Postprint of Aeolian Environment Characteristics Along the Tumushuke-Kunyu Desert Highway in the Western Tarim Basin

Authors: Wei Jinming, Cheng Jianjun, Ma Benteng

Date: 2024-03-01T00:00:00+00:00

Abstract

To investigate the wind-sand environment characteristics along the under-construction Tumushuke-Kunyu Desert Highway and implement targeted wind-sand protection engineering practices based on the wind-sand element features along the desert highway, field surveys, ERA5 wind speed data, and satellite imagery data were employed to analyze the wind-sand activity patterns along the Tumushuke-Kunyu Desert Highway. The results indicate that the annual average wind speed along the highway ranges from 3.03~3.28 $m \cdot s^{-1}$, the annual average sand-driving wind speed ranges from 5.85~6.10 $m \cdot s^{-1}$, and the annual frequency of sand-driving wind ranges from 16.87%~21.41%. Sand-driving winds are concentrated in spring and summer, with April to August being the months with the highest frequency of sand-driving winds throughout the year. The highway corridor is dominated by easterly winds (NE, ENE, E, ESE), and the frequency of westerly sand-driving winds is higher south of the Mazartag Mountains than north of it. The annual drift potential (DP) along the corridor ranges from 99.77 VU to 145.30 VU, belonging to a low wind-energy environment with moderate variability. The volume and density of dunes differ significantly between the northern and southern sides of the Mazartag Mountains. The dune movement rate along the corridor ranges from 1.19~3.69 $m \cdot a^{-1}$, representing a moderate movement speed. There exists a significant negative correlation between dune movement rate and the size of the dune' s vertical projection area. The movement direction ranges from 171.76° to 192.53°, which basically coincides with the resultant drift direction (RDD). For the design of the sand prevention system north of the Mazartag Mountains, the focus should be on the east side, while both east and west sides need to be considered for the area south of it.

Full Text

Characteristics of the Wind-Sand Environment Along the Tumshuk-Kunyu Desert Highway in the Western Tarim Basin

WEI Jinming, CHENG Jianjun, MA Benteng
College of Water Conservancy & Architectural Engineering, Shihezi University, Shihezi 832003, Xinjiang, China

Abstract

To understand the wind-sand environment characteristics along the under-construction Tumshuk-Kunyu Desert Highway, targeted wind-sand protection engineering practices were implemented based on the wind-sand element features along the route. Field surveys, ERA5 wind speed data, and satellite imagery were employed to analyze the wind-sand activity patterns along the highway. Results indicate that the annual average wind speed along the highway ranges from 3.03–3.28 $m \cdot s^{-1}$, with an average sand-driving wind speed of 5.85–6.10 $m \cdot s^{-1}$. The annual sand-driving wind frequency varies between 16.87% and 21.41%. April through August represents the period with the highest frequency of sand-driving winds. The prevailing winds are easterly (NE, ENE, E, and ESE), with higher frequencies of westerly sand-driving winds observed south of the Mazartag Mountains compared to the north. The annual drift potential (DP) along the route falls within 99.77–145.30 VU, indicating a low wind-energy environment with medium variability. Significant differences exist in dune volume and density between the northern and southern sides of the Mazartag Mountains. Dune migration rates along the highway range from 1.19–3.69 $m \cdot a^{-1}$, representing medium movement speeds. A significant negative correlation exists between dune migration rate and the vertical projection area of dunes. The movement direction ranges from 171.76°–192.53°, which aligns closely with the resultant drift direction (RDD). The sand control system design north of the Mazartag Mountains should focus on the eastern side, while both eastern and western sides require attention south of the mountain.

Keywords: desert highway; wind conditions; drift potential; dune migration; Taklamakan Desert

Introduction

The Tumshuk-Kunyu Desert Highway traverses the western part of the Taklamakan Desert as a newly constructed secondary-class highway with a design speed of 80 $km \cdot h^{-1}$ and a total width of 12 m. The overall orientation runs from north to south, crossing the Mazartag Mountains. Previous research has demonstrated that the most economical and effective sand fixation measures involve reed and straw checkerboard barriers, with multi-component sand barrier systems effectively extending protection duration. Studies have also established a linear relationship between drift potential and dune migration distance. The Taklamakan Desert, as the world' s second-largest shifting desert, features extensive tall sand mountains, extremely abundant sand sources, and a low wind-energy environment. Desert surface morphology is closely related to wind dynamics, which simultaneously serve as the driving force for wind-sand disasters. Based on wind-sand hazards experienced by other highways in the Taklamakan Desert, this route faces primarily severe and moderate wind-sand hazards, with road surface burial representing the main threat, necessitating tailored wind-sand control measures.

Over recent decades, numerous scholars have conducted in-depth research on wind-energy environments, dune migration, and wind-sand control measures and their effectiveness in desert regions, providing theoretical foundations for sand hazard mitigation. Detailed analyses of wind-sand activity patterns and hazard types along the Wuma Expressway have led to proposals for "six-belt integrated" sand control systems. However, few studies have combined wind condition data with satellite imagery to investigate dune migration rates and directions. This study focuses on the Tumshuk-Kunyu Desert Highway, integrating ERA5 wind speed data with satellite imagery to conduct a comprehensive analysis of wind-sand activity patterns across various study sections along the highway, aiming to clarify the unique wind-sand environment characteristics and provide theoretical support for highway sand control and prevention.

1.1 Study Area Overview

The Tumshuk-Kunyu Desert Highway project originates at the intersection of the eastern extension of Tumshuk City and the airport expressway, crosses the Xiable River and Yarkant River, traverses the Taklamakan Desert from north to south, and terminates in Kunyu City, with a total length of 276.7 km. According to survey results, the route passes through extensive aeolian sand sections. Based on the *Code for Investigation of Highway Engineering Geology*, the wind-sand hazard degree along the entire route was classified, with the proposed route primarily experiencing severe and moderate hazards. The severely hazardous sections total 178.79 km (64.7% of the route), mainly distributed in compound barchan dune chain intervals and barchan dune chain intervals. Moderately hazardous sections total 50.71 km (18.3%), primarily in semi-fixed shrub dune sections and wind-eroded Gobi sections. Slightly hazardous sections total 21.20 km (7.7%), mainly in compound barchan dune chain intervals and barchan dune chain intervals.

1.2 Data Acquisition

ERA5 reanalysis wind speed data were obtained with a temporal resolution of 0.1°$×$0.1°, allowing arbitrary download of data for any ground point. The data time interval is 1 hour. Based on satellite image acquisition times, wind speed data for corresponding time periods were downloaded. High-resolution satellite imagery data were acquired through Bigemap software. The imagery features high resolution, good clarity, and extensive coverage, and has been applied across various fields. The route was divided into 7 study sections (Fig. [Figure 1: see original paper]). Considering the update frequency and image clarity of satellite imagery data within the highway corridor, two relatively clear-phase images were selected for each section. The satellite image time intervals range from 2–5 years, with each study section having at least two high-definition images.

1.3 Methods

1.3.1 Dune Movement Selected dune satellite imagery must ensure: no cloud cover obstruction, relatively rounded and dispersed dune shapes, minimal shape change between the two phases, and complete, clear morphology. At least 3 dunes meeting these criteria were selected for each study section. Before measuring dune movement, satellite imagery was georeferenced in ArcGIS to eliminate errors. Dune outlines from the satellite imagery were manually extracted [Figure 2: see original paper], and the direction and distance of outline movement represent dune migration direction and distance. The five-point averaging method was typically used to determine dune movement, with at least five characteristic points selected for each dune. These points should be uniformly distributed along the outline, selecting locations with distinct features on the outline. The ratio of the average movement distance of characteristic points to the time interval between the two images yields the dune' s annual average migration rate. The average of the angles of movement direction for all characteristic points represents the dune' s migration direction.

1.3.2 Drift Potential Calculation Downloaded ERA5 raw data were converted to calculate wind direction, wind speed, sand-driving wind frequency, and drift potential. The drift potential (DP) calculation formula is:

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

where: DP represents drift potential; V and V_t represent sand-driving wind speed and threshold sand-driving wind speed (in knots), respectively; t represents the percentage of sand-driving wind hours in total observation hours. Fryberger' s drift potential is an important indicator for evaluating regional wind-energy environments, classifying them into three categories: DP $<$ 200 VU for low wind-energy environment, 200 VU $<$ DP $<$ 400 VU for medium wind-energy environment, and DP $>$ 400 VU for high wind-energy environment. DP can also be used to calculate other wind-energy environment evaluation parameters. Vector summation of DP yields the resultant drift potential (RDP) and resultant drift direction (RDD). Additionally, the directional variability index r (r = RDP/DP) indicates wind direction stability, with larger r values indicating more stable wind directions.

2 Results and Analysis

2.1 Wind Conditions

2.1.1 Annual Wind Conditions The average wind speed at the northern and southern ends of the highway is slightly lower than in the middle section, though the overall difference is minimal, indicating stronger wind-sand weather intensity in the desert interior compared to marginal areas (Table). The average sand-driving wind speed along the entire highway ranges from 5.85–6.10 $m \cdot s^{-1}$, with a spatial distribution pattern similar to that of the annual average wind speed. The average sand-driving wind speed in study section A1 is the lowest, while B1 is the highest. Larger sand-driving wind speeds and higher frequencies produce stronger wind-sand forces. From north to south, the prevailing wind direction gradually shifts from northeast to east-southeast across the study sections (Fig. [Figure 3: see original paper]), with the primary wind direction frequency accounting for an average of 17.68% of total sand-driving wind frequency. The frequency of westerly sand-driving winds increases toward the south but remains lower than the primary and secondary wind direction frequencies. The frequency of easterly sand-driving winds accounts for 12.09% of total sand-driving wind frequency. The probability difference of sand-driving winds on the eastern and western sides of the highway is minimal (Fig. [Figure 4: see original paper]), indicating that wind-sand control efforts should focus primarily on the right side of the road.

2.1.2 Seasonal Wind Conditions Seasonally, the sand-driving wind frequency variation trends across the 7 study sections are consistent, with spring and summer significantly higher than autumn and winter, peaking in summer and reaching minimum values in winter. Study sections A1–A7 show slightly lower sand-driving wind frequencies in spring and summer compared to other sections. The seasonal distribution of average wind speed and average sand-driving wind speed follows the order of spring, summer, autumn, and winter, though inter-seasonal variation in average sand-driving wind speed is minimal. The average sand-driving wind frequencies in spring, summer, autumn, and winter account for 37.28%, 40.07%, 18.62%, and 3.93% of the annual total, respectively. The directional distribution of seasonal sand-driving winds shows consistent variation trends across study sections, with easterly winds dominating in spring, summer, and autumn, while westerly sand-driving winds occur mainly in spring, with relatively higher frequencies in areas south of the Mazartag Mountains. This indicates that wind-sand hazards along the Tumshuk-Kunyu Desert Highway concentrate in spring and summer, when sand control structures and road surfaces are prone to burial, significantly affecting the service life of protective measures. Enhanced inspection and timely removal of accumulated sand during spring and summer are essential to minimize traffic disruption.

2.1.3 Monthly Wind Conditions The monthly variation trends of average wind speed and sand-driving wind frequency are consistent across study sections, with minimal monthly variation in average sand-driving wind speed. April-August represents the period with the highest sand-driving wind frequency, while December-February has the lowest. Overall, annual sand-driving wind frequency and average wind speed follow temperature variation trends. Study section B1 shows the highest sand-driving wind frequency in May, exceeding 12% of the annual total, with the maximum average sand-driving wind speed also appearing in May.

2.2 Wind Energy Environment

Drift potential (DP) is typically used to assess regional wind-energy environment intensity, while resultant drift potential (RDP) and resultant drift direction (RDD) determine overall sand transport capacity and direction. The entire highway lies in a low wind-energy environment (Fig. [Figure 8: see original paper]), with DP values at route margins lower than interior sections. RDP ranges from 50.23-72.98 VU, following the same distribution pattern as DP. The directional variability index ranges from 0.3-0.8, indicating medium variability. Study section B1 shows the highest sand-driving wind frequency in May, exceeding 12% of the annual total.

Seasonally, DP and RDP for all study sections concentrate in spring and summer (Table), accounting for 77.35% of annual DP, with winter DP and RDP extremely low. All study sections show spring DP greater than summer DP, while RDP is greater in spring than summer only in sections A1, A2, and A3. Compared with annual RDD, section A1 shows winter RDD oriented eastward (78.69°), deviating significantly from the annual RDD; section A2 shows autumn RDD oriented south-southeast (162.79°), also deviating substantially; sections A3, A4, and A5 show noticeable deviations in summer and autumn RDD; sections A6 and A7 show significant deviations in both summer and autumn RDD. The directional variability for sections A1 (autumn and winter) and A2 (winter) is low, while remaining sections maintain medium variability similar to annual values.

2.3 Dune Movement

Dune migration represents the outcome of wind-sand processes in desert regions. Dune size, density, vegetation coverage, and wind-energy environment vary across study sections, leading to different migration rates and directions. The Tumshuk-Kunyu Desert Highway exhibits distinct differences in dune characteristics north and south of the Mazartag Mountains. The vertical projection areas of dunes in the three northern sections are 20083 m^2, 14268 m^2, and 13503 m^2, respectively, while those in the three southern sections are 4229 m^2, 2119 m^2, and 2317 m^2, respectively. According to established research, dune migration rate shows a significant inverse relationship with vertical projection area—larger projection areas correspond to slower migration rates, and vice versa.

Dune migration rates across the study sections are 1.19 $m \cdot a^{-1}$, 1.45 $m \cdot a^{-1}$, 2.55

m·a^{-1}, 2.83 m·a^{-1}, 3.26 m·a^{-1}, 3.69 m·a^{-1}, and 2.07 m·a^{-1}, respectively, all classified as medium-speed migration (1-5 m·a^{-1}). A significant negative correlation exists between dune migration rate and vertical projection area across all sections (Fig. [Figure 9: see original paper]). Migration rates also correlate closely with RDP magnitude (Fig. [Figure 8: see original paper]). Dune migration directions are 192.52°, 185.44°, 186.28°, 177.80°, 175.43°, 171.76°, and 178.79°, respectively, showing good agreement with RDD (Fig. [Figure 10: see original paper]).

Section A1 exhibits the slowest dune migration due to relatively large dune volumes, high density, presence of low shrub vegetation, and the smallest RDP. Section A2 shows slightly faster migration than A1 due to marginally smaller dune volumes, minimal vegetation, and larger RDP. Section A3 demonstrates the fastest migration among northern sections due to the largest RDP and smaller dune volumes compared to A1 and A2. Southern sections A5, A6, and A7 have lower dune densities and smaller dune heights, with similar RDP values. Section A5, with larger dune volumes than A6 and A7 and some low vegetation, shows slower migration than A6 and A7. Section A7, with the smallest dune volumes, exhibits the fastest migration. The difference between dune migration direction and RDD is slightly larger in section A7 than in A6.

3 Highway Sand Control Zoning and Measures

Analysis reveals that sand-driving winds concentrate in spring and summer, with significant environmental differences between the northern and southern sides of the Mazartag Mountains. The primary wind direction is easterly north of the mountains, while westerly sand-driving wind frequency increases south of the mountains, though westerly transport potential is substantially greater. Therefore, sand control system design must adapt to local conditions.

Based on past sand control experience, local practices typically employ a comprehensive system comprising peripheral high-vertical sand barriers, 1 m$×$1 m straw checkerboard barriers, chemical materials, and biological sand fixation measures for roadbed slope protection. This integrated approach effectively reduces wind-sand flow energy within the protection zone, prevents external sand intrusion, and ensures unobstructed highway traffic.

According to relevant data and considering wind-sand activity characteristics along the entire route, it is recommended to install 3–4 high-vertical sand barriers on the windward side and 1–2 high-vertical sand barriers with 1 m$×1mstrawcheckerboardbarriersontheleewardsidenorthoftheMazartagMountains.Southofthemountains verticalsandbarrierswith1m×1mcheckerboardbarriers(Fig.[Figure11 : seeoriginalpaper]).Thehigh − verticalsandbarriersshouldsatisfyH = 10H–15H, whereHisthebarrierheight.Theminimumcheckerboardbarrierwidthequalstheproductofhighwayde annual dune migration rate). To prevent accidental fires, a 500 m wide firebreak (without checkerboard barriers) should be installed every 3–5 km.

4 Conclusions

1) The annual average wind speed along the highway ranges from 3.03–3.28 $m \cdot s^{-1}$, with annual sand-driving wind speeds of 5.85–6.10 $m \cdot s^{-1}$ and annual sand-driving wind frequencies of 16.87%–21.41%. Overall differences in annual average wind speed, annual average sand-driving wind speed, and annual sand-driving wind frequency among study sections are minimal, with sections at both ends slightly lower than central sections.

2) From north to south, the prevailing wind direction shifts from northeast to east-southeast, with easterly wind frequencies significantly higher than other directions and southerly wind frequencies negligible. Seasonal differences in average wind speed, average sand-driving wind speed, and sand-driving wind frequency are small across sections, but spring and summer frequencies are markedly higher than autumn and winter, with winter showing the lowest values. Spring and summer sand-driving winds account for 77.35% of the annual total, with westerly winds concentrated in spring. Monthly analysis shows sand-driving winds primarily occur in April–August, with December–February having the lowest frequency. Monthly variation trends in average wind speed and average sand-driving wind speed are consistent with monthly sand-driving wind frequency. South of the Mazartag Mountains, westerly wind frequencies are higher than north of the mountains.

3) Drift potential across study sections ranges from 99.77–145.30 VU, indicating a low wind-energy environment. Dune volumes north of the Mazartag Mountains are significantly larger than those south of the mountains. Interior sections show higher dune migration rates than marginal sections. A significant negative correlation exists between dune migration rate and vertical projection area. Dune migration rate correlates closely with RDP magnitude, and migration direction aligns well with RDD.

4) Based on wind-sand activity patterns derived from ERA5 wind speed data and satellite imagery, sand control engineering for the Tumshuk-Kunyu Desert Highway should focus primarily on the eastern side of the road. North of the Mazartag Mountains, protection should target the eastern side, while south of the mountains, where wind-energy environments on both sides are similar, equal protection measures on both eastern and western sides are recommended.

References

[1] Hu Z, Gao X, Zhao Y, et al. Effect of the Mazar Tagh Mountains on aeolian landforms in the western Taklamakan Desert, northwestern China[J]. Geomorphology, 2022, 418: 108464.

[2] Wang Minzhong. The Study of Sandstorm Weather and Surface Heat Climate Characteristics in Taklamakan Desert[D]. Urumqi: Xinjiang Normal Uni-

versity, 2008.

[3] Wang Xunming, Dong Zhibao, Chen Guangting. Characteristics of blown sand environment in middle Taklimakan Desert[J]. Journal of Desert Research, 2001, 21(1): 59-64.

[4] Guo Caiyun, Han Zhiwen, Li Aimin. Research progress of dust storms in the Taklimakan Desert[J]. Journal of Desert Research, 2016, 36(6): 1646-1652.

[5] Zhou Chenglong, Yang Xinghua, Zhong Xinjie, et al. Dust weather in hinterland of the Taklamakan Desert[J]. Arid Zone Research, 2017, 34(2): 324-329.

[6] Zu Ruiping, Zhang Kecun, Qu Jianjun, et al. Study on wind regime characteristics in the Taklimakan Desert[J]. Arid Land Geography, 2005, 28(2): 167-170.

[7] Sun Xiaoyun, Fang Yanjie, Zhao Jingfeng, et al. Spatial and temporal distribution characteristics of sand drift potential in Taklimakan Desert[J]. Arid Land Geography, 2020, 43(1): 38-47.

[8] Sun W, Gao X. Geomorphology of sand dunes in the Taklamakan Desert based on ERA5 reanalysis data[J]. Journal of Arid Environments, 2022, 207: 104848.

[9] Wang Xu, Wang Yun, Chen Baoxin, et al. Spatial and temporal distribution characteristics of intensity and frequency of wind sand disasters in Tarim Basin[J]. Arid Land Geography, 2021, 44(6): 1590-1600.

[10] Xing Wenjuan, Lei Jiaqiang, Wang Haifeng, et al. Analysis on wind regime and wind borne sand potential in a desert oasis ecotone—A case study in Qira County, Xinjiang[J]. Arid Zone Research, 2008, 24(6): 894-898.

[11] Sun Jiaqi. Wind Regime and Drift Potential in the Badain Jaran Desert Based on Observation[D]. Lanzhou: Lanzhou University, 2020.

[12] Yang Xinghua, He Qing, Huo Wen, et al. Study on wind blown sand characteristics at different directions near the surface in the frontier of an oasis desert ecotone in Qira County, Xinjiang[J]. Arid Zone Research, 2012, 29(6): 1100-1104.

[13] Gu Lixia, Lv Ping, Ma Fang, et al. Drift potential characteristics of Mu Us Sandy Land calculated with different data sources[J]. Journal of Desert Research, 2022, 42(5): 54-62.

[14] Feng Jingxue, Ding Zhanliang, You Li, et al. Wind regimes and drift potentials in the corridor of transverse dunefield in western Korqin Sandy Land[J]. Journal of Desert Research, 2022, 42(4): 110-119.

[15] Yang Junhuai. Study on Dune Movement in Taklimakan Desert[D]. Xi' an: Shaanxi Normal University, 2019.

[16] Li Aimin, Han Zhiwen. Relationship between moving speed and morphological parameters of barchan dunes[J]. Journal of Desert Research, 2020, 40(1): 29-40.

[17] Yang Junhuai, Dong Zhibao, Liu Zhengyao, et al. Aeolian geomorphology and dune migration in the Quruq Desert, China[J]. Journal of Desert Research, 2019, 39(4): 1-8.

[18] Miao Henglu, Wang Jian, Zhang Ruiqiang, et al. Characteristics of wind regime and drift potential of the desert steppe in northern slope of Yinshan Mountains, Inner Mongolia[J]. Journal of Arid Land Resources and Environment, 2022, 36(4): 102-110.

[19] Liu Yusheng. The Study on the Law of Barchan Dunes Movement in the Gobi Area in Northern Alxa[D]. Hohhot: Inner Mongolia Agricultural University, 2018.

[20] Wang Jingpu, Liu Lianyou, Shen Lingling. Research of the barchan dunes movement in the Mu Us Sandy Land on Google Earth software[J]. Remote Sensing Technology and Application, 2013, 28(6): 1094-1100.

[21] Cui Kejun, Li Shengyu, Fan Jinglong, et al. Aeolian sand activity characteristics of wind erosion and desertification in the grassland area of central Mongolia: A case of Choir City[J]. Arid Land Geography, 2022, 45(3): 792-801.

[22] Zhang Kecun, An Zhishan, He Mingzhu, et al. Aeolian sand environments and disaster prevention along Zhongwei section of the Wuhai-Maqin highway[J]. Arid Land Geography, 2021, 44(4): 983-991.

[23] Ma Benteng, Cheng Jianjun, Lei Jiaqiang, et al. Wind-blown sand transport law and control system of wind desert highway of South Xinjiang Tazhong Corp[J]. Arid Zone Research, 2022, 39(5): 1663-1672.

[24] He Chenchen, Wu Yingying, Tian Yongsheng, et al. Variation characteristics of width-height ratio and migration speed of barchans at the margin of Minqin oasis[J]. Arid Zone Research, 2023, 40(2): 280-291.

[25] Xie Shengbo, Qu Jianjun, Lai Yuanming, et al. The causes, distributions, characteristics of sand hazards and its controls for Lhasa-Shigatse railway[J]. Journal of Arid Land Resources and Environment, 2016, 30(2): 170-175.

[26] Zhang Kecun, An Zhishan, He Mingzhu, et al. Progress of research on wind-blown sand prevention and control along highways in China[J]. Journal of Desert Research, 2022, 42(3): 222-232.

[27] Zhang Yunfeng, Ma Yijuan, Su Zhizhu, et al. Dune movement in the joint zone of the Badain Jaran Desert and Tengger Desert[J]. Journal of Desert Research, 2022, 42(5): 82-91.

[28] Dong Z, Chen G, He X, et al. Controlling blown sand along the highway crossing the Taklimakan Desert[J]. Journal of Arid Environments, 2002, 57(3): 329-344.

[29] Li Jinrong, Wang Jian, Wang Ru, et al. Monitoring and influencing factors of dune movement speed along the Yellow River using UAV technology[J].

Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(19): 57-64.

[30] Li Jianjun, Jiao Juying, Cao Xue, et al. Spatial regionalization and response to morphological parameters of dune migration in the Qaidam Basin of China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(7): 309-314.

[31] Saidoula Saiyare, Mao Donglei, Xu Jiarui, et al. Characteristics of wind conditions and dune movement rules on the west edge of Kumtag Desert, China[J]. Journal of Soil and Water Conservation, 2021, 35(6): 62-68.

[32] Chen Fang, Liu Yong. Secular annual movement of sand dunes in Badain Jaran Desert based on geographic analyses of remotely sensed imagery[J]. Remote Sensing Technology and Application, 2011, 26(4): 501-507.

[33] Xi Cheng, Zuo Hejun, Wang Haibing, et al. Wind proof and sand blocking characteristics of high vertical nylon mesh sand barrier and its rational allocation[J]. Arid Zone Research, 2021, 38(3): 882-891.

[34] Ding Lusheng, Cheng Jianjun, Chen Boyu, et al. Field test and numerical simulation of windbreak and sand resisting on high parallel reed sand barriers along railway[J]. Bulletin of Soil and Water Conservation, 2019, 39(3): 156-162.

[35] Fryberger S, Dean G. Dune forms and wind regime[C]//Mckee E D. A Study of Global Sand Seas. Washington: United States Government Printing Office, 1979: 137-169.

[36] Zhu Zhenda. Aeolian Geomorphology of Taklimakan Desert[M]. Beijing: Science Press, 1981.

[37] Li Shengyu, Lei Jiaqiang, Xu Xinwen, et al. Study on the effects of the Tarim desert highway on the process of blown sand movement near the ground surface[J]. Arid Zone Research, 2007, 24(2): 247-254.

[38] Wang Zhenqing. Prevention and Control of Highway Sand Damage in China[M]. Shenyang: Liaoning University Publishing House, 2000.

[39] Jia Guangpu. Morphological Characteristics and Dynamic Evolution Process of Crescent-shaped Sand Dunes in the Alashan Gobi Region[D]. Hohhot: Inner Mongolia Agricultural University, 2022.

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