Postprint: Impact of the Sand Control System along Xinjiang Provincial Highway S214 on Near-Surface Aeolian Sand Flow

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Abstract

Simultaneous observations of wind-sand flow sediment transport and wind speed were conducted both inside and outside the sand control system in the dried lake basin section of Taitema Lake along Xinjiang Provincial Highway S214. Data analysis indicates: during the observation period, the sand-blocking and fixation belt within the sand control system had already intercepted a large amount of wind-blown sand; although the near-surface wind speed was not significantly reduced, 43.26% of the sediment transport in the wind-sand flow could still be intercepted and fixed by the sand control system, while the remaining portion could be transported to the leeward side of the highway with the aid of stronger winds in the roadside sediment transport belt, without causing sand hazards on the road surface. This demonstrates that the combined sand-blocking, fixation, and transport sand control system is highly suitable for strong unidirectional wind-sand environments. The sand control practices along Provincial Highway S214 can provide important reference experience for sand control on highways in other strong wind-sand environments.

Full Text

Influence of Sand Control System on Near-Surface Aeolian Sand Flow in Provincial Highway S214, Xinjiang

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Abstract

Sand disasters affect infrastructure safety, ecological environment quality, and human health, posing a significant threat to economic and social development in aeolian regions. Xinjiang is the core area of the New Silk Road Economic Belt and also the province with the largest and most widely distributed desertified and sandy land in China. Road traffic lines suffer severe aeolian sand disasters, becoming a major constraint on regional economic and social development. Since the founding of the People' s Republic of China, the Chinese government has attached great importance to transportation development in western regions, and experience and technology in sand prevention and control for traffic lines have continuously improved. According to different regional natural conditions and aeolian environments, various road sand control system structure models have been created, including solidification-dominant type, resistance-solidification combination type, and wind-blocking sand-transporting type. However, with the gradual expansion of transportation construction into geographical space, road sand prevention faces more diverse and complex aeolian environments, posing enormous challenges to sand disaster prevention and control. The research team from the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, in collaboration with the Xinjiang Production and Construction Corps, designed a resistance-transport combined sand control system structure based on the regional characteristics of "strong wind and abundant sand," using comprehensive mechanical and vegetation sand control measures for the highway sand control test demonstration section. Synchronous observations of aeolian sand flow transport and wind speed inside and outside the sand control system in the test demonstration area showed excellent protection effects, indicating that this sand control system model is suitable for strong aeolian environments. The results demonstrate that 43.26% of the sand transport can still be intercepted and fixed by the sand control system, while the remaining portion can be transported to the downwind side of the highway with the help of the roadside sand-transporting belt. This sand control experience can provide important reference for highway sand prevention in other strong aeolian environments.

Keywords: strong aeolian environment; sand control system; sand-transporting belt; aeolian sand flow transport; sand control benefit

1 Study Area Background

1.1 Study Area Overview

The dry lake basin of Taitema Lake is located in the eastern part of the Tarim Basin, within Ruoqiang County, Bayingolin Mongol Autonomous Prefecture, Xinjiang Uygur Autonomous Region. It is the terminal lake of the Tarim River, with an extremely arid climate, frequent strong winds, active aeolian sand activity, and large sand transport volume, representing a typical "wind-head water-tail" area. Provincial Highway S214 traverses the dry lake basin area of Taitema Lake from east to west, and is the only road crossing this region, oriented nearly perpendicular to the local dominant wind direction. Various underlying surface types are distributed along the highway, including modern lake areas, lacustrine sandy desert areas, lacustrine saline desert areas, and lakeside desert-oasis transition zones. The sections suffering from sand hazards are mainly located at K4+900–K18,200, belonging to sandy desert areas (Fig. 1).

The regional climate is extremely arid with scarce precipitation and large evaporation. The lacustrine deposits have loose and dry structures with abundant sand sources. The windy season is from [months], with the dominant wind direction being [direction], nearly perpendicular to the highway alignment, with occasional reverse winds [citation]. The underlying surface roughness of the area is [value], the critical friction velocity is 0.0048 m/s, and the high critical threshold wind speed for sand movement is 0.2423 m/s [citation]. The average wind speed of sand-moving winds is 7.41 m/s, with annual drift potential and resultant drift potential being 324.71 VU, mainly concentrated in the [direction] direction, accounting for [percentage] of the sand-moving wind drift potential [citation]. The terrain is flat and dunes move rapidly. The sandy desert sections of the highway suffer severe aeolian sand disasters, with extensive sand accumulation and burial on the road surface, threatening driving safety and even causing traffic interruption, which severely restricts regional economic and social development [citation].

1.2 Highway Sand Control System

To address the sand disasters on Provincial Highway S214, local highway authorities previously constructed a mechanical sand control system on the upwind (northeast) side of the highway, adopting the commonly used resistance-solidification combined structure (high reed sand barriers + reed checkerboard sand fixation belts). Due to the extremely strong aeolian sand activity in the region, the sand control system rapidly failed, with phenomena such as barrier burial, collapse and damage, and complete burial or wind erosion of checkerboards [citation]. Despite several updates to the sand control system, highway sand disasters became increasingly severe. Research found that the resistance-solidification combined sand control system is not suitable for "strong wind and abundant sand" areas. Additionally, checkerboard sand fixation increased the topographic relief near the road, and wind-shadow accumulated sand could evolve into mobile dunes that move forward to bury the road.

Summarizing past lessons, a resistance-transport combined sand control system was designed with a width of 204 m on the upwind side of the highway. On the upwind side of the highway, the outermost part of the sand control system established [number] reed sand barriers with spacing of [value] m, planting stress-resistant sandy shrubs. Adjacent to the sand-blocking belt, row-type semi-concealed reed sand barriers were laid with spacing of 100 m, planting sandy plants with economic value to form a sand-fixing belt. On both sides of the highway embankment, gravel was laid or concealed reed sand barriers were set to form sand-transporting belts (upwind side width [value] m, downwind side width [value] m) to allow smooth passage of aeolian sand flow and prevent road surface sand accumulation [citation]. In [year], a sand control test demonstration area was established in the most severely affected highway section (Fig. 2).

2 Methods

2.1 Observation Setup

In [month], in the sand control test demonstration area, [number] aeolian sand observation points were set up perpendicular to the sand control system (along the main wind direction) (Fig. 3), located respectively at: natural shifting sand land at [location] (Point 1), the middle of the sediment zone of the [number] reed sand barriers (Point 2), the middle of the sand-transporting belt on the upwind side of the highway (Point 3), and the sand-transporting belt on the downwind side of the highway (Point 4). At each monitoring point, a step-type sand sampler with 20 cm square holes was deployed, with collection heights increasing from low to high: 2 cm, 4 cm, 6 cm, 8 cm, 10 cm, 12 cm, 14 cm, 16 cm, 18 cm, and 20 cm. Each collection hole measured 2 cm × 2 cm.

Meanwhile, a self-recording anemometer was deployed at each observation point at [height] cm height, with an observation interval of [value] seconds. The observation period was during the prevailing dominant wind direction, with obvious sand particle activity. Synchronous observations of near-surface aeolian sand flow transport and wind speed were conducted [number] times, each lasting 30-68 minutes, ensuring that the lowest layer sand collection tube of the sampler was not filled. The start and end times of each observation were recorded. After observation, the sand collection tubes from each layer were removed, and sand samples were poured into plastic sealed bags marked with sample collection time, location, and height information.

2.2 Research Methods

1) **Wind speed variation**: Based on wind speed records during observation periods, the average wind speed at each measuring point was calculated. Using the average wind speed at Point 1 as the reference wind speed, the

ratio of wind speed at other measuring points to this reference wind speed was calculated to determine the wind speed change rate at each point.

2) **Aeolian sand flow structure**: The sand transport rate in semi-fixed sandy land generally changes with height following an exponential or power function relationship [Equation (1)], but also varies with region, underlying surface conditions, and weather conditions. Fixed sandy land generally follows a polynomial relationship [Equation (2)], but the fitting degree is not high without obvious patterns. The horizontal sand flux at [number] heights from the sand samplers at each observation point was fitted using the following formulas:

$$q()xa()x$$

where $q()x$ is the sand transport quantity in a certain height range ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$); x is the height of the sand material in the sampler collection layer (cm); a, b, c are fitting parameters.

3) **Sand transport rate variation**: In the laboratory, the mass of samples collected at each height of the sand sampler was weighed using an electronic balance with 0.01 g precision. The sand transport quantity and rate at each observation height of the sand sampler were calculated (sand transport quantity per unit width and per unit time, with units of $\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$). The sum of sand transport rates at all layers is the total sand transport quantity of the aeolian sand flow from 0-20 cm.

4) **Aeolian sand flow characteristic values**: Based on the aeolian sand flow structure function, the characteristic values (λ) of sand flow for each observation point were calculated according to the calculation formula proposed by Wu Zheng for determining surface erosion-deposition conditions [Equation (3)]:

$$\lambda = \frac{Q(0-1\ \mathrm{cm})}{Q(2-10\ \mathrm{cm})}$$

where $Q(0-1\ \mathrm{cm})$ is the sand transport rate within the 0-1 cm height layer ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$), and $Q(2-10\ \mathrm{cm})$ is the sand transport rate within the 2-10 cm height layer ($\mathrm{g \cdot cm^{-1} \cdot min^{-1}}$). When $\lambda > 0.5$, it indicates that the lower layer sand quantity is in an unsaturated state, the airflow still has considerable transport capacity, and is conducive to wind erosion. When $\lambda < 0.3$, it indicates that most transported sand material is close to the ground surface, easily forming accumulation on the surface. When $\lambda = 0.3 - 0.5$, it is in an erosion-deposition equilibrium state.

3 Results

3.1 Average Wind Speed Change

As shown by the average wind speed and average wind speed change rate at each measuring point (Fig. 4), from natural shifting sand land (Point 1) through the sediment zone of the [number] reed sand barriers (Point 2) to the [number] reed sand barriers, the near-surface average wind speed decreased from 8.05 $m \cdot s^{-1}$ to 7.71 $m \cdot s^{-1}$, a reduction of 4.22%, indicating that with the accumulation of large amounts of drifting sand before and after the barriers, their weakening effect on near-surface wind speed was relatively weak. From Point 2 through the sand-fixing belt to the sand-transporting belt on the upwind side of the highway (Point 3), wind speed changed little (7.73 $m \cdot s^{-1}$), indicating that because the sand control plants in the sand-fixing belt were still relatively short at this time, their weakening effect on near-surface airflow was not obvious, but they also prevented significant wind speed increase. Airflow from Point 3 across the highway embankment to the sand-transporting belt on the downwind side of the highway (Point 4) saw wind speed increase from 7.73 $m \cdot s^{-1}$ to 7.88 $m \cdot s^{-1}$, reaching 97.89% of the Point 1 wind speed value, indicating rapid recovery.

3.2 Sand Transport Rate Change

As shown in Fig. 5 for the sand transport rate and change rate of the protection system, the sand transport rate at the natural shifting sand land on the upwind side of the sand control system (Point 1) was 1.11 $g \cdot cm^{-1} \cdot min^{-1}$. At the sediment zone of the [number] sand-blocking belt (Point 2), the sand transport rate increased to [value] $g \cdot cm^{-1} \cdot min^{-1}$, an increase of 10.81%. Although the sand-blocking belt slightly reduced near-surface wind speed, because large amounts of sand accumulated before and after the barriers providing abundant sand sources, the aeolian sand flow approached saturated transport, thus the sand transport rate actually increased and formed unloading accumulation in the wind-shadow vortex zone on the leeward side of the barriers [citation]. From Point 2 through the sand-fixing belt to the sand-transporting belt on the upwind side of the highway (Point 3), the sand transport rate decreased to 0.63 $g \cdot cm^{-1} \cdot min^{-1}$, only 56.76% of Point 2, indicating that due to the interception and fixation by semi-concealed reed sand barriers and protective forest sand-fixing plants in the sand-fixing belt, surface sand source supply was relatively insufficient, and the amount of sand material transportable by aeolian sand flow decreased significantly, reducing damage to the highway to some extent. From Point 3 across the embankment to the sand-transporting belt on the downwind side of the highway (Point 4), the sand transport rate increased to 0.77 $g \cdot cm^{-1} \cdot min^{-1}$, reaching 69.37% of Point 3, showing that the sand-transporting belt greatly enhanced sand transport capacity.

3.3 Sand Flow Structure Change

As shown by the fitted curves of horizontal sand flux at different heights for each observation point (Fig. 6), at the natural shifting sand land on the upwind side of the sand control system (Point 1), the sand-transporting belt on the downwind side of the highway (Point 4), and the sand-blocking belt sediment zone (Point 2), horizontal sand flux decreased with increasing height, following a power function relationship with height, with determination coefficients R^2 all greater than 0.9. At the sand-transporting belt on the upwind side of the highway embankment (Point 3), although horizontal sand flux also decreased slightly with height, it did not follow a power function relationship, only obeying a polynomial relationship with a determination coefficient R^2 of 0.65. The horizontal sand flux at Point 3 was far less than at Points 1, 2, and 4 at the same height, but the difference decreased with increasing height, becoming very small in the 12-20 cm height layer.

Analysis of the aeolian sand flow structure at each observation point (Fig. 7) found that the horizontal sand transport quantity below 10 cm accounted for 61.11% and 61.51% of the total sand transport quantity at Points 1 and 2, respectively, while at Point 3 it was only 38.22%. This indicates that the flat and smooth sand-transporting belt can enable near-surface wind speed to transport sand material in a non-saturated state. When the wind speed at Point 4 recovered to near the value at Point 1, the aeolian sand flow transport rate at Point 4 also increased rapidly, reaching 69.37% of Point 3. Therefore, the sand-transporting belt can maintain aeolian sand flow in an unsaturated state, allowing it to transport through the road surface in a non-accumulating form and avoid road surface sand disasters.

3.4 Surface Erosion/Deposition State Change

As known from the aeolian sand flow characteristic values (λ) of each observation point (Table 1), the λ values at Point 1 were basically all greater than 0.5, with an average λ value of 0.58, indicating that the area has strong wind power while natural surface sand source supply is relatively insufficient, and the surface is in a wind erosion state. At Point 2, the average λ value was 0.52. Due to the interception of aeolian sand flow by the sand-blocking belt and the relative scarcity of sand sources in the sediment zone, the surface was also in a wind erosion state. Most grass heads had small exposed heights (about 1-2 cm), and the protective forest was still relatively short (about 50-80 cm), resulting in limited protection benefits.

Therefore, from Point 1 to the sediment zone of the [number] reed sand barriers (Point 2) and through the sand-fixing belt to the sand-transporting belt on the upwind side of the highway (Point 3), the sand-transporting belt showed strong wind erosion state. The λ value at Point 3 was much smaller than at Point 2, showing that although the wind speed changed little from Point 2 to Point 3 due to the relatively wide sand-fixing belt with strong overall sand interception capacity, the sand source supply on the downwind side of the embankment was richer than on the upwind side.

4 Discussion

The reed sand barriers set up on the periphery of the upwind side of the sand control system are the first sand control barrier, which can intercept large amounts of drifting sand, play an important role in wind prevention and sand blocking, and buy time for plant growth in the sand-fixing belt. The process of sand control measures exerting protective benefits is also a process of their sand control capacity attenuation [citation]. With the accumulation of drifting sand before and after the sand-blocking belt, the exposed height of sand barriers gradually decreases, and they may even be completely buried by invading dunes. Sand barriers in some sections also become damaged, with correspondingly reduced protection benefits.

Therefore, from the natural shifting sand land on the windward side of the sand control system (Point 1) to the sediment zone of the [number] reed sand barriers (Point 2), wind speed only decreased slightly. However, because the sand accumulation body of the reed sand barriers provided abundant sand sources, near-surface aeolian sand flow transport actually increased to some extent (by 10.81%). Although the reed sand barriers could still play a certain sand control role at this time (decomposing invading dunes into aeolian sand flow [citation]), in general highway mechanical sand control practice, they would need to be updated and maintained. Point 1 followed a power function distribution, characteristic of low-roughness underlying surfaces, while Point 3 followed a polynomial distribution, characteristic of fixed sandy land. It is evident that the sand-fixing belt and sand-transporting belt can effectively control near-surface drifting sand transport, causing significant changes in the aeolian sand flow structure, especially in the 2-6 cm height layer.

In previous highway sand prevention practices in sandy areas, the resistance-solidification combination mode was commonly used, and the previous highway sand control system for Provincial Highway S214 also followed this method. However, serious road surface sand damage occurred less than [time] after the sand control system was built, causing traffic interruption. Despite several updates and expansion of the protection scale, the results were minimal. In the above observations, the changes in aeolian sand flow passing through the sand-fixing belt of the newly established sand control system were basically the same as in the previous system. If aeolian sand flow cannot be effectively intercepted, it will lead to highway sand disasters. Actual surveys also found that the previous sand-fixing belts were all set up directly on original aeolian landforms, and aeolian sand flow does not advance uniformly in the sand-fixing belt, but rather easily deposits on the leeward slopes of dunes and other convex terrain. As the sand accumulation body increases, its mobility enhances (Fig. 8), and under wind action it moves forward to bury the road [citations]. This is the main mechanism of highway aeolian sand disaster formation in the study area.

Due to the strong wind power in the study area, a relatively large portion of aeolian sand flow could cross the sand-blocking belt into the sand-fixing belt and deposit there during the observation period. Field observations found that relatively thick sand accumulation had already formed within the semi-concealed sand barriers. In other regions, although highways use the resistance-solidification combined sand control system, highway sand damage is not serious, which is related to weaker aeolian activity in those areas. Considering the extremely strong aeolian activity in the study area, a resistance-transport combined sand control system model was formed (Fig. 9) for sand control practice. Provincial Highway S214 is a successful practice of this sand control model. Its main improvement was adding sand-transporting belts along both sides of the highway on the basis of conventional resistance-solidification combined structures.

Sand-transporting belt construction first requires mechanical leveling of the surface, then setting up concealed sand fixation measures or gravel paving (Fig. 9). The sand-transporting belt has small topographic relief and reduced surface sand source supply capacity, enabling aeolian sand flow to transport through in a non-erosion non-accumulation state. Observation data showed that aeolian sand flow passing through the sand-transporting belt of the upwind side sand control system and the highway embankment to the sand-transporting belt on the downwind side of the highway (Point 4) saw wind speed gradually recover and approach the wind speed value of the upwind side sand control system (Point 1), with near-surface aeolian sand flow transport rate also increasing relatively quickly to 69.37% of Point 3. Therefore, the sand-transporting belt can maintain aeolian sand flow in an unsaturated state, allowing it to smoothly pass over the road surface in a non-accumulating transport form, avoiding road surface sand disasters.

The application of mechanical sand barriers in the sand control system rapidly improved the interception capacity for aeolian sand flow in the study area, while planting sand control plants can compensate for functional loss of damaged mechanical sand barriers and also intercept re-mobilization of accumulated sand in the sand-blocking belt. Vegetation planting and irrigation can increase soil organic matter content and water content, increase soil surface salt content, raise the threshold wind speed for sand movement, and reduce soil wind erosion [citation]. According to the soil water-salt characteristics of the area, sand control plants such as Haloxylon ammodendron, Tamarix, Nitraria, Lycium ruthenicum, and Calligonum can be selected, which are salt-tolerant, barren-tolerant, high-temperature-resistant, stress-resistant, and have certain economic value. The protective forest plants' irrigation water source comes from the nearby [corps], through self-flow water conveyance irrigation for sand prevention. Since the construction of this sand control system in [year], no road surface sand accumulation has occurred, and the highway has operated safely, demonstrating that the resistance-transport combined sand control system is suitable for the study area. It can transport away drifting sand that cannot be intercepted by the sand control system through natural wind power in the sand-transporting belt.

Previous researchers have also proposed the construction concept of resistance-transport combined sand control systems, but it has not been successfully applied in practice [citation].

5 Conclusion

In summary, the resistance-transport combined sand control system adapts to the strong unidirectional aeolian environment in the dry lake basin area of Taitema Lake. Under conditions where the sand-blocking and sand-fixing belts form large amounts of accumulated sand, nearly half of the aeolian sand flow transport can still be intercepted and fixed by the sand control system. The sand flow transport that cannot be intercepted by the sand control system can be transported to the downwind side of the highway using natural wind power, thereby eradicating highway sand disasters. Therefore, for areas with strong aeolian environments, the terrain on both sides of the highway can be leveled and fixed to build sand-transporting belts, making the near-roadside aeolian sand flow unsaturated, allowing sand flow to transport downwind on its own. This achieves the goal of successfully preventing and controlling highway sand disasters with a sand control system of limited width. This is a sand control system construction model with low investment but good sand control effects, which can provide reference for highway sand prevention in other strong aeolian environments.

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References

[1] Ma Guangxue, Jin Haipeng. Explore the hazards of sandstorms to highways and the principles of prevention and control[J]. Ability and Wisdom, 2009, 9(12): 51.

[2] Ma Weigang. Discussion on the harm of sandstorm to highway[J]. China Science and Technology Information, 2011, 9(27): 69.

[3] Wang Xueqin, Lei Jiaqiang. Relationship between the alignment of routes and degrees of wind sand hazard in the drift-sand region: A case study of Tarim Desert Highway[J]. Arid Land Geography, 2000, 23(3): 221-226.

[4] Hu Zhengchao, Kasi Tursun, Wang Huiling, et al. Wind and sand disasters in S214 provincial highway of dry up lake basin region of Taitema Lake[J]. Journal of Inner Mongolia Agricultural University (Natural Science Edition), 2018, 39(6): 48-60.

[5] Yu Xiangxiang. Characteristics of blown sand activity on dry up lake basin region of Taitema Lake[D]. Beijing: University of Chinese Academy of Sciences, 2016.

[6] Li Shengyu, Fan Jinglong, Wang Haifeng, et al. Causes and thoughts of comprehensive control of blown sand disaster at Qiaha Bridge of National Highway 315, in Cele County, Xinjiang, northwest China[J]. Arid Land Geography, 2016, 39(4): 754-760.

[7] Liu Gang, Gao Hainan. Study on the analysis and treatment measures of the road wind sand diseases in the desert area[J]. Highway, 2018, 63(4): 57-59.

[8] Li Shengyu, Lei Jiaqiang, Xu Xinwen, et al. Patterns of blown sand hazard control for traffic arteries in China and its application[J]. Bulletin of Chinese Academy of Sciences, 2020, 35(6): 665-674.

[9] Cai Dongxu, Li Shengyu, Lei Jiaqiang, et al. Study on blown sand characteristic and comprehensive protection system in wind eroded desertification area of Kao Mi highway[C]//Proceedings of the 2018 Annual Conference of China National Sand Control and Desert Industry Society. Golmud: China National Sand Control and Desert Industry Society, 2018: 99-109.

[10] Hu Zhengchao, Liu Yang, Li Shengyu, et al. The wind blown sand hazard potential evaluation of highway on dry up lake basin region of Taitema Lake[J]. Territory & Natural Resources Study, 2018, 40(2): 54-59.

[11] Mao Donglei, Lei Jiaqiang, Wang Cui, et al. Characteristics of sand flow structure and sand transportation particles in Cele Desert-Oasis Ecotone of Xinjiang Wei Autonomous Region[J]. Bulletin of Soil and Water Conservation, 2015, 35(1): 25-33.

[12] Yang Dongliang, Wang Xueqin, et al. Study on vertical distribution of aeolian sand mass flux based on field observation at southern rim of the Taklimakan Desert[J]. Journal of Desert Research, 2012, 32(3): 631-639.

[13] Sauermann G, Kroy K, Herrmann H J. Continuum saltation model for sand dunes[J]. Physical Review E, 2001, 64(3): 031305, doi: 10.1103/PhysRevE.64.031305.

[14] Andreotti B, Claudin P, Douady S. Selection of dune shapes and velocities Part 1: Dynamics of sand, wind and barchans[J]. The European Physical Journal. B: Condensed Matter and Complex Systems, 2002, 28(3): 321-339.

[15] Yang Xinghua, He Qing, Huo Wen, et al. Near surface horizontal sand flux over different underlying surfaces in a desert[J]. Arid Zone Research, 2014, 31(3): 564-569.

[16] Cai Dongxu, Li Shengyu, Wang Haifeng, et al. Aeolian hazard and comprehensive protection of S214 highway in Taitema Playa, Xinjiang, China[J]. Journal of Desert Research, 2020, 40(1): 1-11.

[17] Chen Boyu, Cheng Jianjun, Li Shengyu. Reasonable spacing of high parallel reed sand barriers along the Xinjiang S214 provincial highway[J]. Arid Zone Research, 2020, 37(3): 782-789.

[18] He Qing, Yang Xinghua, Mamtimin Ali, et al. Observation of dust emission by wind erosion in Taklimakan Desert: Field experiment and preliminary report[J]. Journal of Desert Research, 2011, 31(2): 315-322.

[19] Bian Kai, Gao Junliang, Xin Zhiming, et al. Study on wind prevention and sand resistance ability of oasis shelterbelt system in the northeast of Ulan Buh Desert[J]. Journal of Capital Normal University (Natural Science Edition), 2021, 42(1): 48-53.

[20] Wu Zheng. Aeolian geomorphology[M]. Beijing: Science Press, 1987: 27.

[21] Gao Runqing, Dang Bing, Song Zengfeng. The effect of wind and sand on express highway: The case study of Yulin Jingbian express highway[J]. Shaanxi Forest Science and Technology, 2007, 35(3): 106-111.

[22] Yao Zhengyi, Chen Guangting, Han Zhiwen, et al. Decline mechanism and process of mechanical defense system[J]. Journal of Desert Research, 2006, 26(2): 226-231.

[23] Zhang Xingxin, Zhang Kai, Shi Boyuan, et al. Numerical simulation of wind blown sand flow field and formation mechanism of sand damage on road surface in shifting dune area[J]. Arid Zone Research, 2021, 38(4): 1184-1191.

[24] Wang Jiating, Yu Minghan, Yang Hailong, et al. Soil erosibility of typical plant communities in Ulan Buh Desert[J]. Arid Land Geography, 2020, 43(6): 1543-1550.

[25] Wang Xu, Tian Changyan, Zhao Zhenyong, et al. Effects of different planting years of Suaeda salsa on the soil ions distribution in saline sodic soil under drip irrigation[J]. Arid Land Geography, 2020, 43(1): 211-217.

[26] Zhang Kecun, Qu Jianjun, Yan Ping, et al. Progress of research on wind blown sand prevention and control of railways in China[J]. Advances in Earth Science, 2019, 34(6): 573-583.

[27] GB/T 21141-2007. National Standard of the People' s Republic of China: Technical regulations for sandification prevention and control[S]. Beijing: Standards Press of China, 2007.

[28] Liu Xianwan. Experimental wind sand physics and sand engineering[M]. Beijing: Science Press, 1995: 43-50.

[29] Miao Chunping. Renewal and maintenance judgment method of mechanical sand control system[J]. Highway, 2016, 61(4): 221-225.

[30] Dai Yaya, He Qing, Lu Hui, et al. Dust horizontal flux and grain size characteristics of the near surface on compound longitudinal dunes in the hinterland of Taklimakan Desert[J]. Journal of Desert Research, 2016, 36(4): 918-924.