Current Status and Causes of Wind-Blown Sand Hazards along the Circum-Taklimakan Railway and an Optimized Configuration Model for Protection Systems in Characteristic Wind-Sand Zones

2026-06-18

ChinaRxiv

Abstract

The Taklimakan Desert Ring Railway (hereinafter referred to as the Ring Railway) is an economic artery and livelihood link connecting southern Xinjiang, China, and is of great significance for promoting the Belt and Road Initiative and national defense security, while wind-blown sand hazards are the main challenge threatening its safe operation. By comprehensively applying UAV mapping technology and meteorological data analysis, this study systematically evaluated the current status of wind-blown sand hazards along the Ring Railway, revealed the causes of sand damage, and proposed optimized configuration patterns for protection systems in typical sections affected by wind-blown sand hazards. The results show that: (1) The existing sand-control system of the Ring Railway generally performs well, but some sections still face wind-blown sand threats. Among them, the tall dune section from Washixia to Qiemo of the Hotan–Ruoqiang Railway, the mobile dune section west of Minfeng County, and the dry riverbed section in the lower reaches of the Tarim River along the Golmud–Korla Railway have relatively high potential wind-blown sand hazards. (2) The areas along the railway are generally characterized by a low wind-energy environment, with annual sand transport ranging from 0.21 to 8.34 m3•m-1. High wind-energy and strong sand-transport areas are mainly distributed in the open eastern part of the basin, which is the section where wind-blown sand threats to the railway are most concentrated. (3) The Ring Railway currently mainly adopts reed materials to construct an engineering sand-control system centered on "blocking and fixation,"with generally good control effects. However, in local sections with severe sand damage, existing measures still need further optimization and upgrading to enhance their long-term protective capacity.

Full Text

DOI:10.13866/j.azr.2026.04.15
CSTR:32277.14.AZR.20260415

Current Status and Causes of Wind-Blown Sand Hazards along the Circum-Taklimakan Railway and an Optimized Configuration Model for Protection Systems in Characteristic Wind-Sand Zones

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Abstract: The Circum-Taklimakan Desert Railway, abbreviated as the Circum-Taklimakan Railway, is an economic artery and a livelihood link connecting southern Xinjiang, China. It is of great significance for promoting the construction of the "Belt and Road" and for national defense security, while wind-blown sand hazards constitute the main challenge threatening its safe operation. By comprehensively applying UAV surveying and mapping technology and meteorological-data analysis, this study systematically assessed the current status of wind-blown sand hazards along the Circum-Taklimakan Railway, revealed the causes of sand damage, and proposed an optimized configuration model for protection systems for typical sections affected by wind-blown sand hazards. The results show that: (1) The existing sand-control system of the Circum-Taklimakan Railway generally performs well, but some sections still face wind-blown sand threats. Among them, the Washixia–Qiemo high-dune section of the Hotan–Ruoqiang Railway, the mobile-dune section west of Minfeng County, and the dry riverbed section in the lower reaches of the Tarim River along the Golmud–Korla Railway have relatively high potential wind-blown sand hazards. (2) The railway corridor as a whole lies in a low-wind-energy environment, with annual sand transport ranging from 0.21 to 8.34 $m^3 \cdot m^{-1}$. Areas with high wind energy and strong sand transport are mainly distributed in the open terrain on the eastern side of the basin, which is the section where wind-blown sand threats to the railway are most concentrated. (3) At present, the Circum-Taklimakan Railway mainly uses reed materials to construct an engineering sand-control system centered on "blocking and fixation," and the overall control effect is good. However, in local sections with severe sand damage, the existing measures still need further optimization and upgrading to enhance their sustained protective capacity.

Keywords: Circum-Taklimakan Railway; wind-blown sand hazard; protection system; Taklimakan Desert

China has the longest operating mileage of railways affected by wind-blown sand in the world. By the end of 2023, China' s total railway mileage had reached 1.59×10^5 km[1]. With the deepening implementation of the "Belt and Road" initiative, and in order to strengthen railway connectivity among important node cities in sandy regions, some lines have continued to extend into desert and Gobi areas[2]. At present, the mileage of railways affected by wind-blown sand hazards is approximately 1.5×10^4 km[3]. Against the background of global climate change, frequent extreme sand-and-dust weather events have caused some sections to face severe wind-blown sand threats, placing higher demands on railway wind-blown sand prevention and control.

Railway wind-blown sand hazards are mainly manifested in two forms: wind erosion and sand burial[3]. Under strong winds, sand particles not only directly erode the subgrade, but also settle when wind-sand flow is obstructed by the railway line, burying the track and seriously threatening railway traffic safety.

To address sand hazards, China has, through decades of technological accumulation and protective-engineering practice, gradually established a globally leading system for the prevention and control of wind-blown sand along desert railways. In terms of prevention-and-control models, from the "five belts as one" sand-control protection system established on China' s first desert railway—the Baotou-Lanzhou Railway[4]—to the "seven belts as one" integrated protection system developed for the Hotan-Ruoqiang Railway[5], China has successfully achieved the key objective of preventing sand hazards from reaching the track during the construction period, thereby strongly ensuring railway construction and safe operation. For different types of sand-hazard sections, the Qinghai-Tibet Railway has formulated prevention-and-control strategies suited to local conditions: in dune-type sand-hazard sections, it adopts an integrated control approach of "primarily blocking and fixation, blocking at a distance and fixation nearby, with transport guidance as an auxiliary measure" [6]; in valley-type sand-hazard sections, it follows the principle of "blocking sand on bank slopes and fixing sand on bank surfaces," constructing a protection system that combines engineering and biological measures[7]; and for seasonal dry-lake-basin sand-hazard sections, it has formed an integrated protection system incorporating sand blocking, sand fixation, sand pressing, and enclosure for rehabilitation[8]. In addition, in strong-wind and exceptionally strong-wind areas, the Lanzhou-Xinjiang High-Speed Railway uses a composite structure consisting of three rows of frontal sand-blocking belts combined with high, upright, large-grid sand-fixing belts, further optimizing the wind-blown sand protection method for high-speed railways[9]. Through continuous optimization and innovation of prevention-and-control models, China' s capacity for railway wind-blown sand prevention and control has steadily improved, providing reliable support for safe railway operation.

The Circum-Taklimakan Desert Railway, or Circum-Taklimakan Railway, is the world' s first railway loop encircling a desert. It is jointly composed of the Ruoqiang-Korla section of the Golmud-Korla Railway, the Hotan-Ruoqiang Railway, the Kashgar-Hotan Railway, and the Korla-Kashgar section of the Southern Xinjiang Railway, together constituting the full

Date received: 2025-09-10; **date revised:** 2025-11-13
Funding projects: Third Xinjiang Scientific Expedition Program (2021xjkk0305); National Natural Science Foundation of China (42171015); Youth Interdisciplinary Innovation Team Project of the Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands (E4500125)
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The total line length is 2,712 km. In June 2022, with the opening of the Hotan-Ruoqiang Railway, the Taklimakan Desert Ring Railway, which had taken 26 years to build, was fully connected. The completion of this railway is of major strategic significance for promoting regional economic development, strengthening ethnic unity, and serving the construction of the "Belt and Road." The Taklimakan Desert Ring Railway extends along the margin of the Taklimakan Desert, covers a broad area, and the areas along the route are dominated by desert and Gobi landforms, with intense aeolian-sand activity[10–11]. The special geographical environment has led to diverse forms of railway wind-sand hazards; moreover, because regional wind conditions and sand-source conditions differ markedly, the degree of wind-sand hazard also varies significantly among different sections. These factors not only seriously threaten the safe operation of the railway, but also substantially increase the difficulty and cost of maintenance[12]. In recent years, with the rapid development of technologies such as satellite remote sensing, UAV monitoring, and geographic information systems, large-scale analytical methods have been widely applied in railway route selection[13–15] and wind-sand hazard risk assessment[16]. In particular, UAV surveying and mapping technology[17], owing to its efficiency and flexibility, is gradually becoming an important means of investigating the current status of wind-sand hazards. Therefore, in view of the special geographical location and important function of the Taklimakan Desert Ring Railway, conducting in-depth research in this region on the current status of wind-sand hazards, systematically revealing the formation mechanisms of such hazards, and exploring scientific engineering prevention and control approaches are of important theoretical value and practical significance. Based on comprehensive and systematic field investigations, this study aims to clarify the types, intensity, and causes of wind-sand hazards along the Taklimakan Desert Ring Railway, and to propose optimized configuration modes for protection systems in typical sections affected by wind-sand hazards, with the expectation of providing a theoretical basis for the scientific prevention and control of wind-sand hazards along this railway, as well as a reference for wind-sand control practices in major engineering projects in the Tarim Basin and similar regions.

1 Overview of the Study Area and Data Sources

1.1 Overview of the Study Area

The Taklimakan Desert Ring Railway (Fig. 1) is located in the extremely arid zone along the margin of the Taklimakan Desert and faces extremely severe potential wind-sand hazards[18]. The Taklimakan Desert is the largest mobile desert in China and the second largest in the world, extending approximately 1,000 km from east to west and about 400 km from north to south, with a total area of approximately 3.3×10^5 km^2. The region has a warm-temperate, extremely arid climate, with mean annual precipitation of less than 100 mm, while evaporation reaches as high as 2,500–3,400 mm[19]. Sand sources on the desert surface are extremely abundant, and under the influence of distinctive wind-gap terrain, aeolian-sand activity is frequent and intense[20]. Along the railway, multiple geomorphic types are distributed, including desert, Gobi, mud desert, and salt desert[21], causing wind-sand hazards to exhibit clear regional differences in space.

1.2 Data Sources and Processing

Data on sand accumulation in the protection systems were based on field aerial survey results from 49 typical sand-control systems along the Taklimakan Desert Ring Railway in May 2023. Topographic data were collected using a DJI UAV (DJI Mavic3E), and DJI Terra software was used to generate centimeter-level digital surface models, orthophotos, and three-dimensional models. On this basis, with the aid of ArcGIS software, elevation information for the sand-accumulation areas within the sand-control systems on both sides of the railway was extracted along directions perpendicular to the sand-control systems[22]. For each sand-control system, three sand-accumulation cross sections were selected, and their mean value was used to represent the sand-accumulation amount at that site, thereby obtaining sand-accumulation data for the overall system.

Wind-condition data were obtained from 16 meteorological stations deployed along the route (Fig. 1), and were used to monitor changes in wind speed and wind direction along the railway. Along the Golmud–Korla Railway, two-dimensional ultrasonic wind-speed and wind-direction sensors were used; the sensors were installed at heights of 2 m, 6 m, and 10 m, respectively, the data logger model was CR300, and the sampling frequency was 1 min. Along the Hotan–Ruoqiang Railway and the Kashgar–Hotan Railway, HOBO wind-speed and wind-direction instruments manufactured by Onset, USA, were used; the sensor height was 2 m, the data logger model was H21-USB, and sampling data at a 1 min frequency were recorded once every 10 min. The data period was mainly selected as May 2022 to May 2023; owing to limitations of field conditions, data from some stations

Visible map labels and legend in Fig. 1: Kashgar, Aksu, Korla, Ruoqiang, Hotan; Kashgar–Hotan Railway, Southern Xinjiang Railway, Golmud–Korla Railway, Hotan–Ruoqiang Railway; Legend: city, railway, meteorological station, sand collector, Gobi, desert; scale: 0–100 km.

Note: The desert and Gobi data[21] were obtained from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn).

Fig. 1 Schematic map of the geographical setting and distribution of research stations along the Taklimakan Desert Ring Railway.

there were missing data; therefore, other time periods were used instead (for the Golmud–Korla Railway, DK987 used July 2021–July 2022, and DK1128 used August 2021–August 2022; for the Kashgar–Hotan Railway, K1757, K1840, and K1888 used May 2023–May 2024).

Sand-transport potential was calculated using the formula proposed by Fryberger et al.[23]:

$$DP = V^2(V - V_t)t \tag{1}$$

where DP is the sand-transport potential, in vector units (VU); V is the measured wind speed exceeding the threshold sand-moving wind speed, in knots; V_t is the threshold sand-moving wind speed (knot); and t is the frequency of sand-moving winds (%). The relevant parameter settings refer to the original literature[23] and existing research results for the study area[24-25]. To facilitate interregional comparison, wind-speed data at a height of 10 m were used uniformly. The 2 m wind-speed data for the Hotan–Ruoqiang Railway and the Kashgar–Hotan Railway were converted to values at 10 m height using the following formula[25-26], while wind-direction data remained unchanged.

$$U_{10} = \frac{U_2(\ln 10 - \ln z_0)}{\ln 2 - \ln z_0} \tag{2}$$

where U_{10} and U_2 are the wind speeds at heights of 10 m and 2 m, respectively; z_0 is the surface roughness, taken as 5.4×10^{-5} m for desert areas[27] and 3.2×10^{-3} m for Gobi areas[28]. In combination with existing studies in the Taklimakan Desert region, the threshold sand-moving wind speed at 10 m height was set to 6 $\text{m} \cdot \text{s}^{-1}$[29-30].

The sand-transport data came from 14 sets of eight-direction sand collectors installed along the line (Fig. 1). Their inlet dimensions were 1 m (height) ×0.02 m (width) or 0.6 m (height) ×0.02 m (width). The sand-transport amount was the annual cumulative total in all directions, with a collection duration of 1 a. The locations of the observation points and their underlying surface types are shown in Table 1.

Table 1 Mileage locations of sand collectors and underlying surface types

Railway mileage of sand-collector site	Underlying surface type
GKDK840	Saline desert
GKDK890	Mud desert
GKDK905	Mud desert
GKDK910	Mud desert
GKDK966	Mud desert
GKDK987	Mud desert
GKDK1072	Sandy desert
HRDK54	Gobi
HRDK308	Sandy desert
HRDK598	Gobi

Railway mileage of sand-collector site	Underlying surface type
HRDK734	Gobi
KHK1754	Gobi
KHK1837	Gobi
KHK1888	Gobi

Note: GK represents the Golmud–Korla Railway, HR represents the Hotan–Ruoqiang Railway, and KH represents the Kashgar–Hotan Railway. The same applies below.

In studies of vegetation distribution, a variety of vegetation indices have been widely applied[31], among which the normalized difference vegetation index (NDVI) is the most common. The 2022 NDVI data for the Tarim Basin used in this study were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn/)[32]. This dataset is based on MODIS 16 d composite NDVI products with a resolution of 250 m, generated using the maximum-value composite method, and ultimately forms 2022 vegetation-index raster data at 250 m $\times$ 250 m. The data values range from -2000 to 10000 (for integerization, the NDVI values were multiplied by 10000).

2 Current Status of Wind-Sand Hazards

According to UAV aerial survey results, the railway subgrade around the Tarim Basin was generally subject to relatively light sand accumulation, and wind-blown sand deposition was mainly concentrated within the sand-control system. The accumulated sand volume per unit width of the sand-control system sections was 0.7–53.5 $m^3 \cdot m^{-1}$ (Fig. 2), indicating that the wind-sand protection system had an obvious sand-blocking effect. Among all monitoring sections, there were 5 high-risk sand-accumulation sections (system sand accumulation $\geq$ 20 $m^3 \cdot m^{-1}$): DK125, DK586, DK136, and DK54 on the Hotan–Ruoqiang Railway, and DK890 on the Golmud–Korla Railway. Their corresponding sand-accumulation amounts were 53.5 $m^3 \cdot m^{-1}$, 29.1 $m^3 \cdot m^{-1}$, 26.5 $m^3 \cdot m^{-1}$, 21.5 $m^3 \cdot m^{-1}$, and 24.8 $m^3 \cdot m^{-1}$, respectively. These sections are mainly distributed in the high dune area from Washixia to Qiemo along the Hotan–Ruoqiang Railway, the mobile dune area west of Minfeng County, and the dry riverbed section in the lower reaches of the Tarim River along the Golmud–Korla Railway.

There were 11 medium-risk sand-accumulation sections (system sand accumulation between 10 and 20 $m^3 \cdot m^{-1}$), including DK1072+300, DK1072+400, DK1072+700, DK840+63, DK839+600, DK840+440, DK910, and DK987 on the Golmud–Korla Railway, as well as K1707+640, K1890+225, and K1754+697 on the Kashgar–Hotan Railway. The medium-risk sections of the Golmud–Korla Railway are mainly located in mobile dunes at the oasis margin, the dry lake-basin area of Taitema Lake, and dry riverbed sections in the lower reaches of the Tarim River. The medium-risk sections of the Kashgar–Hotan Railway are concentrated at the termini of river alluvial fans.

Among the low-risk sand-accumulation sections (system sand accumulation ≤ 10 $m^3 \cdot m^{-1}$), 12 sections ranged from 5 to 10 $m^3 \cdot m^{-1}$, and 22 sections were less than 5 $m^3 \cdot m^{-1}$. About 70% of the monitoring sections had system sand accumulation below 10 $m^3 \cdot m^{-1}$, indicating that the degree of sand accumulation along most sections of the railway around the Tarim Basin was relatively light. In terms of spatial distribution, system sand accumulation was mainly concentrated along the eastern and southern margins of the Taklimakan Desert, with less sand accumulation on the western and northern sides, showing an overall pattern of pronounced spatial differentiation.

3 Causal Analysis of Wind–Sand Hazards

3.1 Sand Sources

The sand-source characteristics of the high-risk sand-accumulation sections of the railway around the Tarim Basin are as follows: around the Washixia section of the Hotan–Ruoqiang Railway, extensive mobile dunes are distributed, among which the tall dunes can reach heights of 28 m, and dune advance provides this area with ···

Note: GK denotes the Golmud–Korla Railway, HR denotes the Hotan–Ruoqiang Railway, and KH denotes the Kashgar–Hotan Railway.

Fig. 2 Spatial distribution of sediment deposition in cross-sections of the sand-control systems of the Taklimakan Desert Ring Railway

provided a continuous replenishment of sand sources. In the mud-desert section of the lower reaches of the Tarim River along the Golmud–Korla Railway (represented by chainage DK890), the sand source mainly comes from mobile dunes on the mud-desert surface, and the source material is abundant. In addition, under the action of seasonally strong winds, the mud-desert surface in interdune areas undergoes wind erosion and sand entrainment, constituting another important source of sand and dust in this region.

Among the medium-risk sand-accumulation sections, the area from the 33rd Regiment to the 34th Regiment along the Golmud–Korla Railway (represented by chainages DK987 and DK1072) is jointly affected by mobile dunes at the oasis margin and by activation of topsoil caused by cultivation of surrounding farmland, so the sand source is relatively abundant. The dried-lake-basin section of Taitema Lake (represented by chainage DK840) takes the extensive dried lake basin as its main sand source [24]. Along the Kashgar–Hotan Railway, the sand source from Moyu to Zanggui (represented by chainage K1890) is dominated by mobile dunes; the section from Pishan to Yecheng (represented by chainages K1707 and K1754) is mainly affected by deposits of piedmont alluvial–diluvial fans, forming sand-source conditions dominated by alluvial sand.

3.2 Wind-Dynamic Environment

3.2.1 Sand-driving winds

The annual mean wind speed along the Taklimakan Desert Ring Railway is $2.06 \sim 5.11$ m $\cdot$ s^{-1} (Table 2), among which the wind speed is relatively high from Ruoqiang to Taitema Lake. The sand-driving wind frequency along the line ranges from 4.2% to 24%; high-value areas mainly occur from DK917 to DK840 on the Golmud–Korla Railway, near DK598 on the Hotan–Ruoqiang Railway, and in the Pishan–Yecheng section of the Kashgar–Hotan Railway.

Table 2 Average wind speed and sand-driving wind regime along the Taklimakan Desert Ring Railway

Chainage	Annual mean wind speed /(m $\cdot$ s^{-1})	Sand-driving wind frequency /%	Principal direction(s) of sand-driving winds
GKDK840	5.11	24	NE
GKDK883	4.07	19.7	ENE, NE
GKDK901	3.34	15.9	NE, ENE
GKDK917	3.15	14.8	ENE, NE
GKDK951	2.98	12.4	ENE, NE
GKDK987	3.41	9.6	E, ESE, ENE
GKDK1072	2.83	7.6	E, ESE, ENE, NW
GKDK1128	2.06	4.2	E, NNW, NW
HRDK54	3.05	11.7	NE, ENE
HRDK125	2.91	11.7	E, ENE
HRDK308	2.58	8	ENE, NE, SW
HRDK598	4.11	15.5	SSW, SW, S, N
HRDK734	3.43	11.3	WNW, NW
KHK1757	4.17	18.6	WNW, W, WSW, SW
KHK1840	3.46	12.1	W, WSW, WNW, ENE
KHK1888	3.28	12	WNW, W, NW

Affected by regional topography, the spatial distribution of sand-driving wind directions along the Ring Railway differs markedly (Table 2). From Ruoqiang to Korla along the Golmud–Korla Railway, the principal sand-driving wind directions are NE, ENE, and E. Around the dried lake basin of Taitema Lake (DK840 and DK883), ENE and NE dominate. As the line extends toward Korla, the sand-driving winds gradually deflect toward the east and southeast; at the margins of the 33rd Regiment and the Yuli oasis (DK1072 and DK1128), the principal sand-driving wind directions shift to E and ESE, accompanied by secondary NW or NNW winds. Along the Hotan–Ruoqiang Railway (from east to west), the principal sand-driving wind directions change from NE and ENE to SSW and WNW. Specifically, near Washixia (DK54 and DK125), NE, ENE, and E dominate; in the Qiemo section (DK308), ENE and NE dominate, with secondary SW winds; in the Yutian section (DK598), the principal directions are SSW, SW, and S, with secondary N winds; and in the Cele section (DK734), WNW and NW dominate. Along the Kashgar–Hotan Railway, the principal sand-driving wind directions are WNW, W, and WSW. Among them, at K1757, WNW, W, WSW, and SW dominate; at K1840, W, WSW, and WNW dominate, with secondary ENE winds; and at K1888, WNW, W, and NW dominate.

3.2.2 Sand-transport potential

The annual sand-transport potential along the Taklimakan Desert Ring Railway ranges from 41.1 to 1016.2 VU (Fig. 3), and overall it is characterized by a low-wind-energy environment (< 200 VU)

Fig. 3 Spatial distribution map of annual drift potential along the Taklimakan Desert Ring Railway and drift-potential rose diagram

···predominates, and the high-wind-energy environment (> 400 VU) is mainly distributed along the Ruoqiang-DK883 section of the Golmud–Korla Railway on the eastern side of the basin.

The annual drift potential along the Ruoqiang-Korla section of the Golmud–Korla Railway ranges from 41.1 to 1016.2 VU and can be divided into three wind-energy zones: the high-wind-energy environment ($DP > 400$ VU) is concentrated in and around the dry basin of Taitema Lake (DK840–DK883); the medium-wind-energy environment ($200 \leq DP \leq 400$ VU) is mainly distributed near DK901; and the low-wind-energy environment ($DP < 200$ VU) is widely distributed from DK917 to the oasis margin of Yuli County (Fig. 3). The spatial differentiation of wind-regime types in this section is evident: the area around Taitema Lake is characterized by a narrow unimodal wind regime, which gradually changes toward the Thirty-Third Regiment and the margin of the Yuli oasis into an obtuse bimodal wind regime.

The annual drift potential along the Hotan–Ruoqiang Railway ranges from 70.3 to 264.1 VU. Except for DK54 and DK598, which belong to the medium-wind-energy environment, all other sections are low-wind-energy environments (Fig. 3). The wind-regime type varies along the route: the Ruoqiang–Qiemo section is characterized by a narrow unimodal wind regime, the Minfeng–Yutian section changes to an obtuse bimodal wind regime, and the area near Cele changes again to a narrow unimodal wind regime.

The annual drift potentials along the Kashgar–Hotan Railway are 185.0 VU, 169.3 VU, and 232.6 VU, respectively. Among them, K1888 belongs to the medium-wind-energy environment, while the others belong to the low-wind-energy environment (Fig. 3). Specifically, the wind-regime characteristics are as follows: K1757 has a broad unimodal wind regime, with the drift potential from the WNW, W, WSW, and SW directions accounting for 84.5% of the total drift potential; K1840 has an obtuse bimodal wind regime, with the drift potential from the W, WSW, and WNW directions accounting for 62.2%, and that from the ENE direction accounting for 14.3%; K1888 has a broad unimodal wind regime, with the drift potential from the WNW, W, and NW directions together accounting for 84.3%.

3.3 Sand transport volume

During June 2022–May 2023, the sand transport volume along the Golmud-Korla Railway ranged from 0.24 to 1.63 $m^3 \cdot m^{-1}$ (Fig. 4). The maximum sand transport volume occurred in the DK890 section, which belongs to dry riverbed and floodplain landforms. The ground surface there is hard and flat, vegetation is sparse, and only a small number of shrubs are distributed. Upwind, mobile dunes and semi-fixed shrub dunes are widely developed; the ground surface is subject to strong wind erosion and readily forms wind-sand flows, resulting in a significant sand transport volume. The next highest occurs in the oasis-margin area of the Thirty-Third Regiment. This section is a mobile-dune area with abundant sand sources; the sand material is mainly fine sand and very fine sand, which is readily transported by wind

Fig. 4 Spatial distribution map of sand transport volume along the Taklimakan Desert Ring Railway and the eight-direction sand transport volume map

Fig. 5 Spatial distribution map of NDVI along the Taklimakan Desert Ring Railway

This produces relatively strong wind–sand activity.

During June 2022–May 2023, the sand-transport quantity along the Hotan-Ruoqiang Railway ranged from 0.29 to 8.34 $m^3 \cdot m^{-1}$ (Fig. 4). Among the monitored sections, DK308, DK598, and DK734 had relatively low sand-transport quantities, at 0.48 $m^3 \cdot m^{-1}$, 0.30 $m^3 \cdot m^{-1}$, and 0.29 $m^3 \cdot m^{-1}$, respectively. The maximum occurred at DK54 in the Ruoqiang–Washixia section. There, the ground surface is sandy-gravel gobi, with a gravel cover of 20%; the matrix is dominated by very fine sand and silt/clay. With abundant sand sources and strong winds, the annual sand-transport quantity reached 8.34 $m^3 \cdot m^{-1}$. In terms of sand-transport direction, DK54 and DK308 were both dominated by NE and E, accounting for 87.3% and 72.1% of the total sand-transport quantity, respectively; DK598 was dominated by SW, W, and NE, which together accounted for 72.6%; and the sand-transport directions at DK734 were concentrated in W and NW, together accounting for 73.8%.

During November 2023–October 2024, the sand-transport quantity along the

Kashgar-Hotan Railway ranged from 0.21 to 2.2 $m^3 \cdot m^{-1}$ (Fig. 4). The sand-transport quantities at K1754, K1837, and K1888 were 1.2 $m^3 \cdot m^{-1}$, 2.2 $m^3 \cdot m^{-1}$, and 0.21 $m^3 \cdot m^{-1}$, respectively. At K1754, the sand-transport directions were mainly W and NW, accounting for 42.3% and 34.3% of the total sand-transport quantity, respectively; at K1837, the main directions were W and SW, accounting for 44.9% and 16.5%, respectively; and at K1888, W was dominant, accounting for 57.3% of the total sand-transport quantity.

3.4 Vegetation Coverage

Vegetation can effectively inhibit aeolian sand transport[33] and reduce the degree of damage caused by wind-sand flow to railway engineering works[34-35]. Constrained by natural conditions such as an arid climate and low soil organic matter content, vegetation along the Taklimakan Desert Ring Railway is dominated by xerophytic species, and the overall coverage is low. NDVI data show (Fig. 5) that vegetation is mainly distributed in oasis areas along the basin margin. Coverage is relatively dense on the western and northern sides, where the corresponding railway sections suffer lighter wind-sand hazards; by contrast, vegetation is sparse on the eastern and southern sides, which have become concentrated occurrence zones for different grades of sand damage along the Taklimakan Desert Ring Railway. Specifically, oases are widely distributed around the Korla-Kashgar section of the Southern Xinjiang Railway; the section as a whole lies in the desert-gobi transition belt, and after long-term control and protection[36-37], railway sand hazards have been effectively controlled. The Kashgar-Yecheng section of the Kashgar-Hotan Railway benefits from the buffering effect of oases, and in 90% of the section the sand accumulation in the system is less than 10 $m^3 \cdot m^{-1}$, making it a low-risk sand-accumulation zone. However, the Yecheng-Pishan section has relatively little vegetation cover, and the influence of wind-sand hazards is comparatively pronounced. The Ruoqiang-Korla section of the Golmud-Korla Railway and the Hotan-Ruoqiang Railway traverse the desert margin, where vegetation is sparse and wind-sand hazards are likewise relatively prominent.

3.5 Human Activities

Human activities have a dual influence on wind-sand hazards. On the one hand, sand-control and desertification-control projects can effectively suppress desert expansion and slow the process of land desertification, thereby reducing the harm of wind-sand to railways[38]. On the other hand, disturbance of the ground surface caused by human development activities cannot be ignored. Agricultural reclamation and engineering construction along oasis margins intensify the release of surface dust and sand. In particular, in hard-surface areas such as saline deserts and mud deserts, engineering activities destroy natural crusts and significantly enhance dust emission[39-40]. In addition, during construction, repeated compaction of the ground by large construction machinery activates originally stable surfaces, further increasing the risk of dust and sand release. As development in the Taklimakan Desert region continues to advance, construction activities for facilities such as wind power and photovoltaic projects themselves generate new anthropogenic sand sources in situ, thereby potentially exacerbating the occurrence of regional wind-sand hazards.

4 Optimized Configuration Model for the Protection System in Characteristic Wind-Sand Zones of the Taklimakan Desert Ring Railway

Because the various sections of the Taklimakan Desert Ring Railway were constructed in different periods, the configuration modes of their protection systems differ markedly. The Korla-Kashgar section of the Southern Xinjiang Railway has undergone more than 20 years of protection practice; vegetation coverage has increased significantly, surface stability has been enhanced, and the protection effect is good[36-37]. The Kashgar-Hotan Railway adopts a road···

Body protection measures combined with planar protection measures such as high vertical sand barriers and reed-checkerboard sand barriers have effectively ensured the safety of railway operations [41]. On the Golmud-Korla Railway, mechanical sand-control measures using reed as the principal material have been widely adopted, and existing studies [42-43] have demonstrated the effectiveness and applicability of these protection measures. The newly built Hotan-Ruoqiang Railway integrates engineering and biological measures [5], providing longer-term protective benefits. Along the Tarim Basin railway loop, sand-source types, wind-dynamic environments, and vegetation distribution all exhibit pronounced spatial heterogeneity; therefore, the configuration of the protection system should follow the principle of "adapting measures to local conditions and designing defenses according to the hazard." In particular, in the southeastern section of the railway, the constricted-tube effect increases wind speed, making aeolian sand disasters especially severe. Based on the aeolian sand environmental characteristics of this region and practical experience with existing sand-control systems, this paper proposes the following recommendations for optimizing the configuration of the protection system.

4.1 Configuration of the Aeolian Sand Protection System in Gobi Sections

Gobi is one of the main desert types in the Tarim Basin and is widely distributed across piedmont alluvial-proluvial plains. The southeastern section of the Tarim Basin railway loop lies in a high-wind-energy environment; when sand-laden airflow is obstructed and deposits, sand damage to the railway in this section becomes prominent. For aeolian sand disasters in Gobi areas, the prevention and control principle of "blocking as the main measure, with blocking and fixation combined" should be followed. Effective sand-blocking measures should intercept through-flowing sand-laden wind, while sand-fixation measures between the subgrade and the sand-blocking belt should suppress local sand entrainment. In sections with severe aeolian sand disasters, the following protection configuration is recommended: on the windward side, at 40–70 m outside the foot of the subgrade slope, install a 24 m-wide medium-height vertical reed-bundle large-grid sand barrier system (6 groups; 4 m × 4 m × 0.8 m); outside this sand barrier, at intervals of 30–40 m, install three rows of high vertical HDPE sand barriers, 2 m high, with porosity controlled at 40%–50% [44]. On the leeward side, at 40–70 m outside the foot of the subgrade slope, install a 16 m-wide medium-height vertical reed-bundle large-grid sand barrier system of the same specification (4 groups); 30–40 m outside it, install one row of high vertical HDPE sand barriers, with the same height and porosity requirements as on the windward side (Fig. 6).

Fig. 6 Schematic diagram of the protection system in severe aeolian sand disaster zones of Gobi sections

4.2 Configuration of the Aeolian Sand Protection System in Dry Salt-Lake Areas

The dry salt-lake area of the Tarim Basin railway loop is located in the DK817–DK858 section of the Golmud–Korla Railway, within the dried-up basin of Lake Taitema. This area is flat and open, with frequent strong winds and widely developed polygonally cracked salt crusts on the surface. The sand sources threatening the railway mainly originate from local sand entrainment within the dried-up lake basin [45]. For this type of aeolian sand environment, the prevention and control principle of "blocking as the main measure, while also considering sand fixation" should be followed, and the railway protection system should be configured rationally. In sections with severe aeolian sand disasters, the following protection configuration is recommended: on the windward side, at 40–60 m outside the foot of the subgrade slope, install a 60 m-wide reinforced reed-bundle large-grid sand barrier system (6 groups; 10 m × 10 m × 1.5 m); outside it, at intervals of 60 m, install two rows of high vertical HDPE sand-blocking panels, 2 m high, with porosity of 40%–50%; at the outermost side, with another 60 m interval, install one row of high vertical perforated steel-plate windbreaks, 3 m high, with porosity of 30% [44], to reduce wind speed. On the leeward side, at 40–60 m outside the foot of the subgrade slope, install a 40 m-wide reed-bundle large-grid sand barrier system (4 groups); 60 m outside it, install one row of high vertical HDPE sand-blocking panels, 3 m high, with porosity of 40%–50% (Fig. 7).

4.3 Configuration of the Aeolian Sand Protection System in Mud-Desert Areas

The mud-desert areas of the Tarim Basin railway loop are mainly distributed in the dry riverbed area of the lower Tarim River (DK876–DK1007). In this region, mobile dunes are extensively developed, sand sources are abundant, and large areas of mud-desert surface occur between dunes, forming an efficient sand-transport surface. As a result, dunes migrate rapidly and the risk of aeolian sand hazards is prominent. In view of these environmental characteristics, the protection principle of "adapting measures to local conditions, and using blocking and fixation in combination" should be followed. Because the mud-desert surface has relatively high hardness, it is not suitable for the direct installation of straw checkerboards; instead, gravel can be thrown and laid to form checkerboards, thereby enhancing the surface' s resistance to wind erosion. In sections with severe aeolian sand disasters, the following protection configuration is recommended: on the windward side, at 20–30 m outside the foot of the subgrade slope, install a 300–600 m-wide composite sand-barrier belt composed jointly of reed checkerboards (1 m × 1 m × 0.3 m) and gravel checkerboards (1 m × 1 m); outside the sand barrier, at intervals of 30–40 m, install three rows of high vertical HDPE sand barriers, 2 m high, with porosity of 40%–50%. On the leeward side, at 20–30 m outside the foot of the subgrade slope, install a composite sand barrier of the same width consisting of reed checkerboards and gravel checkerboards; 30–40 m outside it, install one row of high vertical HDPE sand barriers of the same specification (Fig. 8).

Visible labels in the schematic: high vertical sand-blocking barrier; large-grid sand barrier; railway; distances of 60 m, 40–60 m, and 40 m.

Fig. 7 Schematic diagram of the protection system in severe aeolian sand disaster zones of dry salt lake area

Visible labels in the schematic: high vertical sand-blocking barrier; reed checkerboard sand barrier; gravel checkerboard sand barrier; railway; distances of 30–40 m, 300–600 m, 20–30 m, and 30–40 m.

Fig. 8 Schematic diagram of the protection system in severe aeolian sand disaster zones of playa area

5 Conclusion

According to the field investigation, the main body of the roadbed of the railways around the Taklimakan Desert is basically free of sand accumulation, and aeolian sand deposition is mainly concentrated within the sand-control system. Among them, in the tall dune section from Washixia to Qiemo on the Hotan–Ruoqiang Railway, the mobile dune section west of Minfeng County, and the playa section in the lower reaches of the Tarim River on the Golmud–Korla Railway, the amount of sand accumulated in the protection system is relatively large. Coupled with the high annual regional sand transport, the protection facilities in these sections require priority maintenance.

The sand-driving wind directions along the railways around the Taklimakan Desert show obvious spatial differentiation: along the Golmud–Korla Railway, they are mainly NE, ENE, and E; along the Hotan–Ruoqiang Railway, the prevailing wind directions include NE, ENE, SSW, and WNW; and along the Kashgar–Hotan Railway, they are mainly WNW, W, and WSW. Overall, the railway corridor belongs to a low-wind-energy environment, with annual sand transport ranging from 0.21 to 8.34 $m^3 \cdot m^{-1}$. Areas with high wind-energy environments and relatively large sand transport are all located in the open zone on the eastern side of the basin. Under the combined influence of strong winds, sparse vegetation, and abundant sand sources, the southeastern section of the railways around the Taklimakan Desert has become the section with the most severe aeolian sand disasters along the entire line.

The existing aeolian sand protection system performs well overall and has effectively reduced the pressure of sand accumulation on the roadbed; however, local sections with severe sand hazards still require further optimization and reinforcement. In view of the aeolian sand environmental characteristics of different regions, the protection system of the railways around the Taklimakan Desert adopts differentiated configurations: in Gobi areas—especially the southeastern part—wind-resistant sand-blocking fences such as high vertical HDPE panels are used as the main sand-blocking measure, combined with medium-height reed-bundle large grids for auxiliary sand fixation; in dry salt lake areas, emphasis is placed on wind prevention and sand blocking, using wind-resistant fences such as high vertical perforated steel plates to effectively reduce wind speed, together with reed-bundle large grids to enhance surface stabilization; in playa areas, reed checkerboards and dumped gravel are arranged to increase surface roughness, thereby effectively suppressing surface wind erosion. It should be noted that sand-control materials in some sections are currently damaged, and the prefabricated assembly of sand-control materials needs to be strengthened to ensure the long-term stable performance of the protection system.

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Aeolian sand hazards along the Taklimakan Desert Ring Railway: Current status, causes, and optimized protection system configuration in characteristic sandy regions

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Abstract: The Taklimakan Desert Ring Railway (TDRR), an economic artery and vital link for people' s livelihood in southern Xinjiang, plays a pivotal role in advancing the Belt and Road Initiative and bolstering national defense security. However, aeolian sand disasters pose the primary challenge to its safe operation. In this study, unmanned aerial vehicle mapping and meteorological data analysis were integrated to systematically assess the current state of aeolian sand disasters along the TDRR, reveal their causes, and propose optimized configurations for the protection system in typical sand disaster sections. The results indicate the following. First, although the existing sand-control system along the TDRR is generally effective, certain sections remain threatened by sand hazards. Substantial potential hazards are present in three key areas: (1) the Washixia-Qiemo segment, featuring tall and large dunes; (2) the west section of Minfeng County along the Hotan-Ruoqiang Railway, which has mobile dunes; and (3) the lower reaches of the Tarim River along the Golmud-Korla

Railway, where dry riverbeds are prevalent. Second, the overall wind energy environment along the TDRR is low, with an annual sand flux ranging from 0.21 to 8.34 $m^3 \cdot m^{-1}$. Areas of high wind energy and strong sand transport are primarily located in the open eastern region of the basin, which are most severely threatened by aeolian sand hazards. Third, the current engineering protection system along the TDRR primarily uses reed materials focused on "blocking and fixing" sand, achieving good overall control. Nevertheless, existing measures in localized sections with severe sand damage still require further optimization and upgrading to enhance their long-term protective capacity.

Keywords: the Taklimakan Desert Ring Railway; aeolian sand disaster; protection system; the Taklimakan Desert

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