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Patterns of Blown-sand Hazard Control for Traffic Arteries in China and Its Application

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Abstract

Highways and railways are important infrastructures of land transportation. The blown-sand hazard control of traffic arteries in sandy areas has always been one important issue in the national economy and society. In view of the characteristics of aeolian environment and the demand for safe operation of traffic arteries, China has carried out a large number of sand hazard control experiment and practices mainly on technology innovation of materials, measures, comprehensive system, maintenance, summed up four configuration patterns of sand control system, and created some patterns of sand hazard control technology for desert traffic arteries in different aeolian environments with Chinese characteristics, the patterns have been applied successfully in the Baotou-Lanzhou Railway, Qinghai-Tibet Railway, Tarim Desert Highway and Open Channel in Gurbantunggut Desert. China's achievements in the sand hazard control for land transportation arteries have a broad application prospect in sandy areas in the world, especially in the countries along the Belt and Road.

Keywords

highway; railway; blown-sand hazard; sand prevention measures; sand control system

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Abstract: Highways and railways are important infrastructures of land transportation. The blown-sand hazard control of traffic arteries in sandy areas has always been one important issue in the national economy and society. In view of the characteristics of aeolian environment and the demand for safe operation of traffic arteries, China has carried out a large number of sand hazard control experiment and practices mainly on technology innovation of materials, measures, comprehensive system, maintenance, summed up four configuration patterns of sand control system, and created some patterns of sand hazard control technology for desert traffic arteries in different aeolian environments with Chinese characteristics. At the same time, the patterns have been applied successfully in the Baotou-Lanzhou Railway, the Qinghai-Tibet Railway, Tarim Desert Highway in Taklimakan Desert, and the Open Channel in Gurbantunggut Desert. China's achievements in the sand hazard control for land transportation arteries have a broad application prospect in sandy areas in the world, especially in the countries along the Belt and Road.
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Keywords: highway; railway; blown-sand hazard; sand prevention measures; sand control system

The road traffic, a significant symbol for civilization and productivity [1], is closely related to subsistence and development of mankind, and as a ground construct, is influenced by diversified regional natural conditions. As a phenomenon of gas–solid two-phase flow [2], the blown-sand activity mainly appears in arid and semi-arid regions and semi-humid regions such as those along rivers and lakes as well as coastal lands. In China, sandy areas are mostly distributed in interior inter-mountain basins and vast upland plains, stretching like an arc stripe from northwest, through north, to northeast. They, about 4,000 km long and 60 km wide, have a total area of 1.308×10^6 km^2, accounting for nearly 13.6% of the national territories [3].

After the Industrial Revolution developed in the 18th century, modern roads (highways and railways) have appeared, which greatly advanced the development of human beings [1]. As of the end of 2019, China has owned highways of $4.846\ 5 \times 10^6$ km in total, including 1.426×10^5 km expressways; railways of 1.39×10^5 km have opened to traffic, including 3.5×10^4 km for the high-speed one [4]. During 1950s–1980s, a period for traffic arteries to be built, China launched works for the prevention and control of blown-sand hazard troubling the traffic in deserts, desert edges, or Gobi in arid and semi-arid areas, especially in Shapotou section of the Baotou-Lanzhou Railway [5,6], leading to the accumulation of precious experience and technologies for the blown-sand hazard control for traffic arteries [7,8]. Then in 1980s–1990s when oil and gas resources in Tarim Basin were explored and developed, China successfully completed the oil-transporting highway, which runs through the Taklimakan Desert, working out difficulties in efforts to deal with the blown-sand hazard faced by highways in drifting deserts [9,10]. After 2000, with the implementation of the strategy for the development of the western region in China, traffic arteries in sandy areas were built on a large scale, and techniques for sand prevention were gradually improved. Since 2010, and in particular when the Belt and Road Initiative was proposed in 2013, faster moves were conducted toward the establishment of expressways in sandy areas, further perfecting sand prevention techniques [11–13].

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1 Damaging forms of blown-sand hazard to traffic arteries and prevention & control principles

1.1 Damaging forms

Damages that may be caused by the blown-sand activity involve road facilities (wind erosion of subgrade, blocking of culverts, and damages of signboards), deterioration of driving environment (sand accretion or burying at subgrade and poorer visibility), machinery damage to vehicles (parts depreciation and scuffed appearances), overturning accidents, casualties, as well as property loss [14]. Generally speaking, the damaging forms only refer to damages to traffic facilities and threats to vehicles by the wind erosion and sand burying.

1.2 Prevention & control principles of blown-sand hazard

To prevent and control the blown-sand hazard to traffic arteries should abide by the following principles: ① putting prevention first, and combining prevention with control; ② adapting measures to local conditions and applying sand prevention measures in specific hazard areas; ③ taking comprehensive treatment to give full play to various measures [15]. In the phase of designing traffic arteries, scientific and appropriate schemes should be fashioned to bypass sections where serious blown sand rages, and experts should try to make roads go in parallel with the predominant wind direction or intersect in a small angle, apart from the construction of subgrade with an appropriate section [8,16].

On a smooth and level road surface, blown-sand flow can pass without accumulation of sands. At present, the waveform guardrail board commonly used for high-grade highways easily leads to the accumulation of sands on the road surface [17], and accordingly, such highways require a greater standard of sand prevention than normal ones. On the other hand, sands are prone to accumulate on the rough and rolling track bed (including ballast, sleeper, and track), causing not only a threat to traffic safety but archway damages [16]. As a result, railways need higher standards of sand prevention than highways.

2 Configuration and maintenance of sand control system in traffic arteries

2.1 Sand prevention measures and principles

Through practices, China has created multiple measures for sand prevention, achieving effective control of the blown-sand hazard. In term of the material property, relevant measures can be divided into mechanical, chemical, and biological ones; from the perspective of dynamics, there are six kinds of measures: enclosed (enclosing roadbed slope with rubble), fixed (straw checkerboard barrier), fencing (such as upright sand barrier and forest belt), guiding (guiding winds downward), transforming (sand control embankment arranged like a feature), and dispersing (sand blowing embankment) [18]. Principles for different measures are as follows: to stop or curb the gas-solid two-phase flow from touching and interplaying with the earth; to enhance capacities of targets which are prone to sand accumulation or earth surface against the wind erosion; to increase or decrease the resistance to motion of blown-sand flow in regional areas; to guide the change in the motion direction of blown-sand flow.

Such factors as the sand source, wind regime, landform, precipitation, underground water should be taken into consideration during the construction of projects against sands, and in particular full attention should be paid to the materials, which are mainly from natural inorganic materials, plant stalks, synthetic polymer materials, lower and higher plants. In view of project costs and environmental protection, the projects tend to employ local materials.

2.2 Structural configuration mode of sand control system

The spatial structure arrangement of sand prevention measures along the traffic arteries is called sand control system. Sand control system is not only related to engineering safety but also determines the engineering construction cost and later operation and maintenance cost, so it is necessary to implement the idea of adapting measures to local conditions and applying sand prevention measures in specific hazard areas.

According to the combination of wind force and sand sources, there are four qualitative types for complicated and different aeolian environments: weak in wind force and less sandy, weak in wind force and sandy, strong in wind force and less sandy, strong in wind force and sandy (Table 1). Correspondingly, four patterns are used for the sand control system in traffic arteries: putting sand fixation first; combining resistance and fixation; preventing wind and discharging sands; integrating resistance, fixation, and discharge (Table 1). Moreover, resisting sands outward, a measure for the pattern of combining resistance and fixation, can be replaced with sand diversion [19,20], which means to use the pattern of combining diversion and fixation instead, when roads have a small included angle with the local predominant wind direction and there exists an appropriate area for sand diversion.

2.3 Maintenance of the sand control system

As for traffic arteries in sandy areas, not only maintenance management of resistance to wind erosion is needed for the subgrade and road surface [26], but the maintenance of sand control system is a focus to which importance should be attached [27]. That is because the system function will decline as it works for wind prevention and sand fixation [28], and materials used will also prone to aging. Thus, continuous maintenance and upgrading are necessary to prolong the

Table 1 Qualitative classification of aeolian environments and sand prevention patterns in traffic arteries

Aeolian environment	Typical area	Principal hazardous factor	Pattern of sand control system	Cases
Weak in wind force and less sandy	Gurbantunggut Desert	Partial active quicksand	Putting sand fixation first	Zhundong Oilfield Highway [21] and Open Channel in Gurbantunggut Desert
Weak in wind force and sandy	Taklimakan Desert	Vast quicksand	Combining resistance and fixation	Tarim Desert Highway in Taklimakan Desert [10] and Alar–Hotan Desert Highway [22]
Strong in wind force and less sandy	Bailifeng District	Strong wind	Preventing wind and discharging sands	Bailifeng section of Lianyungang–Khorgos Expressway [23] and Bailifeng section of Lanzhou–Xinjiang Railway/Lanzhou–Urumqi High-speed Railway [24]
Strong in wind force and sandy	Taitema Playa	Large-volume sand discharge with gale	Integrating resistance, fixation, and discharge	S214 Provincial Highway [25]

lifespan of the system. However, the declining of sand prevention function does not mean that the windward edge of the system will gradually shrink inward for a reason that wind erosion and sand burying may also happen synchronously in rolling areas inside the system [29]. A wider system needs higher cost of maintenance, and the long-term maintenance cost is higher than the cost of single upgrading as the regular small-scale work in various areas is lack of scale merit. At this point, the theoretically calculated width [30] of a sand control system (always exaggerating the blown-sand hazard technologically [31]) is not optimal in economics, and instead, the system with an appropriate width has lower long-term upgrading costs, more practical in reality.

3 Patterns of blown-sand hazard control for traffic arteries and successful cases

Over the years, scientific and technical workers in China, taking into account the environmental conditions and characteristics of the blown-sand hazard in different regions, have integrated advantages of mechanical, chemical, and biological measures [32] to make reasonable allocation and take measures to local conditions. As a result, the sand control system for traffic arteries has been gradually established and improved, ensuring the safe operation of roads.

3.1 "Four-belt integrated" prevention and control pattern for blown-sand hazard in drifting desert—Baotou-Lanzhou Railway

Baotou-Lanzhou Railway, built and put into practice in 1958, runs through the southeast of Tengger Desert at Shapotou section. Trellised migratory dunes in a large scale lean from northwest to southeast with ladder-shaped distribution. The railway is right below the stepped dunes. Swept by the west-northwest and northwest winds that prevail here all the year round, the railway goes properly in a 45° angle with the predominant wind direction, as a result of which it suffers severe blown-sand hazard caused by movement forward and burying of secondary dune ridges [32,33].

After long-term experiments, a "four-belt integrated" sand control system that works for resistance, fixation, discharge, and diversion is initially established, with the "four belts" referring to the sand resistance belt at the forefront that consists of upright fences, sand fixation belt by straw checkerboard barriers and non-irrigated plants, forest belt of arbor and shrub needing irrigation, as well as sand discharge belt that is buffered by a gravel platform [32,33]. In view of the difficulty to realize sand discharge on the basis of the gravel platform and limited by water resources for the irrigation of forest belt, two basic belts are developed and kept: the sand prevention zone shaped by setting up upright fences at the most forefront facing the wind; the sand fixation belt formed with semi-concealed 1 m × 1 m straw checkerboard barriers in which plants are grown at some density for the fixation. At the end, a comprehensive sand control system that "puts fixation first and combines resistance and fixation" is put into effect [34] (Figure 1).

Figure 1 Prevention and control project for blown-sand hazard in Shapotou section of Baotou-Lanzhou Railway

The establishment and improvement of Shapotou sand control system play an effective role in controlling regional blown-sand activities [32], exerting a sound effect on the prevention and protection work. In the sand fixation zone, near-surface wind velocity slows by over 50%, and sand discharge amount decreases by nearly 80%, with the dune surface stable [34]. The artificial shrub and semi-shrub forest belts firstly created on the trellised dunes, gradually, are replaced by such natural vegetation as herbaceous plants and semi-shrub, contributing to soil crusts (mosses and therophyte), and thus the biological sand fixation effect is enhanced [34]. Novel plant and animal species come into sight in the vegetation area, constructing a stable ecological system of sand fixation, which is attributed to the improved environment showing a tendency that the intrazonal (quicksand) geological environment is evolved into zonal geological environment (steppe desert) [34]. This sand control system has accumulated relevant experience about how to realize sand fixation in drifting deserts, the first successful case of blown-sand hazard control for traffic arteries in drifting deserts in China [32].

3.2 A pattern of upright sand barriers with big grids for blown-sand hazard control in aeolian environment—Qinghai-Tibet Railway

The Qinghai-Tibet Railway, completed and opened to traffic in 2006, is the globally first one in plateau that is built highest and goes through permafrost and deserts. As revealed by research and studies, most areas passed by the railway are arid or semi-arid, where it rains less but blows more, and blows in the dry season, providing dynamic conditions for blown-sand activities [34,35]. With global climate change, environmental deterioration in Qinghai-Tibet Plateau, involving glacial recession, permafrost degradation, as well as alternate freezing and thawing, causes loose soil structure on the ground surface, increased sand sources and serious wind erosion and desertification [35]. In addition, human activities like railway construction bring about more disturbances on the original ground surface. Consequently, the blown-sand hazard along the railway is becoming increasingly serious, with 270 km section bothered by it [36], leaving the prevention and control work instant.

Facing natural environments in different areas along the railway and the reality of more serious blown-sand hazard, a comprehensive control system is established in sections with rich sand sources, which, focusing on mechanical measures while coupling with biological and chemical counterparts, serves to resist sands far and fix sands near, and at the same time combines sand discharge and diversion [35,37]. As shown in studies, the threshold friction velocity, the proportion of saltation sands, and saltation height of sands are relatively high in an environment where the altitude is high and atmospheric pressure low, compared with that in a low-altitude area, because of the difference in air density in the two kinds of environments [36]. Taking into consideration such a movement mode of sands in the high-altitude area and structural features of blown-sand flow, researchers propose a conception that wind velocity is lowered and quicksand is fixed through increasing the height of engineering measures and develop the critical technology of upright sand barriers with big grids for sand prevention [19,36] (Figure 2). Mechanical measures including high-density polyethylene (HDPE) upright sand-resistance fence, upright sand-fixation barrier with big grids, stone checkerboard barrier, as well as gravels for compacting sands, chemical measures like sand-fixing agent, and biological measures of surface vegetation protection and restoration, function together to construct the comprehensive technological system suitable for prevention and control of blown-sand hazard along the Qinghai-Tibet Railway [32,34–39].

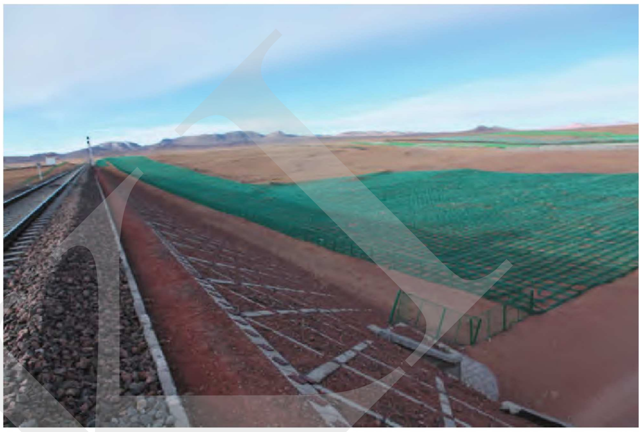

Figure 2 Blown-sand hazard control project in Qinghai-Tibet Railway

On the basis of the prevention and control technology of upright sand barrier with big grids for the blown-sand hazard in an alpine environment, a series of prevention and protection measures are implemented according to different sand sources such as valley, seasonal playa, and deteriorated grassland along the railway [36], exerting an obvious control effect on blown-sand flow. To be specific, the coverage of natural vegetation is over 30%, and the annual amount of sands cleared away is reduced significantly, only 12 000 m^3 at present [36], indicating great achievement. The pattern fills in the gap of study relevant to blown-sand hazard control for traffic arteries in alpine sandy areas, providing experience for scientific efforts to control blown-sand hazard in ecologically vulnerable alpine areas.

3.3 A pattern of afforestation needing irrigation with brackish water in arid quicksand environment—Tarim Desert Highway in Taklimakan Desert

The time of 1990s witnessed the success of China that Tarim Desert Highway in Taklimakan Desert running through Taklimakan Desert was completed, which plays a role of significance in the development of oil and gas resources and economic growth in South Xinjiang [40]. With the extremely dry climate in the Taklimakan Desert, the northeast wind prevails in most sections along the highway, which is highly strong; dunes in complicated and diversified forms serve as a cause of evident regional differences; with high coverage of quicksand, the sand sources are abundant [41,42]. Consequently, the blown-sand hazard remains a critical threat to desert highway safety [43,44].

The mechanical sand control system, despite its effectiveness in ensuring the safety of desert highways during their early stage of services [44], has a short service life and also costs more in maintenance and upgrading. Accordingly, the priority should be given to the ecological project of protection forest with biological measures as core, the best choice to keep desert highways constantly open. To cope with disadvantages along the Tarim Desert Highway in Taklimakan Desert, such as shortage of freshwater resource, salt accumulation, together with a poor water retention capacity of aeolian sandy soils, China, organically integrating soil types, plant species, irrigation cycle, irrigation mode, and irrigation quota, establishes a scientific irrigation system [45] (in the initial stage of afforestation, the irrigation quota for *Tamarix chinensis* and *Haloxylon ammodendron* is 30 kg/plant, with a cycle of 15–20 days, and for *Calligonum mongolicum*, 20 kg/plant, with a cycle of 10–15 days. As the age of stand rises, the irrigation quota and cycle should be increased [46,47]), and defines procedures of irrigation using brackish water for culture of seedlings, leading to the formation of technique for seedling cultivation with brackish water in shifting sandy lands. Besides, the critical techniques of irrigation with brackish water are proposed ①, involving well drilling in higher-altitude areas, relatively even well spacing (with a spacing of 4 km), water supplying by branching pipes (differentiating irrigation according to water consumption characteristics of plants), compensating drip irrigation (pressure compensating drip irrigation with small flows), irrigation with smaller amounts but more frequencies, and forcing salt into soils with irrigation at the end of year [45,48].

Technological achievements resulting from afforestation needing irrigation with brackish water in shifting sandy lands are directly applied to the construction of ecological protection forest project along the Tarim Desert Highway in Taklimakan Desert, giving birth to an artificial green corridor [45] (Figure 3) with an area of 3 128 hm^2, totally 436 km long and 72–78 m wide, in which more than 2 000 plants are grown with a survival rate of over 85%. As a result, the blown-sand hazard bothering desert highways is totally under control, ensuring safe and unimpeded traffic. The technological pattern expands water resources available to ecological conservation, and breaks through the impossibility of afforestation in "areas unsuitable for forest," providing a successful case for blown-sand hazard control as well as ecological restoration and reconstruction in extremely arid areas, which gains extensive attention in China and other countries.

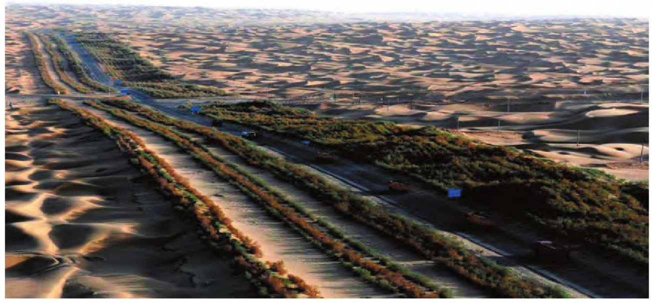

Figure 3 Ecological protection forest project along the Tarim Desert Highway in Taklimakan Desert

3.4 Non-irrigation afforestation pattern in activating dunes—Open Channel in Gurbantunggut Desert

In the early 21st century, China invested in the water resource project of economic belt established in the north slope of Tianshan Mountains. Wherein, the Open Channel section of Gurbantunggut Desert and its concomitant highway cross the Gurbantunggut Desert. With small precipitation and large evaporation along the Open Channel, no water sources for irrigation can be found [49]. The wind there is strong in a single direction. The activating dunes become a serious threat to the safety of the channel and highway under the influence of construction disturbance and vegetation deterioration.

Stable snow cover is seen in winter of the Gurbantunggut Desert, with a snowfall accounting for about 30% of the annual precipitation [49]. It is melt in spring, of which 79%–92% water that is stored will transform into soil moisture and form layers of suspended and humid sands [50,51]. The critical technique, utilizing soil moisture in such sand layers to conduct non-irrigation afforestation in fixed and semi-fixed sandy areas, is created from experiments and researches [52]. This technique mainly involves over ten appropriate plants (including *H. ammodendron*, *Haloxylon persicum*, *C. mongolicum*, *Elaeagnus angustifolia*, *Xanthoceras sorbifolium*, *Amorpha fruticosa*, *Hedysarum scoparium*, *Salsola ruthenica*, *Halogeton glomeratus*, *Agriophyllum squarrosum*, *Artemisia desertorum*, and *Seriphidium santolinum*), two cultivation periods (late autumn and early spring), two afforestation methods (seedling planting and direct seeding), two treatment approaches (dipping tree roots with water-retaining agent and afforestation by sand replacement), three structural layouts (spacing between rows respectively 2 m × 2 m, 2 m × 1 m, and 1 m × 1 m), as well as four site conditions (shady slope of fill section, sunny slope of fill section, shady slope of excavation section, and sunny slope of excavation section) [52–54].

On the basis of the researched and developed technique of non-irrigation vegetation restoration, an optimized mode is created for engineering protection system establishment in

① Technology Service Platform for Comprehensive Ecological Improvement of Southwest Edge of Tarim Basin (http://3w.detts.org/Item/6769.aspx) fixed and semi-fixed sandy areas by combining multiple sand prevention techniques. Applied to the whole line (168 km) of Open Channel in Gurbantunggut Desert (Figure 4), the mode helps achieve 30 000 *mu* afforestation, with a survival rate of at least 85%, and lowers the cost of sand control system by over 80%. In consequence, vegetation in areas suffering construction disturbance is quickly restored, and the ecological environment along the channel is obviously improved [55,56], thus guaranteeing the smooth construction and safe operation of the open channel. It serves as a precedent for eco-utilization of water in layers of suspended and humid sands and expands the technological development and practice of non-irrigation afforestation and ecological project construction, generating great social influence.

Figure 4 Ecological protection forest project along the Open Channel in Gurbantunggut Desert

4 International promotion and application prospect of blown-sand hazard control techniques for traffic arteries in China

The world's arid and semi-arid areas, accounting for nearly 40% of global lands [57], include deserts with an area of $3.6 \times 10^7 km^2$ [57,58]. Influenced by both climate change and human activities, these areas, especially those along the Belt and Road, are confronted with severe water resource shortage and desertification, directly threatening infrastructure construction and safety. In particular, traffic arteries are at risk of serious blown-sand hazard. Six economic corridors of the Belt and Road, facing problems of arid environment and blown-sand to different degrees, have their sections totally about 6 000 km under the blown-sand hazard, with railways, highways, projects of oil and gas transmission pipelines, and energy resource bases directly endangered.

Despite many experiments and practical technologies developed by countries for prevention and control of blown-sand hazard in traffic arteries, the reality is that the technologies cost higher in materials are put into effect just with relatively single measures, which yield an inconspicuous effect and have a short life and are difficult to maintain. As a result, they encounter certain limitations when being promoted and applied. According to blown-sand environment characteristics along traffic arteries in China, the prevention and control patterns for traffic arteries hazarded by blown-sand are formed in such areas as drifting deserts, fixed and semi-fixed deserts, and alpine sandy areas by technological experiments, demonstration, integration, and application. Moreover, these patterns are successfully applied in the Baotou-Lanzhou Railway, the Qinghai-Tibet Railway, the Tarim Desert Highway in Taklimakan Desert, the Open Channel in Gurbantunggut Desert, and other traffic arteries in sandy areas. Such well-established technological patterns in a complete set, featured with advantages of low costs, simple operation, great benefits, and long service life, can provide an important reference value for traffic sand prevention and ecological construction in sandy areas of the world, and has a broad application prospect in arid and semi-arid areas, especially those along the Belt and Road.

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