Damage by wind-blown sand and its control measures along the Taklimakan Desert Highway in China (Postprint)

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Abstract

Desertification is one of the most serious environmental problems in the world, especially in the arid desert regions. Combating desertification, therefore, is an urgent task on a regional or even global scale. The Taklimakan Desert in China is the second largest mobile desert in the world and has been called the " Dead Sea'' due to few organisms can exist in such a harsh environment. The Taklimakan Desert Highway, the longest desert highway (a total length of 446 km) across the mobile desert in the world, was built in the 1990s within the Taklimakan Desert. It has an important strategic significance regarding oil and gas resources exploration and plays a vital role in the socio-economic development of southern Xinjiang, China. However, wind-blow sand seriously damages the smoothness of the desert highway and, in this case, mechanical sand control system (including sand barrier fences and straw checkerboards) was used early in the life of the desert highway to protect the road. Unfortunately, more than 70% of the sand barrier fences and straw checkerboards have lost their functions, and the desert highway has often been buried and frequently blocked since 1999. To solve this problem, a long artificial shelterbelt with the length of 437 km was built along the desert highway since 2000. However, some potential problems still exist for the sustainable development of the desert highway, such as water shortage, strong sandstorms, extreme environmental characteristics and large maintenance costs. The study aims to provide an overview of the damages caused by wind-blown sand and the effects of sand control measures along the Taklimakan Desert Highway. Ultimately, we provide some suggestions for the biological sand control system to ensure the sustainable development of the Taklimakan Desert Highway, such as screening drought-resistant species to reduce the irrigation requirement and ensure the sound development of groundwater, screening halophytes to restore vegetation in the case of soil salinization, and

planting cash crops, such as Cistanche, Wolfberry, Apocynum and other cash crops to decrease the high cost of maintenance on highways and shelterbelts.

Full Text

Preamble

Damage by Wind-Blown Sand and Its Control Measures Along the Taklimakan Desert Highway in China

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Abstract

Desertification is one of the most serious environmental problems worldwide, particularly in arid desert regions, making its control an urgent task on regional and global scales. The Taklimakan Desert in China, the world' s second-largest mobile desert, has been called the "Dead Sea" due to the scarcity of organisms that can survive in such a harsh environment. The Taklimakan Desert Highway, the longest desert highway crossing a mobile desert globally (446 km total length), was constructed in the 1990s and holds important strategic significance for oil and gas exploration while playing a vital role in the socio-economic development of southern Xinjiang. However, wind-blown sand seriously damages the highway' s smooth operation. Early protection efforts employed a mechanical sand control system (including sand barrier fences and straw checkerboards), but unfortunately, more than 70% of these structures have lost their functionality, and the highway has frequently been buried and blocked since 1999.

To address this problem, a 437-km-long artificial shelterbelt was constructed along the desert highway beginning in 2000. Nevertheless, several challenges remain for sustainable development, including water shortages, intense sandstorms, extreme environmental conditions, and high maintenance costs. This study provides an overview of wind-blown sand damage and evaluates sand control measures along the Taklimakan Desert Highway. We offer recommendations for the biological sand control system to ensure sustainable development, including screening drought-resistant species to reduce irrigation requirements and protect groundwater, selecting halophytes to restore vegetation in saline soils, and planting cash crops such as Cistanche, Wolfberry, and Apocynum to offset high maintenance costs.

Keywords: wind-blown sand; sand barrier fences; artificial shelterbelt; mechanical sand control measure; biological sand control measure; sustainable development; Taklimakan Desert Highway

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1 Introduction

Desertification, a symbol of environmental degradation and economic poverty, represents an urgent global environmental problem that has attracted worldwide attention (Malagnoux et al., 2007; Ofori and Showstack, 2010; Yu et al., 2017). Beyond threatening the environment, desertification also impedes global economic development. According to the United Nations Development Program (UNDP), global desertification is increasing at a rate of approximately 5.0×10^{4}–7.0×10^{4} km^2/a, causing economic losses totaling 42.31×10^{9} USD annually and affecting about two-thirds of dryland regions across 54 countries.

China is among the most severely desertified countries worldwide (Nash, 1999), with desertification particularly severe in Xinjiang Uygur Autonomous Region, a typical arid and semi-arid area (Tuoheti et al., 2013; Li et al., 2015). Forestation has proven to be a vital eco-engineering measure for combating desertification and is widely employed in fragile regions globally (Cao, 2008; Li et al., 2018). However, situations become particularly complex when forestation projects are implemented in mobile desert regions such as the Taklimakan Desert in southern Xinjiang (Li et al., 2017).

The Taklimakan Desert, the world' s second-largest mobile desert, is located in the hinterland of the Tarim Basin in southern Xinjiang. It is an extremely arid region with mean annual precipitation of less than 50 mm and mean annual pan evaporation of 3000 mm, with no surface runoff (Lei et al., 2008; Zhang et al., 2017; Wang et al., 2018; Dong et al., 2020). Wind-blown sand poses a serious environmental problem, and the simple vegetation community structure means most areas lack organisms entirely, earning the region its "Dead Sea" designation due to the harsh environment (Chen, 1993; Lei et al., 2008; Wang et al., 2008; Li et al., 2015). Following the discovery of abundant oil and gas resources, the Taklimakan Desert Highway—the world' s longest desert highway across a mobile desert—was initially constructed in 1993 and completed in 1995. Spanning 446 km, the highway holds important strategic significance for oil and gas exploration and Tarim Basin development, while playing a vital role in southern Xinjiang' s socio-economic development (Zhou et al., 2006; Li et al., 2015).

Early protection employed mechanical control measures such as sand barrier fences, but unfortunately, more than 70% of these fences and straw checkerboard barriers have lost their functions since 1999, with the highway frequently buried and blocked. Consequently, a 437-km-long green corridor (artificial shelterbelt) was built along the highway to provide protection (Xu et al., 2006; Huang et al., 2015; Zhang et al., 2016). However, challenges remain for sustainable development, including water shortages, strong sandstorms, extreme environmental characteristics, and high maintenance costs. This study thoroughly discusses the causes of wind-blown sand damage and its threats to the Taklimakan Desert Highway, systematically describes sand control measures along the highway, evaluates the efficiency of mechanical and biological systems, and provides recommendations for the biological sand control system to ensure sustainable development.

2 The Causes of Wind-Blown Sand Damage

Wind-blown sand damage requires three basic conditions: strong wind power, complex landforms, and abundant sand sources (Lei et al., 2008). Unfortunately, all these conditions occur along the Taklimakan Desert Highway, making it highly susceptible to wind-blown sand damage.

2.1 Strong Wind Power

The degree of wind-blown sand damage correlates with sand blowing intensity; stronger winds cause greater damage, making wind power intensity a reliable indicator of damage severity (Han et al., 2003). The Taklimakan Desert experiences serious wind-blown sand problems, characterized by an annual average wind speed of 2.0 m/s, maximum instantaneous wind speeds of 20.0 m/s, and sand-shifting windy weather exceeding 130 days per year. Wind patterns are primarily controlled by airflow through the eastern gap in the Tarim Basin and downdrafts from the Tianshan Mountains (Dong et al., 2004; Zhang et al., 2017). These strong, steady winds provide the dynamic conditions necessary for wind-blown sand activity along the highway.

2.2 Complex Landforms

Topography influences sand movement primarily through wind power redistribution, affecting airflow direction, form, and strength. Complex landforms serve as both the exchange interface for wind-sand energy and material and the product of wind-sand interactions. Along the Taklimakan Desert Highway, complex and diverse landforms—particularly the varied shapes and scales of sand dunes—greatly differentiate both sides of the highway and significantly impact wind-blown sand processes (Zhu et al., 1981; Wang et al., 2000).

2.3 Abundant Sand Sources

Wind-blown sand coverage is extensive along the Taklimakan Desert Highway, with sand composed primarily of fine and very fine particles. Approximately 61.3% of the highway region is covered by mobile sand dunes on both sides, with fine and very fine sand particles constituting nearly 90.0% of the total sand content (Chen, 1993). Additionally, incomplete soil development and low plant coverage along the highway further increase sand availability (Dong et al., 2004).

3 Wind-Blown Sand Damage to the Desert Highway

Wind-blown sand damage to the desert highway typically involves three dynamic processes (Johnson, 1996; Khier et al., 2000; Han et al., 2007). The first is aeolian erosion, which occurs primarily in regions with strong winds, bare surfaces, and sparse vegetation (Copley, 1987; Bergstrom et al., 1992; Zhang et al., 2010). Most highway sections lie in the center of strong windy regions experiencing over 130 days of sand-shifting wind annually, providing sufficient energy for sand activities (Wang et al., 2008). The second process is sand aggregation that buries sand barrier fences and straw checkerboard barriers, ultimately depositing sand on the road surface and shoulders. The third is moving dune coverage on the road surface and shoulders.

3.1 Aeolian Erosion

Aeolian erosion primarily undercuts and displaces sand barrier fences along the Taklimakan Desert Highway. When airflow encounters a fence, it forms a reflux at the fence' s interior base, which induces wind-blown sand materials to gradually undercut and move the fence' s fixed piles. Ultimately, these piles lose stability or become completely exposed. Combined with wind pressure effects, the sand barrier fences become lodged and lose resistance. In sand-fixing bands, aeolian erosion on straw checkerboard barriers creates blowout pits within a certain range on both the windward and leeward dune slopes.

3.2 Sand Aggregation

Sand aggregation forms when wind speed decreases after encountering obstacles, reducing wind' s capacity to transport sand and causing deposition on road surfaces and shoulders. In the desert highway' s sand control system, sand aggregation forms around sand barrier fences and buries them when sand flow encounters their periphery. As the fences' resistance weakens, sand flow on the leeward side forms sand-fallen slopes that advance as shifting sand. Once formed within the sand control system, this sand flow produces stranded sand, buries straw checkerboard barriers, and creates sheet-sand aggregation on road surfaces and shoulders, endangering highway smoothness.

3.3 Moving Dune Coverage

Moving dune coverage results from sand aggregation and manifests as forward dune movement and burial of the sand control system or desert highway. Beyond risking peripheral burial of the sand control system, dune movement also covers straw checkerboard barriers as well as road surfaces and shoulders.

4 Sand Control Measures

4.1 Mechanical Sand Control Measures

The mechanical sand control system comprises two components: sand-blocking (sand barrier fences such as reeds and nylon mesh) and sand-fixing (straw checkerboard barriers). From exterior to interior, the specific structure consists of sand barrier fences (e.g., reeds or nylon mesh), a deposited sand belt, and straw checkerboard barriers (Fig. 1 [Figure 1: see original paper]) (Lei et al., 2003; Zhang et al., 2009). The sand barrier fences stand approximately 1.1 m high and are arranged in parallel at the highway' s outermost edge as a sand-blocking belt. The deposited sand belt, typically 10–20 m wide, accumulates between the fences as a sand-fixing belt. The straw checkerboard grid measures 1 m × 1 m, with widths of 50–70 m on the windward side and 40–60 m on the leeward side (Xu et al., 2006).

Since 1999, more than 70% of sand barrier fences and straw checkerboard barriers along the Taklimakan Desert Highway have lost their functions. Most fences have been buried (Fig. 2a [Figure 2: see original paper]), large amounts of sand have aggregated in the straw checkerboard barriers (Fig. 2b), and ultimately, shifting sand or dunes have buried the highway (Fig. 2c) (Lei et al., 2003). Table 1 shows that damage to straw checkerboard barriers in typical sections increased from March 1997 to May 1999, with total damaged area reaching 90.50% on the east side and 77.77% on the west side by May 1999. Sand barrier fences showed a similar trend, with total damaged area reaching 89.85% on the east side and 75.81% on the west side by May 1999 (Table 2).

4.2 Biological Sand Control Measures

In 2000, a 437-km-long eco-engineering artificial shelterbelt was constructed along the Taklimakan Desert Highway to prevent desertification. This biological sand control system includes 40 species from three genera (Haloxylon, Tamarix, and Calligonum) and spans 70–100 m in width. The system comprises sand-blocking and sand-fixing components arranged in three patterns (Fig. 3 [Figure 3: see original paper]). At interdune and sparsely distributed dune sections, the windward structure consists of four belts: two sand-fixing belts and two sand-blocking belts (Fig. 3a). At ridge-depression transition sections, three belts are arranged: sand-fixing belt–sand-fixing belt–sand-blocking belt (Fig. 3b). At high compound ridge sections, two belts are distributed: sand-fixing belt–sand-fixing belt (Fig. 3c). Plant species are irrigated using saline groundwater along the highway (Xu et al., 2006).

The artificial shelterbelt currently appears stable, providing multiple benefits for sand erosion control along the highway (Fig. 4 [Figure 4: see original paper]). First, it effectively reduces wind speed and controls aeolian erosion. Wind speed at 1.0 m above mobile dunes reaches 6.6 m/s but decreases to 1.5–3.3 m/s within the shelterbelt, generally preventing sand from blowing onto the road surface except under strong sandstorm conditions (Lei et al., 2008). Second, the shelterbelt improves soil properties by increasing water and nutrient contents (C, N, and P) while decreasing bulk density, gradually transforming aeolian soil into fixed and semi-fixed soil (Gu et al., 2000; Jin et al., 2008). Third, it enhances biodiversity, particularly for herbs and animals, with approximately 13 herb species recorded since construction, benefiting vegetation recovery (Zhang et al., 2011). Fourth, the shelterbelt ameliorates local microclimate by decreasing air temperature and increasing relative humidity through plant transpiration and canopy interception of solar radiation (Lei et al., 2008). Additionally, it enhances carbon sequestration capacity through photosynthesis (Mariscal et al., 2007). In summary, the artificial shelterbelt not only ensures highway smoothness but also improves the local ecological environment, playing a vital role in ecological restoration and environmental protection in the Taklimakan Desert.

4.3 Effects of Different Sand Control Measures Along the Taklimakan Desert Highway

Researchers have conducted various experiments on mechanical, biological, and chemical sand control measures to evaluate their effectiveness (Table 3). Results indicate that chemical measures are ineffective and have not been applied to the entire protection system. Regarding ecological benefits and sustainability, biological measures outperform mechanical and chemical approaches, though they require higher initial investment. Specifically, biological sand control investment is 2–3 times greater than the other measures over short terms (<15 years) (Gong et al., 2001). However, considering long-term sustainability, eco-efficiency, and desert industry development, biological measures likely reduce investment costs over extended periods, making them the most effective protection measure for sustainable highway development.

Table 3. Effects and Investment of Different Sand Control Measures

Sand Control Measure	Effects	Investment (CNY/(km·a))	Ecological Benefit	Sustainability
Mechanical sand control measure	More than 70% of sand barrier fences are buried; straw checkerboard barriers contain aggregated sand; moving dunes bury the desert highway (Lei et al., 2008)	$0.50\times10^{6}-0.77\times10^{6}$ (Gong et al., 2001)	Unsustainable	Unsustainable

Sand Control Measure	Effects	Investment (CNY/(km · a))	Ecological Benefit	Sustainability
Biological sand control measure	More than 90% of artificial shelterbelt is effective; generally no sand on road surface except under strong sandstorm conditions (Lei et al., 2008)	1.30$\times10^{6}$–1.70$\times10^{6}$ (Gong et al., 2001)	Increases biodiversity; improves eco-environment (Lei et al., 2008; Zhang et al., 2011)	Sustainable
Chemical sand control measure	Ineffective (Xu et al., 1998)	0.40$\times10^{6}$–1.20$\times10^{6}$ (Gong et al., 2001)	Brings chemical materials to the desert, damaging the eco-environment (Xu et al., 1998; Han et al., 2000)	Unsustainable

Although the artificial shelterbelt significantly benefits highway smoothness and ecological restoration, sustainability challenges remain. While scientific shelterbelt planting may improve habitats and rehabilitate vegetation, the rationality of species selection and irrigation technology requires clarification. The long-term impacts of saline irrigation on plant quality and groundwater reserves and quality remain uncertain. Furthermore, without financial support, high maintenance costs (approximately 3.0×10^{7} CNY/a) hinder sustainable development of both the highway and shelterbelt. These issues require further in-depth study.

We propose several recommendations. First, although current studies indicate that long-term saline irrigation has not impacted groundwater quality, future effects remain unknown (Zhang et al., 2016). Therefore, we should enhance long-term groundwater monitoring to understand hydrological dynamics and predict future trends (Fan et al., 2017; Wei et al., 2017). Additionally, screening drought-resistant species could reduce irrigation requirements and ensure groundwater sustainability (Li et al., 2015). Second, long-term saline irrigation inevitably causes soil salinity accumulation, making halophyte screening essential for vegetation restoration (Zhang et al., 2016). Third, given high maintenance costs for the highway and shelterbelt, improving economic efficiency is necessary. Planting cash crops such as Cistanche, Lycium, and Apocynum species could generate income. For example, inoculating Cistanche at suitable densities along the shelterbelt could yield 9.0×10^{6} CNY/a, while developing a biological salt industry could both increase income and remove salts from soil (Xu et al., 2006).

5 Conclusions

This study demonstrates that wind-blown sand damage through aeolian erosion, sand aggregation, and moving dune coverage poses significant threats to the Taklimakan Desert Highway. Comparisons of sand control measures indicate that the biological sand control system is the most effective approach for sustainable highway development. However, several problems still influence the sustainability of the biological system and highway. We therefore provide recommendations: first, screen drought-resistant species to reduce irrigation requirements and ensure groundwater sustainability; second, screen halophytes for vegetation restoration; and third, plant cash crops such as Cistanche, Wolfberry, and Apocynum to reduce high maintenance costs. In conclusion, desertification control and plant protection/restoration in desert regions should balance social, economic, and eco-efficiency benefits to ensure sustainable development.

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