates that summer transport directions are more complex (lower RDP/DP), while autumn directions are more stable (higher RDP/DP). Spring shows concentrated transport directions, increasing hazard potential on the upwind side of the highway, while summer' s variable directions complicate control efforts. Sections 2–5 maintain stable transport directions across seasons, indicating consistent upwind hazard locations [FIGURE:9–10].

3.3 Dune Movement Characteristics

Dune movement characteristics are closely related to the wind-sand environment. In Yuli and Section 1, the weak-wind, low-transport environment results in slower dune migration (3.05 $m \cdot a^{-1}$). In Sections 2–5, the strong-wind, high-transport environment increases migration rates (up to 5.03 $m \cdot a^{-1}$ in Section 3) with concentrated transport directions, creating severe sand hazards. The directional stability (high RDP/DP) in Sections 2–5 further intensifies hazards by maintaining consistent attack angles on the highway.

4 Discussion

4.1 Wind-Sand Hazards and Causes

The Yuli-Qiemo Desert Highway faces severe wind-sand hazards due to harsh natural conditions: arid climate, sparse vegetation, abundant sand sources, and frequent sand-driving winds. Highway construction disturbs local wind equilibrium and destabilizes dunes, inevitably leading to sand hazards. Contour maps based on dune migration rates illustrate hazard intensity along the route. In Yuli and Section 1, dune movement parallels the highway with low migration rates, resulting in minor hazards. In Sections 2–5, dune movement directions intersect the highway at large angles (particularly in Sections 3–4), with maximum migration rates indicating high hazard potential.

The highway' s north-south orientation intersects the dominant sand transport direction at large angles in Sections 1–4 [Figure 11: see original paper], increasing hazard threats. Seasonal RDP/DP analysis shows that spring and summer transport is strongest and most directionally stable [FIGURE:9–10], posing the greatest risks. The large intersection angle between transport direction and highway orientation means sand hazards primarily occur on the upwind side, necessitating enhanced protection there.

4.2 Wind-Sand Control System

Highway sand hazards originate from wind-sand flow, whose intensity depends on dynamic factors (wind) and material factors (sand). Control measures should adapt to local conditions, optimizing barrier width to reduce costs while ensuring effectiveness. Based on the spatial variability of wind-sand environments, the control system width should be adjusted accordingly. Sections 2–5, with higher dune migration rates and medium wind energy environments, require wider protection systems, especially on the upwind side. Currently, no explicit standards exist for desert road protection widths, but referencing previous studies, Sections 3–4 employ 110 m upwind checkerboard barriers (reduced based on migration rates), with downwind widths set at half the upwind width, and vertical sand barriers spaced at 20 m intervals.

The integrated control system follows a blocking-fixing principle [Figure 12: see original paper]. Vertical sand barriers on the outer perimeter reduce wind speed, causing sand to accumulate before entering the inner reed checkerboard barriers where it is stabilized. Where water conditions permit, vegetation is cultivated within the checkerboards, which initially protect plants from wind erosion, improving survival rates and creating a comprehensive control system.

5 Conclusion

The wind-sand environment along the Yuli-Qiemo Desert Highway exhibits significant spatiotemporal variability. Sand-driving wind frequency increases from Yuli to Qiemo, while average wind speed peaks in Section 2. The main sand-driving directions are ENE and E. Seasonal patterns show strong consistency with annual patterns, with spring and summer winds dominating.

The sand transport potential ranges from 106.48 to 293.70 VU, with Yuli and Section 1 in low wind energy environments and Sections 2–5 in medium environments. The directional variability index (0.49–0.74) indicates moderate variability, with stable directions in Sections 2–5 facilitating hazard prediction.

Dune migration rates (3.05–5.03 $m \cdot a^{-1}$) correlate with wind-sand environments, with higher rates in Sections 2–5 where strong, concentrated winds create severe hazards. Based on these findings, a blocking-fixing control system combining vertical barriers and checkerboards was designed, with widths adjusted according to wind energy levels and dune migration characteristics. This cost-effective, efficient system provides theoretical and practical guidance for wind-sand control along this and other desert highways.

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