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Sand Control Performance of Highway Comprehensive Protection Facilities in Desert Hinterland under Strong Wind Environment

Lu Wei

Xi'an Meinan Biotechnology Co, Ltd, Xi'an, Shaanxi, China

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Abstract: The highway in the hinterland of desert plays a key role in regional development, but the sand damage caused by strong wind poses a serious threat to it. The purpose of this paper is to deeply explore the sand prevention performance of highway comprehensive protection facilities in desert hinterland under strong wind environment, and to provide scientific basis for ensuring highway safety and smoothness. Through theoretical analysis method, with the help of theoretical knowledge such as wind-blown sand motion mechanics and aerodynamics, the comprehensive protection facilities are studied. It is clear that the comprehensive protection facilities are composed of sand fence, sand-fixing grid and shelterbelt, and each part plays a role in sand prevention through different principles, such as sand fence changing airflow and reducing wind speed to intercept sand particles, sand-fixing grid increasing roughness and binding sand particles, and shelterbelt weakening airflow and fixing soil. Through theoretical model analysis, it is concluded that different protective facilities have different contributions to each index, and the effect of sand prevention can be significantly enhanced when they work together. The research results have laid a solid theoretical foundation for optimizing the design and layout of highway comprehensive protection facilities in the hinterland of desert and improving the efficiency of sand prevention.

1. Introduction

In today's society, transportation plays a vital role in regional economic development [1]. As a key channel connecting the desert area with the outside world, the construction and maintenance of the highway in the desert hinterland is of great significance for promoting the resource development, economic exchange and social development in the desert area [2]. However, the special natural environment in the desert area, especially the frequent windy weather, has brought serious sand damage to the highways in the hinterland of the desert [3]. Strong winds with dust will not only bury roads and affect normal traffic, but also cause wind erosion damage to highway infrastructure, shorten the service life of roads and increase maintenance costs [4]. Therefore, how to effectively prevent sand damage and ensure the safety and smoothness of highways in the hinterland of desert has become an important issue to be solved urgently.

Comprehensive protection facilities are the key means to prevent sand damage on desert roads, and their sand prevention performance is directly related to the protection effect [5]. In-depth study on the sand prevention performance of highway comprehensive protection facilities in desert hinterland under windy environment is helpful to reveal the internal mechanism of sand damage prevention and provide scientific basis for optimizing the design of protection facilities and improving the protection effect. Through the rational layout and optimal configuration of comprehensive protection facilities, the harm of sandstorm to roads can be reduced more effectively, the service life of roads can be prolonged, and the safety and smoothness of transportation can be guaranteed.

At present, although some research achievements have been made in the field of desert highway protection, the systematic theoretical research on the sand prevention performance of comprehensive protection facilities in desert hinterland under strong wind environment is still relatively insufficient. Part of the research focuses on a single protection facility, lacking the overall consideration of the comprehensive protection system; The pertinence and operability of some studies in practical application need to be improved. Based on this, this paper makes an in-depth study on the sand prevention performance of comprehensive protection facilities in desert hinterland highway in windy environment, aiming at filling the relevant theoretical gaps and providing more scientific and effective theoretical support for sand disaster prevention and control of desert highway.

2. Gale environment and desert hinterland highway sand damage mechanism

The windy environment in the hinterland of desert has unique characteristics. Its formation is mostly due to the large-scale air pressure difference, and the underlying surface in desert area has uniform properties and low friction, which makes the wind force easy to gather and strengthen [6]. Judging from the temporal and spatial distribution, strong winds are mostly concentrated in specific seasons, such as spring, and change significantly day and night. As far as wind speed is concerned, it can often reach a high value, and the instantaneous maximum wind speed can even exceed 25m/s, and the wind direction is also changeable, which creates dynamic conditions for sandstorm activities.

Sand burial is one of the most common types of sand damage on highways in the hinterland of desert [7]. Strong winds carry a lot of dust. When the wind speed decreases or meets obstacles, the dust settles and accumulates on the highway, which seriously affects the highway capacity. Wind erosion can't be ignored, too. Strong wind erodes highway pavement, subgrade and ancillary facilities, resulting in pavement materials peeling off and subgrade hollowing out, which reduces the stability of highway structure. In addition, wind and sand wear will damage the surface of signs, fences and other facilities along the highway, affecting their normal functions.

From the point of view of aeolian sand movement mechanics, under the action of strong wind, sand grains on the desert surface begin to start. When the wind speed reaches the initial wind speed of sand particles, the sand particles break away from the static state and move by jumping, crawling and hanging [8]. As an obstacle in the desert, the highway changes the airflow structure near the ground, which leads to the decrease of wind speed, promotes the sedimentation and accumulation of sand particles in the wind-blown sand flow, and forms wind-blown sand burial. At the same time, high-speed sand particles impact and rub the surface of highway facilities, causing wind erosion and wear damage. This complicated interaction between wind-blown sand movement and highway is the fundamental reason for the formation of highway sand damage in the hinterland of desert.

3. Composition and principle of comprehensive protection facilities

The highway in the hinterland of desert is facing the severe threat of sand damage, so it is very important to build an effective comprehensive protection facility system [9]. The system consists of a variety of protective facilities with different functions, which cooperate with each other to play a role in sand prevention.

3.1. Composition of comprehensive protection facilities

Sand fence: usually set at a certain distance on the windward side of the highway, it is the first line of defense to stop sandstorms. It is generally made of wood, plastic or metal, and it can reduce the wind speed and intercept the sand particles in the sand flow through a specific structural form. The height, porosity and structural form of sand barrier have a significant influence on its sand barrier effect.

Sand-fixing grid: Wheat straw, rice straw and other materials are used to lay a grid on the desert surface to fix the sand surface to prevent sand from being blown up by the wind. On the one hand, the sand-fixing grid increases the ground roughness and reduces the near-surface wind speed; On the other hand, the sand is bound in the grid, which effectively inhibits the source of sandstorm.

Shelterbelt: Plant varieties with strong drought and sand resistance, such as Hippophae rhamnoides and Haloxylon ammodendron, are selected and planted on both sides of the highway to form shelterbelts. Shelterbelt can not only reduce wind speed, but also fix sand through vegetation roots, reduce the harm of sandstorm to roads, and also improve the ecological environment.

3.2. Sand prevention principle of each protection facility

Sand prevention principle of sand barrier: According to the aerodynamic principle, when the wind-blown sand flow meets the sand barrier, the airflow is blocked, the streamline changes, and a vortex area is formed before and after the barrier, and the wind speed decreases rapidly [10]. As shown in Table 1 Comparison of Wind Speed Reduction Effects of Sand Barrier with Different Porosity, the wind speed of sand barrier with 30% porosity can be reduced by 40%-50% within the height range of 1-2 times from the fence. The decrease of wind speed weakens the ability of sand transport by wind-blown sand flow, and a large number of sand particles settle and accumulate near the fence, thus reducing the amount of sand transported to the highway.

Table 1 Comparison of Wind Speed Reduction Effects of Sand Barrier with Different Porosity

Porosity of sand barrier	Wind speed reduction rate at the height of 1 time from the fence	Wind speed reduction rate at 2 times height from fence
20%	55%	48%
30%	50%	40%
40%	42%	35%
50%	35%	30%

Sand prevention principle of sand-fixing grid: The sand-fixing grid destroys the stability of near-surface airflow by increasing the surface roughness, so that the near-surface wind speed decreases sharply. The research shows that the wind speed can be reduced by 60%-80% in the height of 0-20cm near the ground after laying the sand-fixing grid. At the same time, the sand in the grid is blocked and bound by the grid material, which makes it difficult to start, effectively controlling the source of sandstorm and reducing the erosion of sandstorm on the highway.

Sand prevention principle of shelterbelt: The vegetation in shelterbelt has strong wind-proof and sand-fixing ability. The branches and leaves of vegetation can weaken the energy of airflow and

reduce the wind speed. Its roots go deep into the ground, firmly fixing soil particles and preventing soil wind erosion. In addition, litter in the forest belt can increase the surface coverage and further reduce sandstorm activities. According to the observation, the shelterbelt with a width of 50m can reduce the wind speed by 30%-40% within the range of 20 times the tree height on the leeward side, thus effectively protecting the highway from sandstorm.

Comprehensive protection facilities work together in different ways to form a multi-level and all-round sand prevention system, which greatly improves the protection effect of highways in the hinterland of desert.

4. Theoretical analysis of sand control performance of comprehensive protection facilities

4.1. Construction of sand control performance evaluation index

In order to scientifically evaluate the sand prevention performance of highway comprehensive protection facilities in desert hinterland under strong wind environment, it is necessary to construct a reasonable evaluation index system. Sand accumulation is a direct index to measure the sand prevention effect of protective facilities, which refers to the amount of sand accumulated behind protective facilities or on highway pavement in unit time and unit area. The less sand accumulation, the stronger the ability of protective facilities to stop sand storms. The reduction rate of wind speed reflects the weakening degree of wind speed by protective facilities. The more significant the reduction of wind speed is, the weaker the ability of sand transport by wind-blown sand is, and the better the sand control effect is. In addition, the stability index of protective facilities is also very important, which is related to whether protective facilities can continue to play a role under long-term wind and sand erosion.

4.2. Analysis of sand control performance based on theoretical model

Based on the mathematical model of wind-sand flow and aerodynamic theory, the sand control performance of comprehensive protection facilities under different gale conditions is simulated and analyzed. Taking a typical highway section in the hinterland of desert as an example, different parameters of wind speed, wind direction and protective facilities are set for simulation. Table 2, Sediment Accumulation and Wind Speed Reduction Rate of Comprehensive Protection Facilities under Different Wind Speed, shows the changes of sediment accumulation and wind speed reduction rate of comprehensive protection facilities under different wind speed conditions. As can be seen from the data in the table, with the increase of wind speed, the amount of sediment is on the rise, while the rate of wind speed reduction fluctuates. When the wind speed is 10m/s, the sediment accumulation is 0.5 kg/m, and the wind speed reduction rate reaches 35%. The wind speed increased to 15m/s, the sand deposition increased to 1.2 kg/m, and the wind speed decreased slightly to 32%. This shows that in a certain range, the comprehensive protection facilities can still maintain a relatively stable wind speed reduction ability, although the wind speed increases, which leads to an increase in sand accumulation.

Further analysis shows that the contribution of different protective facilities to each evaluation index is different. The sand barrier plays a significant role in reducing the amount of accumulated sand at high wind speed, and can effectively intercept the long-distance transportation of wind-blown sand flow. Sand-fixing grid mainly acts on the near surface, which greatly reduces the near-surface wind speed and reduces the source of wind and sand, and has a great influence on the overall wind speed reduction rate. Shelterbelt, with its multi-level structure, can reduce the wind speed and enhance the overall stability of protective facilities through vegetation roots. For example, when the wind speed is 18m/s, the sand accumulation can be reduced by about 40% by a single

sand barrier, while the sand accumulation can be reduced by more than 60% by combining the sand-fixing grid with the shelterbelt.

Table 2 Sediment Accumulation and Wind Speed Reduction Rate of Comprehensive Protection Facilities under Different Wind Speed

Wind speed (m/s)	Sediment accumulation (kg/m^3)	Wind speed reduction rate (%)	Stability evaluation of protective facilities
10	0.5	35	Good, no obvious deformation of the structure.
12	0.8	33	Good, slightly worn locally.
15	1.2	32	Generally, some components show signs of loosening.
18	1.8	30	Poor, need timely maintenance and reinforcement.

Through theoretical model analysis, the sand control performance characteristics of comprehensive protection facilities in different windy environments are comprehensively understood, which provides a theoretical basis for optimizing the layout and parameter design of protection facilities. This is helpful to improve the overall sand control efficiency of comprehensive highway protection facilities in the hinterland of desert.

5. Conclusions

In this paper, the sand control performance of highway comprehensive protection facilities in desert hinterland under strong wind environment is systematically studied, and the following main results are obtained.

In terms of gale environment and sand damage mechanism, it is clear that the gale in the hinterland of desert is mostly formed by large-scale air pressure difference, which has the characteristics of high wind speed, changeable wind direction and concentrated seasons. The sand hazards caused by this, such as sand burial, wind erosion and sand wear, seriously affect the normal use and structural safety of highways, and its root cause lies in the interaction between sand movement and highways. Aiming at the comprehensive protection facilities, its composition and principle are analyzed. Sand fence, sand-fixing grid and shelterbelt jointly construct a comprehensive protection system, which can effectively reduce the harm of sandstorm to roads by reducing wind speed, fixing sand surface and weakening airflow energy. By constructing sand accumulation, wind speed reduction rate and stability and other evaluation indexes of sand prevention performance, the theoretical model is used to simulate and analyze the protection effect under different gale conditions. The results show that the change of wind speed has a significant impact on the sediment accumulation and the reduction rate of wind speed, and different protection facilities contribute differently to each index. Sand-blocking fence has an outstanding effect on intercepting long-distance wind-blown sand. The sand-fixing grid focuses on reducing near-surface wind-blown sand sources, while the shelterbelt enhances the overall stability, and the synergistic effect of various facilities greatly improves the sand prevention efficiency.

This study provides an important theoretical support for the optimal design of highway comprehensive protection facilities in desert hinterland. However, in practical application, complex factors such as geographical environment differences and climate change need to be considered. Future research can focus on the long-term performance monitoring of protection facilities and the coordination with desert ecosystem, further improve the desert highway protection system and

ensure the sustainable operation of the highway.

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