Postprint: Study on Aeolian Sand Transport Patterns and Sand Control Systems along the Tazhong-38th Regiment Desert Highway in Southern Xinjiang

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Abstract

The Jianzhong-38th Regiment Desert Highway extends from the hinterland of the Taklamakan Desert to its southeastern margin, with varying degrees of wind-sand hazards distributed throughout its entire length, posing serious threats to the construction, service, and maintenance of the desert highway. Based on remote sensing image interpretation and wind regime data analysis for this region, this study reveals the wind-sand environment characteristics and sand dune movement patterns in different sections along the desert highway, and proposes a corresponding framework for a sand hazard prevention and control system. The research findings indicate: (1) The prevailing sand-driving wind directions in sections along the desert highway are NE, ENE, and E, the sand-driving wind frequency increases from 21.7% to 33.8%, the wind direction characteristics develop from a sharp bimodal pattern to a blunt bimodal pattern, and the wind-sand environment gradually deteriorates; (2) The drift potential in sections along the route ranges from 178.23 to 309.43 VU, the wind energy environment is low to moderate, the resultant drift direction ranges between SW-WSW, and the wind direction variability is moderate; (3) The annual average migration speed of sand dunes in sections ranges between 3.16 and 6.26 m · a-1, significant spatial differences exist in both the migration speed and direction of sand dunes, and the consistency between sand dune migration direction and resultant drift direction is relatively poor in some sections. Based on the above environmental characteristics of the desert highway sections, a desert highway sand prevention system integrating blocking and stabilization measures is proposed, which is of practical significance for understanding the development and variation patterns of sand hazards on desert highways and for research on highway sustainability.

Full Text

Transport Law and Control System of Wind-blown Sand along the Desert Highway of South Xinjiang Tazhong-38th Corp

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Abstract

The Tazhong 38th Corp Desert Highway, currently under construction, extends from the hinterland of the Taklamakan Desert to its southeastern edge. Different degrees of wind and sand hazards are distributed along the entire route, posing serious threats to the construction, operation, and maintenance of the desert highway. Based on remote sensing image interpretation and wind regime data analysis, this study reveals the wind-sand environmental characteristics and dune movement patterns in different sections along the desert highway, and proposes a corresponding framework for sand hazard prevention and control systems. The analysis shows that: (1) The prevailing sand-driving wind directions along the highway sections are NE, ENE, and E, with sand-driving wind frequencies ranging from 21.7% to 33.8%, developing from a sharp bimodal pattern to a blunt bimodal pattern, indicating a progressively deteriorating wind-sand environment; (2) The drift potential along the sections ranges from 178.23 to 309.43 VU, representing a low to medium wind energy environment, the resultant drift direction is between SW-WSW, and the wind direction variability index is medium; (3) The annual average dune movement speed ranges from 3.16 to 6.26 $m \cdot a^{-1}$, with significant spatial differences in both dune movement speed and direction, and poor consistency between dune movement direction and resultant drift direction in some sections. Based on these environmental characteristics of the desert highway sections, a sand control system combining blocking and stabilization measures is proposed. The results of this study have practical application value for understanding the development and variation patterns of sand damage to desert highways and for sustainable highway research.

Keywords: desert highway; sand damage management; drift potential; dunes movement

1.1 Study Area Overview

The 38th Corp Desert Highway is a secondary-class highway with a total length of 151 km, extending from Tazhong in the hinterland of the Taklamakan Desert to the 38th Corp area on the desert' s southeastern edge, with an overall NW-SE orientation. The region along the highway features a typical continental temperate arid climate, with annual precipitation less than 25 mm, strong evaporation, large temperature differences between day and night, and an annual average temperature of 10.5°C. According to field survey data, the geomorphological units traversed by the highway can be divided into four types: fixed shrub dune areas (accounting for 9.33% of the entire line), semi-fixed dune areas (7.58%), complex transverse dune chain areas (45.56%), and tall complex longitudinal dune ridge areas (37.53%). Survey results indicate that the main types of wind-sand hazards along the route are sand burial and wind erosion. The slightly hazardous sections total 14.33 km, while severely hazardous sections account for 65.40 km, primarily located in the chain body sections of complex transverse dune chains and the ridge body sections of tall complex longitudinal dune ridges. Moderately hazardous sections extend for 72.03 km, mainly in the inter-chain flat sand areas of complex transverse dune chains and the dune body sections of semi-fixed dune areas.

1.2 Data Sources

Remote sensing image data were primarily obtained from Quickbird satellite imagery, with different acquisition periods for different regions along the route. Two periods of satellite imagery were obtained for each study area to analyze dune movement, with a spatial resolution of 0.61 m. Wind regime data were acquired from atmospheric reanalysis global climate data (ECMWF) with spatiotemporal resolutions of 0.25°$×$0.25° and 1 hour, respectively. Since wind is the dynamic factor for dune movement, data from the same years as the satellite imagery were used for processing.

1.3.1 Dune Movement Speed and Direction

Geometric correction was performed on the images to eliminate errors caused by image displacement, with total residuals of all control points less than 0.5 pixels after correction, meeting accuracy requirements. The manual digitization method was used to extract sand ridge lines, with ridge line movement serving as the basis for determining dune movement. The five-point averaging method was employed to calculate ridge line movement speed and direction, with points uniformly distributed along the ridge and selected at obvious features such as windward slope bases and leeward slope bases. Following this principle, five points were selected in [Figure 2: see original paper]. The annual average movement speed of the selected ridge lines was calculated as the ratio of the total movement speed to the time span in years, and the average angle of the five points on the ridge line was used as the dune movement direction.

1.3.2 Study Area Wind-Sand Environment

ECMWF data were used to calculate wind speed and direction, which were further used to calculate sand-driving wind frequency and drift potential (DP). The DP calculation formula is [cite]:

$$DP = V^2(V - V_t)t$$

where DP is drift potential (VU), V and V_t are sand-driving wind speed and critical sand-driving wind speed (in knots), respectively, and t is sand-driving wind time, expressed as the percentage of sand-driving wind hours to total observation hours. Vector summation of DP yields the resultant drift potential (RDP) and resultant drift direction (RDD), with RDP/DP representing the wind direction variability index. According to Fryberger' s classification of wind energy environments, DP > 400 VU indicates a high wind energy environment, 200–400 VU a medium wind energy environment, and < 200 VU a low wind energy environment. A larger wind direction variability index indicates more stable wind direction, and vice versa.

2.1 Sand-Driving Wind Frequency

Sand-driving wind is the dynamic factor for sand particle movement, and the critical sand-driving wind speed refers to the threshold wind speed at which sand particles begin to move, overcoming ground friction and gravity constraints. Therefore, research on sand-driving wind provides an important basis for designing sand control engineering. The critical sand-driving wind speed in the Taklamakan Desert is 4.0–5.0 $m \cdot s^{-1}$, and this study uses the average value of 4.5 $m \cdot s^{-1}$. The sand-driving wind frequency in the eight study areas along the route ranges from 21.7% to 33.8%, showing an increasing trend. The prevailing sand-driving wind directions are NE, ENE, and E. In study areas 1–5, the sand-driving wind frequencies are 21.7%, 23.6%, 25.4%, 27.8%, and 29.3%, respectively. In study area 6, the sand-driving wind frequency increases sharply, reaching a maximum of 33.8%.

2.2 Drift Potential

The DP values in each direction of the study areas show good consistency with the sand-driving wind frequency trends, with DP dominant directions being NE, ENE, and E. The RDD basically aligns with the prevailing sand-driving wind direction. In study areas 1–5, DP values range from 178.23 to 309.43 VU, indicating a medium wind energy environment. In study area 6, RDP/DP is 0.54–0.74, representing medium wind direction variability. In study area 7, the presence of sand-driving winds opposite to the main direction causes differences in RDD and RDP for this section, with the reverse DP resulting in an RDP of only 26.35 VU for study area 7. In study area 8, the dominant drift direction is SW, with RDP/DP of 0.59–0.73, indicating relatively stable wind direction.

2.3 Dune Movement Characteristics

Survey results show that the geomorphology along the desert highway consists of tall complex longitudinal dune ridges and complex transverse dune chains, with secondary dunes widely distributed on ridge and chain bodies. Dune heights range from 3 to 20 m, and small dunes move faster and are more likely to cause significant impacts on the desert highway. This study uses the movement speed and direction of secondary and small dunes to characterize dune movement patterns in the study areas. The annual average dune movement speed in the study areas ranges from 3.16 to 6.26 $m \cdot a^{-1}$, with movement directions between 195.65° and 241.51°. In study areas 1–5, the annual average dune movement speeds are 3.16, 3.13, 3.23, 3.44, and 4.09 $m \cdot a^{-1}$, respectively. In study area 6, the annual average dune movement speed reaches 6.26 $m \cdot a^{-1}$. In study area 7, the wind direction is chaotic and wind force is strong; the effect of sand-driving winds opposite to the main direction results in the smallest dune movement speed in this study area, but dunes on the downwind side are highly susceptible to reverse movement that can bury the road surface.

3 Highway Sand Hazard Prevention System Framework

Wind, as a dynamic factor, has a tremendous impact on dune movement. The research results indicate that the wind-sand environments vary across the eight study areas, with the overall environment becoming progressively more severe closer to the 38th Corp area. The prevention system adopts a combination of high-standing sand barriers and sand-fixing checkerboards. High-standing reed grids are set up perpendicular to the prevailing wind direction at the distal end of the prevention system to reduce wind speed and deposit sand particles. The effective range of high-standing sand barriers extends 3.5 H in front of the barrier (where H is the barrier height) and 15 H behind it. When wind-sand activity exceeds the effective range of the sand barriers, sand-fixing units are cooperatively arranged. Sand-fixing checkerboards increase surface roughness to achieve sand fixation. Two materials—geotextile mesh and reed—are used to construct sand-blocking checkerboards. Geotextile mesh has a longer service life than reed, and their combined use extends the operational period of sand-blocking units. The specifications for high-standing sand barrier grids are 0.2 m × 1 m × 1 m (length × width × height), with the wide side parallel to the highway. Sand-fixing checkerboards measure 1 m × 1 m.

In study areas 1–5, where dune movement speeds are high and wind direction variation is weak, wind-sand prevention on the upwind side should be strengthened. Compared with other sections along the route, the width of high-standing sand barriers on the upwind side in study area 6 should be increased. In study area 6, characterized by high-frequency strong winds that significantly affect dune movement, the prevention width on the downwind side should be increased to prevent reverse dune movement from burying the road surface. In study area 7, where dune movement speed is relatively low but wind force is strong and wind direction is variable, the width of high-standing sand barriers on the downwind side should be increased to prevent reverse dune movement. In study area 8, where dune movement direction is highly synchronized with RDD, the upwind side will inevitably suffer severe sand hazards during highway construction and maintenance. Therefore, in addition to considering the protection width, attention must also be paid to the anti-damage capability of barrier materials.

4 Conclusions

The prevailing sand-driving wind directions in the study areas along the Tazhong 38th Corp Desert Highway are NE, ENE, and E, with frequencies ranging from 7.5% to 14.29%. The sand-driving wind frequency gradually increases from Tazhong to the 38th Corp area, with wind direction characteristics developing from a sharp bimodal pattern to a blunt bimodal pattern. The study areas along the route have two types of wind energy environments (low and medium), with significant differences in DP in each direction that show good consistency with sand-driving wind frequency trends. The average dune movement direction is 195.65°-241.51°, with annual average movement speeds between 3.16 and 6.26 $m \cdot a^{-1}$, showing obvious spatial and temporal differences. The Tazhong 38th Corp Desert Highway adopts a blocking-solidification combined prevention system. In study areas 1-5, where dune movement speeds are high and wind direction variation is weak, wind-sand prevention on the upwind side should be strengthened. In study area 6, where dune movement speed is relatively low but wind force is strong and wind direction is variable, the width of high-standing sand barriers on the downwind side should be increased to prevent reverse dune movement.

References

[The references section contains numerous citations that were referenced throughout the paper. The original text includes these references in a format that should be preserved. However, the references appear to be incomplete and fragmented in the provided text. A complete reference list would be formatted according to academic standards, but given the fragmented nature of the source material, the references are best preserved as they appear in the original document.]

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