Postprint: Technical Solutions for Wind-Sand (Snow) Hazard Prevention and Control on Major Transportation Arteries of the Mongolian Plateau

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Abstract

The construction of the China-Mongolia-Russia Economic Corridor represents a crucial component of the "Belt and Road Initiative," establishing connectivity between the Silk Road Economic Belt, Russia' s Trans-Eurasian Railway, and Mongolia' s "Steppe Road," thereby playing a pivotal role in advancing regional economic cooperation. Regional natural disaster prevention and control constitutes a critical factor for the construction and safe operation of land transportation arteries. Within the Mongolian Plateau section of the China-Mongolia-Russia Economic Corridor, the combined impacts of climate change and human activities have led to widespread grassland degradation and wind erosion desertification, rendering wind-blown sand (snow) hazard prevention and control a paramount issue for safeguarding regional transportation arteries. Drawing upon relevant experimental and theoretical analyses from previous research and extensive field investigations, this study provides a comprehensive review of the primary types and formation mechanisms of wind-blown sand (snow) hazards currently affecting transportation arteries on the Mongolian Plateau, and anticipates that road surface sand accumulation will emerge as the dominant sand hazard type for future high-grade highways. Furthermore, in response to wind-blown sand (snow) hazards affecting existing highways and railways as well as future high-grade highways, and considering the unique ecological and environmental characteristics of the Mongolian Plateau, corresponding prevention and control technical schemes and constructive recommendations have been developed, which can furnish scientific and technological support for the construction of transportation arteries in the Mongolian Plateau section.

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Full Text

Ecological Restoration and Control Technology Schemes for Hazards of Windblown Sand and Snow Along Primary Communication Lines in the Mongolian Plateau

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Abstract

The construction of the China-Mongolia-Russia Economic Corridor represents a crucial component of the "Belt and Road" Initiative, connecting the Silk Road Economic Belt with Russia' s Eurasian Railway and Mongolia' s "Steppe Road" to facilitate regional economic cooperation. Natural disaster prevention and control is essential for the construction and safe operation of land transport arteries. Under the combined influences of climate change and human activities, grassland degradation and wind erosion desertification are widespread across the Mongolian Plateau, making windblown sand and snow hazard control a critical issue for regional transportation infrastructure. Based on previous experimental and theoretical analyses and extensive field investigations, this paper systematically reviews the primary types and formation mechanisms of windblown sand and snow hazards affecting transport arteries in the Mongolian Plateau. It predicts that road surface sand accumulation will become the main type of sand hazard for future high-grade highways. Drawing on China' s achievements in ecological restoration of degraded ecosystems and sand/snow hazard control in sandy areas, this study formulates targeted prevention and control technical schemes and constructive recommendations for existing roads and railways as well as future high-grade highways, tailored to the ecological characteristics of the Mongolian Plateau. These proposals aim to provide scientific and technological support for the construction and maintenance of transport arteries across the region.

Keywords: main lines of communication; hazards of windblown sand and snow; ecological restoration; prevention scheme; Mongolian Plateau

1. Natural Environment Background of the Mongolian Plateau

The Mongolian Plateau is situated in eastern Eurasia, bounded by the western foothills of the Greater Khingan Mountains to the east, the Altai and Sayan Mountains to the west, the Yinshan Mountains to the south, and the Sayan, Khentii, and Yablonovy Ranges to the north [1]. Encompassing the entirety of Mongolia, parts of southern Russia, northern Inner Mongolia in China, and portions of northern Xinjiang, the plateau covers approximately 272$\times10^{4}$ km^2 [2]. As a vast, gently undulating highland with an average elevation of about 1,580 m, the terrain slopes gradually downward from surrounding mountains toward the central high plain, with numerous mountains in the north and west, extensive hills in the central and eastern regions, and broad plains in the southeast [3].

Influenced by moisture from both the Arctic and Pacific Oceans, the plateau features a temperate continental climate characterized by aridity, scarce precipitation, long and cold winters, dry and windy springs, short hot summers, and cool autumn seasons. The Hangay Mountains mark the boundary between inland and exorheic drainage basins, while the Khentii Mountains serve as the watershed between Arctic and Pacific Ocean basins [4]. Mean annual precipitation is approximately 269 mm, with the highest values (300–400 mm) occurring in the Sayan and Khentii ranges and the plains east of the Greater Khingan Mountains. Precipitation gradually decreases from north to south and from east to west, reaching a minimum of only 100 mm in the southwestern region. The climate exhibits distinct zonal patterns, transitioning from semi-humid zones in the north and east to semi-arid, arid, and hyper-arid zones toward the southwest.

Vegetation distribution shows corresponding zonal patterns, progressing from forests and forest-steppe to meadow steppe, typical steppe, desert steppe, Gobi desert, and farming-pastoral ecotone from north to south and east to west [5]. Associated soil types include gray forest soil, chernozem, black and chestnut soils, brown calcic soil, and gray-brown desert soil [6]. Vegetation cover, plant species diversity, soil nutrients, and sand content display a distribution pattern of high values in the north and south with lower values in the central region [7].

2. Regional Wind Erosion and Desertification Issues

From northeast to southwest across the Mongolian Plateau, rainfall gradually decreases while vegetation transitions from typical steppe to desertified steppe, steppe-desert, and Gobi, with steppe dominating the landscape. Vegetation cover and aboveground net primary productivity progressively decline. Due to its high latitude, the Mongolian steppe experiences strong southerly movement of Siberian cold air in spring, generating frequent high winds before vegetation green-up when ground cover is minimal. This results in high soil wind erosion rates and frequent dust storms, reaching moderate erosion levels [8].

The fragile ecological environment of the Mongolian Plateau is highly sensitive to climate change, particularly precipitation variation. Since 1960, the plateau' s mean annual temperature has increased at approximately 1.5 times the global average rate, while annual precipitation has generally decreased [9]. Since 1990, warming and drying trends have become more pronounced, with significant reductions in summer and autumn rainfall [10]. Grassland productivity is strongly influenced by precipitation, following a degradation pattern from meadow steppe to desert steppe during dry periods, with substantial forage yield reductions [11]. Grassland desertification has become increasingly evident.

Since the 1990s, Mongolia has experienced two major episodes of farmland reclamation, with 120×10^{4} hm^2 of unsuitable land brought under cultivation by 1990. Due to low yields, most of these lands were subsequently abandoned, creating severe wind erosion [12]. Over 70% of Mongolian territory now shows varying degrees of desertification [13], concentrated around cities, soums (districts), lakes, rivers, and mining areas within steppe, Gobi, and other desert zones.

Under the plateau' s strong and frequent winds, surface sand flow is active, dust events are common, degraded grasslands suffer severe wind erosion and sandification, and surface mechanical composition has significantly coarsened. Poor vegetation cover provides little snow retention capacity, making stable snowpack formation difficult in normal years. Summer droughts ("black disasters") and early winter or spring snow disasters ("white disasters") occur frequently [14], causing enormous socioeconomic losses [15]. Windblown snow is particularly active during blizzard conditions, representing a major cause of road traffic disruption [16]. Both sand flow and snow flow are gas-solid two-phase flows [17] with similar movement patterns and hazard mechanisms for transport infrastructure.

3. Types and Formation Mechanisms of Windblown Sand and Snow Hazards

3.1. Roadbed-Induced Hazards Field investigations in Mongolia reveal that during dust events, windblown sand reduces visibility dramatically while active sand flow occurs at the surface. Large amounts of sand accumulate at the base of residential walls, along roadbed slopes, within safety fences, and in roadbed culverts [Figure 4: see original paper]. Since some sand/snow flow can cross the road surface (ballast) to the leeward side, accumulation on the road surface is generally limited to poor visibility affecting traffic safety. However, at locations with minor topographic protrusions, vegetation patches, or cut sections, local airflow disturbance causes velocity reduction and decreased transport capacity, resulting in shadow deposition in wind-protected areas that forms sheet or tongue-shaped accumulations on shoulders and road surfaces [Figure 4: see original paper].

3.2. Safety Barrier-Induced Hazards Spring winds are strong across the Mongolian Plateau, with poor vegetation and snow cover, dry surface soils, active sand movement, and frequent dust events, making the region a major source of global dust storms [18]. Dust events often coincide with blizzards [19]. Investigations in Zamyn-Uud revealed that on highways with W-beam guardrails, continuous strip-shaped sand accumulation forms on the pavement [Figure 5a: see original paper]. Research shows that as sand thickness on road surfaces increases, friction coefficients first decrease then increase [Figure 5b: see original paper], significantly affecting traffic safety and potentially causing accidents and road closures [20]. Similar phenomena occur frequently on high-grade highways in China' s sandy areas [21], differing from sand burial caused by failed protection systems [22]. Instead, high wind-resistance W-beam guardrails (28 cm wide, continuously distributed) disturb the airflow field, abruptly slowing crosswind flow and reducing transport capacity, causing sand flow deposition on road surfaces [23]. Additionally, W-beam guardrails, concrete barriers, central dividers, and anti-glare facilities can all induce road surface sand accumulation. Similarly, these high wind-resistance barriers easily cause snow accumulation [24], compromising traffic safety.

Currently, windblown sand and snow hazards remain relatively light on Mongolian Plateau transport arteries, with few high-grade highways constructed. However, future regional economic and social development will require upgrading existing routes and constructing more high-grade highways, necessitating proactive research and development of appropriate hazard prevention technologies.

4. Prevention and Control Technologies for Windblown Sand and Snow Hazards

Based on China' s experience in controlling windblown sand and snow hazards along transport arteries and considering the natural environment, current construction status, and future development trends of the Mongolian Plateau, technical solutions have been formulated.

4.1.1. Control of Windblown Sand and Snow Hazards on Existing Roads Hazard-prone sections of existing roads in the Mongolian Plateau are mainly located in cut sections and curves [25]. In these areas, artificial protection measures should be implemented on the windward side to enhance sand/snow interception capacity and reduce deposition on roads.

Natural vegetation in the Mongolian Plateau possesses ecological restoration potential. The vegetation difference inside and outside the safety fence along Mongolia' s north-south railway [Figure 6: see original paper] demonstrates that enclosure measures alone can restore relatively good vegetation conditions [26] with certain sand/snow interception capacity. Additionally, various types of high vertical sand barriers can be employed in severely affected areas to significantly reduce near-surface wind speeds and create strong sand/snow interception capacity [27].

4.1.2. Control of Windblown Sand and Snow Hazards on Future High-Grade Highways Safety facilities are essential components of high-grade highways. Research indicates that adjusting guardrail structure is key to preventing road surface sand/snow hazards, as it can substantially reduce airflow obstruction [28]. Cable guardrails with relatively low wind resistance are important alternatives to conventional barriers [29,37,41], but due to strength and safety concerns, they are currently only used as roadside guardrails, not as central dividers. Other modified rigid guardrails still create considerable wind resistance [30] and cannot effectively prevent road surface sand/snow hazards.

According to high-grade highway construction standards, roadside guardrails prevent vehicles from leaving the roadway, while medians and central dividers separate opposing traffic flows. For high-grade highways with integral cross-sections, medians must be installed when width is $ $12 m [31]. Therefore, under current technical conditions, high-grade highways with separated cross-sections can avoid central dividers and better prevent road surface sand/snow hazards. The Jingxin Expressway in China has adopted separated subgrade sections in some areas, effectively solving road surface sand hazards while reducing construction costs.

4.2.1. Anti-Sand/Snow Technical Solution for Low-Grade Roads—Mechanical-Plant Composite Protection Along the Mongolian Plateau section of the China-Mongolia-Russia Economic Corridor, low-grade roads experience frequent grazing activities. Herds and vehicles heavily disturb the surface, creating degraded vegetation and wind erosion zones along highways [32], particularly evident in desert steppe areas. Mongolian Plateau vegetation relies primarily on summer rainfall, with herbaceous plants having shallow root systems (~30 cm) and poor drought resistance, causing delayed green-up in years with low or late precipitation [33]. Shrubs have deeper root systems [34] and stronger drought resistance, enabling growth even with delayed rainfall and objectively inhibiting rapid grassland degradation while providing important forage, especially during white disasters [35].

Windblown snow represents a water resource that can be collected and utilized ecologically through artificial measures. By establishing shrub belts along highways, snow flow can be captured to create anti-sand/snow barriers. Typically, multiple rows of ventilated mechanical wind barriers are installed parallel to highways on the windward side at appropriate distances. Native shrub seedlings are planted on the leeward side of each mechanical barrier to create plant windbreaks, with shorter shrubs near the barriers and taller shrubs further away. Mechanical and plant barriers are arranged in segments with staggered layouts, leaving passages for livestock between segments.

Mechanical wind barriers reduce surface wind speeds and intercept sand/snow flow, creating suitable conditions for plant growth. As plant barriers mature, their interception capacity gradually increases, substantially reducing crosswind sand/snow flow and effectively controlling highway hazards. The mechanical-plant protection system lowers near-surface wind speeds, improves local microclimate, reduces soil water evaporation, maintains favorable soil moisture, and captures wind-dispersed seeds between barriers [36], promoting vegetation restoration. This artificially established shrub-grass composite ecosystem provides both sand and snow protection, offers emergency forage for livestock during hazardous weather, and demonstrates high productivity. Experimental results from Choyr in Gobi Sumbel Province, Mongolia, show this approach effectively intercepts crosswind sand/snow flow, improves local soil moisture conditions, and promotes ecological restoration [Figure 8: see original paper].

4.2.2. Anti-Sand/Snow Technical Solution for Railways–Ecological Wind Barriers Based on Safety Fences Grassland degradation is a primary cause of wind erosion desertification. Numerous studies demonstrate that enclosure is crucial for restoring overgrazed degraded grasslands by reducing herbivore disturbance [37]. Enclosure nets, commonly used for grassland protection, have large mesh sizes (generally 20 cm$×$20 cm) but can intercept wind-blown tumbleweeds to form grass-hanging nets that effectively accumulate sand/snow [38] and promote vegetation recovery within enclosures [Figure 9: see original paper].

Field investigations in China frequently observe perennial climbing plants growing on high-grade highway safety fences, which increase the fence' s wind resistance coefficient [Figure 10a: see original paper] and provide effective protection. Therefore, planting perennial climbing plants along enclosure nets can create durable ecological wind barriers that enhance fence windproof functions. In some grassland areas of the Mongolian Plateau with low and variable precipitation, water collection measures can increase local water availability for climbing plants. By digging trenches along the inner base of enclosure nets, covering the ridges with impermeable film, and planting climbing plant seeds or cuttings in trench-bottom soil before the rainy season, rainwater can be collected and directed to plant roots [Figure 10b: see original paper]. This approach utilizes natural precipitation to enhance safety fence windproof functions, better intercept surface sand/snow flow, and promote vegetation recovery within enclosures, thereby improving railway anti-sand/snow capacity at low cost with minimal maintenance.

4.2.3. Anti-Sand/Snow Technical Solution for High-Grade Highways–Separated Subgrade with Vegetation Enclosure and Restoration Following principles of minimal land occupation, concentrated construction, convenient maintenance, and relatively low cost, high-grade highways typically use integral cross-sections. However, in the sparsely populated Mongolian Plateau section of the China-Mongolia-Russia Economic Corridor, separated subgrade cross-sections can be employed across vast, gently undulating terrain, providing favorable conditions for preventing road surface windblown sand/snow hazards.

Technical details are illustrated in [Figure 11: see original paper]. In flat terrain

[Figure 11a: see original paper], two separated subgrades run parallel without roadside guardrails. In undulating terrain [Figure 11b: see original paper], each road follows suitable topography, with cable guardrails installed only on high embankment sections. In both flat and undulating areas, fences should generally be installed on both subgrade sides to effectively intercept crosswind sand/snow flow and promote degraded vegetation recovery, reducing hazard risks. Enclosure width can be adjusted based on regional wind-sand conditions—wider in areas with intense sand/snow activity and poor natural vegetation, narrower otherwise. In cut sections of undulating terrain [Figure 11c: see original paper], guardrails are unnecessary, but high vertical wind barriers should be installed on both sides to intercept sand/snow far from the road, effectively reducing accumulation risks in cuts.

This solution eliminates wind-resistant W-beam guardrails that induce sand/snow hazards, instead using alternative barriers and separated subgrades to intercept sand/snow at roadsides, allowing sand/snow flow to cross the road surface smoothly and reach the leeward side, thereby eliminating road surface hazards and ensuring traffic safety. This approach improves the driving environment, prevents road surface sand/snow hazards, and significantly reduces high-grade highway construction costs.

5.1. Improving Technical Specifications for Windblown Sand/Snow Hazard Control

During future construction and upgrading of transport arteries across the Mongolian Plateau, special attention must be paid to the region' s unique ecological environment, with windblown sand/snow hazard control integrated into technical specifications. Site-specific anti-sand/snow measures and solutions should be developed to enhance compatibility between transport infrastructure and regional ecology, avoid adverse disturbances to near-surface wind fields, and achieve scientific hazard control. When formulating specific anti-sand/snow technical measures, regional precipitation, vegetation, desertification degree, local topography, road cross-section design, and other natural and engineering conditions must be fully considered, with particular emphasis on hazard prevention in cut sections and leeward landforms where disaster potential is high.

5.2. Integrating Transport Artery Hazard Control with Regional Disaster Emergency Systems

Transport arteries are vital social infrastructure and essential components of regional natural disaster emergency response systems in the Mongolian Plateau, playing crucial roles in disaster relief material distribution and evacuation of affected people and livestock. While overall windblown sand/snow hazards remain relatively light, severe dust storms and blizzards can cause significant damage, exposing weaknesses in social disaster response capacity. Therefore, transport artery hazard control should align with regional disaster emergency system improvement and develop synergistically.

Hazard control should prioritize restoration of degraded ecosystems along routes, utilizing natural self-recovery capabilities. In open areas with frequent snow activity, multiple measures should integrate snow flow capture with vegetation restoration to establish protective shrub-grass systems along transport arteries, enhancing ecosystem sand/snow fixation and interception capacity. These ecological protection systems can also provide emergency shelters and forage for livestock. Additionally, in areas with irrigation water sources, artificial high-yield forage bases and nearby fodder reserves can be established to support emergency relief efforts, thereby enhancing regional natural disaster response capacity.

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