Characteristics of snow cover distribution along railway subgrade and the protective effect of snow fences (postprint)

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Abstract

Railways built in cold, snowy, and lightly populated areas are subjected to wind and snow disasters. In this study, we selected a snow hazard prevention and control section of the Altay–Zhundong Railway in Xinjiang Uygur Autonomous Region of China as the research object. We investigated the deposited snowfall variation characteristics on the two sides and in the embankment pavement area of snow fences with different porosities, fence heights, and arrangement distances using single-factor tests and orthogonal tests based on global atmospheric reanalysis climate data, field survey data, and a multi-phase flow analysis model. The results showed significant differences in the characteristics of snow cover distribution and snow cover thickness between the embankment and the cutting in the absence of snow protection measures. The maximum snow cover thickness of the embankment pavement decreased by 12.6% relative to the cutting pavement. The snow cover thickness of the embankment exhibited an increasing trend from windward shoulder to leeward shoulder, whereas the snow cover thickness of the cutting presented a declining trend from windward shoulder to leeward toe. In the collaborative prevention and control of snow fences and embankments, the three factors can be ranked in terms of their sensitivity to deposited snowfall within the influence scope of snow fences as follows: fence height>arrangement distance>porosity. At the same time, fence height yielded a significant relationship for the influence scope of snow fences ($P<0.05$). The three factors can also be ranked in terms of their sensitivity to deposited snowfall on the pavement as follows: porosity>fence height>arrangement distance. For the embankment protection of the Altay–Zhundong Railway against wind and snow, snow fence with a porosity of 75%, a fence height of 4.8 m, and an arrangement distance from the embankment of 60 m produced the best snow control effect. By revealing the characteristics of snow cover distribution along railway subgrade and the protective effect of snow fences, this study provides

valuable references for the engineering applications of railway construction in areas prone to wind and snow disasters.

Full Text

Preamble

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Characteristics of Snow Cover Distribution Along Railway Subgrade and the Protective Effect of Snow Fences

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Abstract: Railways built in cold, snowy, and sparsely populated areas are frequently subjected to wind and snow disasters. This study selected a snow hazard prevention and control section of the Altay–Zhundong Railway in Xinjiang Uygur Autonomous Region, China as the research object. Using global atmospheric reanalysis climate data, field survey data, and a multi-phase flow analysis model, we investigated the variation characteristics of deposited snowfall on both sides and on the embankment pavement area of snow fences with different porosities, fence heights, and arrangement distances through single-factor tests and orthogonal tests. The results revealed significant differences in snow cover distribution characteristics and thickness between embankments and cuttings in the absence of snow protection measures, with the maximum snow cover thickness on the embankment pavement decreasing by 12.6% relative to the cutting pavement. Snow cover thickness on the embankment exhibited an increasing trend from the windward shoulder to the leeward shoulder, whereas the cutting showed a declining trend from the windward shoulder to the leeward toe. In the collaborative prevention and control system of snow fences and embankments, the three factors can be ranked by their sensitivity to deposited snowfall within the influence scope of snow fences as follows: fence height > arrangement distance > porosity. Fence height demonstrated a significant relationship with the influence scope of snow fences ($P<0.05$). The factors can also be ranked by their sensitivity to deposited snowfall on the pavement as: porosity > fence height > arrangement distance. For embankment protection of the Altay–Zhundong Railway against wind and snow, a snow fence with 75% porosity, 4.8 m height, and 60 m arrangement distance from the embankment produced the optimal snow control effect. By revealing the characteristics of snow cover distribution along railway subgrade and the protective effect of snow fences, this study provides valuable references for railway construction engineering applications in areas prone to wind and snow disasters.

Keywords: snowdrift; numerical simulation; orthogonal test; porosity; fence height; arrangement distance; Altay–Zhundong Railway

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Introduction

Snowdrifts undergo creep, saltation, and suspension in the flow field, redistributing snowfall regularly and causing snow depths in some areas to reach 3–8 times the average snow depth [**?**]. However, established railway lines in traffic network construction projects are rarely altered simply due to harsh natural environments, making them vulnerable to wind and snow disasters. During snowmelt, the mixture of ice, snow, and water infiltrates the railway subgrade, resulting in settlement or collapse and traffic interruption [**?**]. Owing to the complexity of railway track structures, light snow cover often limits the execution of train traction, braking, and bogie systems, while heavy snow cover may even lead to out-of-service maintenance [**?**, **?**]. To maintain railway working efficiency and stable operation while reducing late-stage input costs, it is necessary to identify the characteristics of snow cover distribution along railways and implement appropriate protective measures.

Field surveys, wind tunnel tests, and computational fluid dynamics (CFD) numerical simulation represent different methods for studying snow cover distribution characteristics and protective measures. Field research provides researchers with information about site geological conditions, enabling evaluation of actual protective measure effects [**?**, **?**]. In this regard, field surveys serve as a direct and effective method for obtaining wind speed, snow thickness, start-up conditions, and other information for laboratory simulation [**?**, **?**]. However, conducting precise quantitative research for railway lines passing through areas prone to wind and snow disasters or sparsely populated Gobi regions is challenging, mainly due to large accidental errors, low reproducibility of measurements, and numerous uncontrollable external factors [**?**]. Researchers have widely recognized wind tunnel tests due to advantages in controllable environmental variables and systematic parametric measurement [**?**, **?**]. Wind tunnel tests allow scaling of building entities by adopting granular materials with different properties and performing calculations according to similarity criteria [**?**]. However, wind tunnel tests are inadequate, expensive, and only partially adaptable to similarity criteria [**?**, **?**].

In recent years, with optimization of simulation calculations and theoretical models, many researchers have widely adopted CFD numerical simulation to study snowdrifts [**?**]. Different forms of snow fences can be erected to effectively alleviate the impact of wind and snow disasters on railway operations [**?**]. The control effects of snow fences relate to structural factors such as porosity, arrangement distance, fence height, and arrangement form of multiple rows [?], as well as environmental factors like wind direction, wind frequency, snow thickness, topography, geomorphology, elevation, and complex wind-snow conditions. Thus, establishing specific design standards or universal protective measures remains difficult [?]. Basnet et al. [?] highlighted that snow accumulation in the bottom gap of snow fences is often insignificant, making this design effective for areas with severe snow-drifting hazards. Liu et al. [?] examined snow deposition and erosion distribution on both sides of temporary snow fences considering various porosities, fence heights, and bottom holes, establishing a simplified relationship between fence characteristics and snow deposition sites. Prokop and Procter [?] modified existing snow fence structures for field application based on topography and wind data. Currently, theoretical support for predicting snow cover distribution characteristics along railway subgrade is lacking, and the protective effects of different snow fence forms remain unclear. To improve prediction precision, it is imperative to explore the inducements of snow cover distribution and study the collaborative prevention and control effects of snow fences and subgrade.

Some sections along the Altay–Zhundong Railway suffer from snow damage, which seriously threatens safe railroad operation. The impact of snow damage on the railway line must be observed and monitored, as snow damage prevention and control is key to railroad safety. Due to the uninhabited railroad line during the snowfall period and lack of meteorological information, studying snow damage prevention and control for the Altay–Zhundong Railway is difficult. Based on the erosion–accumulation model [?] and multi-phase turbulent flow theory [?, ?], this study used global atmospheric reanalysis (ERA5) climate data to validate and parameterize wind speed, wind frequency, snow density, snow thickness, and other data acquired from field surveys, thereby supporting laboratory simulation tests. On this basis, we analyzed the collaborative prevention and control effect of snow fences and subgrade along the Altay–Zhundong Railway from perspectives of porosity, fence height, and arrangement distance, and designed orthogonal tests to explore each factor's sensitivity to different areas and related prevention and control effects. This study provides theoretical guidance and technical support for predicting snow cover distribution and constructing snow protection facilities along railways in cold, windy, and snowy areas.

Regional Geographical Characteristics

The Altay–Zhundong Railway (88°05 24 –89°33 48 E, 44°44 24 –47°43 12 N), also known as the Altay–Fuyun–Zhundong Railway [Figure 1: see original paper], is located in northern Xinjiang Uygur Autonomous Region, China. It starts from Altay Railway Station in the north, ends at Zhundong North Railway Station in the south, and connects with the Urumqi–Jiangjunmiao Railway at the north end. The Altay–Zhundong Railway spans 420.4 km and serves as a key railway in the Northern Xinjiang Railway Loop. This study primarily investigates wind and snow disasters threatening the Altay–Fuyun section.

Built at the southern edge of the Altay Mountains and north of the Junggar Basin, the Altay–Zhundong Railway lies in the hinterland of Eurasia and experiences a typical cold temperate continental climate. The railway is persistently subjected to snow hazards that severely impact local traffic operation due to cold winters, frequent precipitation, thick snow cover, and long snow cover duration [Figure 2: see original paper]. This necessitates erecting snow protection facilities along the railway to prevent snow coverage. However, existing snow protection facilities have uneven effects, and the railway still suffers from snow hazard damage.

Regional Snow Source Conditions

Abundant snow sources are necessary for snow disaster formation. To identify regional snow cover patterns, this study selected a site (88°41 24 E, 47°21 00 N) along the railway as the research focus. Global atmospheric reanalysis (ERA5) climate data served as the data source to acquire snow depth and snow density data for the study area in 2018, 2019, and 2020. Statistical analysis revealed that the annual average snow density was 132.26, 134.94, and 130.99 kg/m^3 in 2018, 2019, and 2020, respectively, with a three-year average of 132.73 kg/m^3. The main snowfall forms in the study area were fresh snow (wet snow) and fine snow (generally less than 0.50 mm in grain size). The threshold wind speed was 3.7–4.3 m/s, with a median of 4.0 m/s. The threshold wind speed increased linearly with the square root of snow grain size at temperatures below –6°C, as expressed in the following equation [**?**]:

$$V_t = 0.022\sqrt{D}$$

where V_t is the threshold wind speed (m/s) and D is snow grain size (mm). The calculated snow grain size range was 0.04–0.36 mm, with a median of 0.20 mm. The number of snow-covered days in 2018, 2019, and 2020 was 162, 161, and 170 days, respectively, lasting from October to April of the following year. Days with snow thickness above 10 cm numbered 50, 111, and 56 in 2018, 2019, and 2020, respectively. The maximum snow thickness in the three years was 44 cm [Figure 3: see original paper]. Generally, the study area is snow-covered for about half the year, with snow thickness exceeding 10 cm for approximately 2–3 months annually. This thick, long-duration snow cover provides favorable conditions for snow disaster formation.

Regional Wind Conditions

In addition to snow sources and geomorphological conditions, strong winds contribute to wind-snow disaster formation. Wind data for the three years were derived from ERA5. Statistical analysis revealed that west-northwest (WNW) azimuth frequencies reached 53.45%, 54.55%, and 57.29% in 2018, 2019, and 2020, respectively, while east-northeast (ENE) azimuth frequencies in winter reached 73.49%, 89.55%, and 81.51%, respectively. Wind speed statistics showed that wind speeds exceeding the threshold accounted for 16.56% of total annual time, with WNW as the dominant direction, average wind speed of 5.56 m/s, and maximum of 12.57 m/s. In winter, wind speeds exceeding the threshold accounted for 9.55% of total winter time, with ENE as the dominant direction, average wind speed of 4.32 m/s, and maximum of 9.38 m/s. Overall, the maximum WNW azimuth frequency was 57.29%, making WNW the prevailing annual wind direction, while the maximum ENE azimuth frequency in winter was 89.55%, making ENE the prevailing winter wind direction. The prevailing winter wind direction differed greatly from the annual prevailing direction [Figure 4: see original paper]. The study area exhibited characteristics of intermittent snow transport with stable transport direction. Since wind-snow disasters necessarily involve snowfall, winter data are more precise and reasonable, justifying the selection of ENE as the prevailing wind direction in this study. ERA5 data were used to obtain wind direction, wind speed, and real-time snow thickness. Considering snow thickness and wind speed simultaneously, wind speed was determined when snow thickness was large (the necessary condition for forming blowing-snow disasters). Combined with the actual project layout, snow thickness from ERA5 data helped determine wind speed, which was further applied as the inlet wind speed during numerical simulation.

Geometric Model and Grid Division

On-site buildings were reproduced at 1:1 scale using Unigraphics NX modeling to ensure authenticity and effectiveness. The snow fence model involved multiple parameters including fence height, porosity, and arrangement distance, detailed in the single-factor and orthogonal test design section. Modeling was illustrated using a snow fence with 4.8 m height, 75% porosity, and 20 m arrangement distance. Fence width, embankment height, slope, and pavement width were 3.2 m, 2.0 m, 1.0:1.5, and 8.0 m, respectively [Figure 5: see original paper]. The cutting model and embankment model maintained the same calculation domain size and pavement width. The cutting depth is 2.0 m, embankment height is 2.0 m, and slope is 1.0:1.5. The spatial resolution of ERA5 data is approximately 0.25°. The coordinates along the Altay–Zhundong Railway selected in this study are 88°41 24 E and 47°21 00 N. Based on the point coordinates of the study area, ERA5 data containing the minimum range of known coordinates were downloaded, with other data discarded. Considering calculation accuracy and efficiency, the computational domain was 150.0 m × 32.0 m × 30.0 m (length × width × height) [Figure 6: see original paper].

Unstructured tetrahedral grid division was adopted, with densified grids for snow fences, embankments, and ground surfaces. Grid independence was validated before calculation to ensure result reliability. Related grid models were built by adjusting size parameters of snow fences, embankments, and ground grids. The minimum grid size for the model was set to 0.18, 0.16, 0.15, 0.14, 0.13, 0.12, 0.11, 0.10, 0.09, and 0.08 m. An incoming wind with constant speed of 5.0 m/s was applied vertically to the snow fence. The average wind speed of the monitoring surface 10 m behind the entrance of the computational domain served as the index. Results showed that as grid size decreased, grid number multiplied, and the wind speed variation rate of the monitoring surface first decreased then stabilized [Figure 7: see original paper]. Simultaneously, as grid number multiplied, calculation time also multiplied. Considering calculation precision and efficiency, the minimum grid size was set to 0.09 m, yielding 3.70$×10^{6}$ grids, a relative error of approximately 0.3%, and an average grid quality rating of 0.83 (excellent). In the simulation, the governing equation residual declined to 10^{-7}, with stability of monitored physical quantity taken as convergence criteria and solved using double-precision.

Parameters and Boundary Conditions

A multi-phase flow analysis model was built based on CFD numerical simulation. User-defined function (UDF) was used to load the model and optimize boundary conditions. The Euler two-fluid method was adopted to calculate steady state first and transient state afterward. The standard K-epsilon model was employed. Air was selected as the major phase, and snow grains as the minor phase. Default air parameters from the software served as major phase parameters. The three-year average snow density (132.73 kg/m^3) was adopted as snow grain density (minor phase), with 0.20 mm grain size as the median. Under initial conditions, the volume fraction of snow grains was set to 0.05. The variation trend of entrance wind speed along height was expressed by a logarithmic function:

$$v = \frac{v_*}{k} \ln \left(\frac{y}{y_0} \right)$$

where v is friction wind speed (m/s), y is height (m), k is the von Karman coefficient (taken as 0.40), and y_0 is ground roughness (taken as 0.0005 m) [**?**]. The remaining boundary conditions are shown in Table 1 .

Mathematical Models and Equations

During snow transport, the effect of snow grain sedimentation should be considered in the convective term for the suspension layer. The control equation is given as follows [**?**]:

$$\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x_j}(U_j \phi) = \frac{\partial}{\partial x_j} \left(D_t \frac{\partial \phi}{\partial x_j} \right) + \frac{\partial}{\partial x_3}(w_f \phi)$$

where ϕ is snow concentration, t is time (s), w_f is snowfall speed (m/s), D_t is turbulent diffusion coefficient, U_j is wind velocity vector component, x_j is spatial coordinate vector component, x_3 is vertical spatial coordinate component, ν_t is turbulent kinematic viscosity, and S_{ct} is turbulent Schmidt number.

The model proposed by Naaim et al. [?] was used to evaluate snow grain erosion and deposition in the simulation, as given in Equations 5 and 6:

$$q_{ero} = Aero \cdot u_* \cdot (u_*^2 - u_t^{*2}) \quad (u_* > u_t^*)$$

$$q_{dep} = \phi_s \cdot w_f \cdot \left(1 - \frac{u_*^2}{u_t^{*2}}\right) \quad (u_* < u_t^*)$$

where $Aero$ is the erosion constant (set as –7.0\$×10^{-4}\$), q_{ero} is erosion flux ($\mathrm{kg/(m^2 \cdot s)}$), q_{dep} is deposition flux ($\mathrm{kg/(m^2 \cdot s)}$), u_* is wall friction velocity (m/s) calculated by $u_* = \sqrt{\tau_w/\rho_a}$ (τ_w is wall shear stress, ρ_a is air density), u_t^* is threshold friction velocity of snow grains (m/s, set as 0.15 m/s), and ϕ_s is snow mass concentration ($\mathrm{kg/m^3}$), expressed as $\phi_s = \rho_s f$ (where ρ_s is snow grain density ($\mathrm{kg/m^3}$) and f is snow-phase volume fraction).

For unification of calculated quantities in simulation, q_{total} ($\mathrm{kg/(m^2 \cdot s)}$) was used as a substitute for q_{ero} and q_{dep}, representing the amount of snow cover on the ground considered as a product of erosion and deposition motion. The amount of snow cover on the ground produced by snow grain motion within time Δt (s) is defined as Δh (m), expressed as:

$$\Delta h = \frac{q_{total} \cdot \Delta t}{\gamma \cdot \rho_s}$$

where γ is the maximum volume fraction of snow cover (set as 0.62).

Design of Single-Factor Tests

Generally, fence height should be set at the moderate level of 2.0–6.0 m, as excessively low snow fences produce poor snow resistance while excessively high ones compromise stability and increase construction costs [?]. To increase snow cover on both sides of snow fences and facilitate protective effect analysis, invariant fence height, arrangement distance, and porosity were set as 4.8 m, 80 m, and 75%, respectively. Computational variables and working conditions are provided in Table 2 .

Design of Orthogonal Tests

L16 (4^3) orthogonal tests were designed according to three factors (fence height, arrangement distance, and porosity) from single-factor tests. Orthogonal conditions and results are provided in Table 3 . The area within the influence scope of the off-embankment fence was designated as Area I, ranging from 20 m in front of the snow fence to the embankment behind it. The embankment pavement area was designated as Area II. Variance and range analysis methods were used to analyze factors affecting deposited snowfall on both sides of snow fences and the embankment pavement area.

Comparative Analysis Between Embankment and Cutting

Calculations for embankment and cutting were performed in the absence of snow fences, revealing significant differences in snow cover distribution characteristics and thickness. Comparing maximum snow cover thickness points, the maximum dimensionless snow cover thicknesses were 0.153 for embankment and 0.175 for cutting. The maximum snow cover thickness on the embankment pavement decreased by 12.6% relative to the cutting pavement. Snow cover thickness on the embankment presented a gradually rising trend from windward shoulder to leeward shoulder, whereas the cutting showed a gradually declining trend from windward shoulder to leeward toe [Figure 8: see original paper]. Due to the embankment's blocking effect on wind speed, a vortex formed at the windward slope toe, with flow direction negatively correlated with upper-layer wind speed, reducing wind speed in the study area and weakening wind's ability to transport snow grains. Consequently, snow thickness showed a transient rising trend near the embankment's windward slope toe. In the windward slope toe-to-shoulder stage of the embankment, snow cover thickness on the ground dropped abruptly because upper-layer wind speed was not blocked or interfered with by the embankment. In contrast, deposited snowfall variation on the slope surface depended on the snow-carrying capacity of upper-layer air. In the pavement stage, snow grains on the ground were carried by wind speed, causing friction velocity to exceed the threshold and snow cover thickness to increase rapidly along the wind direction. In conclusion, the embankment itself possesses a protective effect against wind and snow disasters, suggesting that embankments should be preferentially built in areas prone to such disasters.

Flow Field Distribution Around Snow Fence

Figure 9 [Figure 9: see original paper] compares flow fields with and without snow fences on the Altay–Zhundong Railway. Without snow fences [Figure 9a: see original paper], airflow velocity was redistributed after embankment disturbance, forming deceleration and turbulence zones on windward and leeward slopes, respectively. Airflow on the embankment top divided into a lower layer with greatly reduced velocity near the surface (forming a weak wind zone) and an upper layer with strengthened velocity (forming a strong wind zone). Since airflow velocity attenuation is the main cause of snow deposition, windward and leeward slope toes were the primary snow accumulation areas.

With snow fences [Figure 9b: see original paper], reasonable placement on the embankment windward side effectively altered flow field distribution. When airflow approached the anti-snow fence, normal airflow was stopped, decreasing velocity on the windward side. Airflow increased rapidly and reached the fence top as it passed through, forming a reverse flow area on the leeward side due to reverse pressure gradient, which led to snow settlement near the leeward side. Consequently, wind-carried snow was greatly reduced, effectively decreasing snow settlement on the embankment windward slope. For the leeward side, the turbulence zone range was greatly reduced, effectively decreasing snow settlement at the leeward slope foot. For the embankment pavement, reasonable snow fence placement increased pavement wind speed, enhancing wind's ability to carry snow and effectively reducing snow settlement on the pavement. In summary, setting snow fences to change flow field distribution around embankments can affect and control the quantity and settlement trend of snow particles transported on the subgrade's windward slope, road surface, and leeward slope.

Porosity

Figure 10 [Figure 10: see original paper] shows deposited snowfall under different porosities. Only black lines and white balls display some streamlines and snow grains to reduce cloud atlas overlap. Snow cover distribution patterns and streamlined vortex forms in front of and behind snow fences varied greatly with porosity changes.

Under porosities of 0% (impervious), 25%, 50%, and 75%, average volume fractions of snow grains on both sides of snow fences (within 10 m scope) were 0.523, 0.502, 0.475, and 0.530, respectively, while those in front of the embankment (within 10 m scope) were 0.536, 0.532, 0.522, and 0.493, respectively. Average volume fractions on the windward side slope were 0.191, 0.187, 0.184, and 0.192, respectively, whereas those on the railway pavement were 0.108, 0.111, 0.105, and 0.103, respectively. Under 0%, 25%, and 50% porosities, the vortex formed in front of snow fences transformed into a jet under pore action, causing friction velocity to increase suddenly and snow to be blown away from both sides. However, at 75% porosity, the large porosity produced weak wind resistance capacity, making it difficult to form high wind speed in pores or a jet, resulting in more snow accumulation on both sides. When porosity increased from 0% to 75%, deposited snowfall on both sides first decreased then increased, with an inflection point at 50% porosity. Deposited snowfall in front of the embankment continuously decreased, while accumulation and transport capacity behind snow fences continuously weakened. Deposited snowfall on the windward side slope first decreased then increased (inflection at 50% porosity), while pavement deposited snowfall first increased then decreased (inflection at 25% porosity). Under 75% porosity, snow fences had the strongest snow resistance capacity and largest deposited snowfall on both sides, with weakest transport capacity behind fences and smallest deposited snowfall in front of embankment and on pavement, producing the best protective effect against snowdrifts.

Fence Height

Figure 11 [Figure 11: see original paper] shows deposited snowfall under different fence heights. Snow cover distribution patterns and streamlined vortex forms varied greatly with fence height changes. Under fence heights of 2.1, 3.0, 3.9, and 4.8 m, average volume fractions on both sides of snow fences were 0.392, 0.443, 0.327, and 0.359, respectively, while those before the embankment were 0.461, 0.401, 0.626, and 0.601, respectively. Average volume fractions on the pavement were 0.159, 0.150, 0.120, and 0.104, respectively.

Vortex forms before and after snow fences changed with fence height. At 2.1 m height, several small vortexes formed behind the fence, far apart without wind speed superposition, resulting in weak snow grain transport capacity and concentrated deposited snowfall behind the fence. At 3.0 m, mesoscale vortexes formed behind and small vortexes in front of the fence. Mesoscale vortexes concentrated in a narrow area behind the fence did not improve transport capacity, so snow grains concentrated behind the fence with only minor deposition in front. At 3.9 m, two relatively large vortexes formed behind the fence with a mutually reinforcing trend in the middle area, improving transport capacity and expanding snow deposition distribution scope. At 4.8 m, two large vortexes formed behind the fence, greatly improving snow grain transport capacity. However, due to reasonable arrangement distance setting, the improved transport capacity did not significantly affect pavement deposited snowfall. Considering only pavement snow cover, 4.8 m fence height produced the largest leeward side snow cover area, smallest pavement deposited snowfall, and best protective effect.

Arrangement Distance

Figure 12 [Figure 12: see original paper] shows deposited snowfall under different arrangement distances. Snow cover distribution patterns and streamline vortex forms in front of and behind snow fences and on pavement varied greatly with changing distance between snow fence and subgrade. Under arrangement distances of 20, 40, 60, and 80 m, average volume fractions on both sides of snow fences were 0.405, 0.405, 0.386, and 0.344, respectively; before the embankment were 0.619, 0.624, 0.554, and 0.621, respectively; and on the pavement were 0.121, 0.099, 0.083, and 0.103, respectively.

When arrangement distance increased from 20 to 80 m, deposited snowfall on both sides of snow fences continuously decreased. Pavement deposited snowfall continuously decreased from 20 to 60 m, showed an inflection point at 60 m, and presented a rising trend from 60 to 80 m. Snowfall deposited in front of the embankment was largest at 40 m and least at 60 m. At 40 m, snow grains began to span across the embankment, significantly increasing leeward deposited snowfall. When distance decreased from 40 to 20 m, leeward deposited snowfall continuously increased. At 20 m, the vortex scope behind the fence covered part of the pavement area, with snow deposition acting on the pavement. Pavement deposited snowfall was far greater than in the absence of a snow fence and under other arrangement distances, producing no snow protection effect. Under 4.8 m fence height and 75% porosity, the optimal arrangement distance was 60 m, producing the smallest deposited snowfall in front of the embankment and on pavement, and the best protective effect.

Deposited Snowfall Within Influence Scope of Off-Embankment Fence

Table 4 provides variance analysis of average snow grain volume fraction in Area I. The difference relationship produced by the three factors for Area I can be determined from Table 4. The model's coefficient of determination (R^2) is 0.841, indicating that 84.1% of variance in Area I was caused by arrangement distance, fence height, and porosity. Fence height produced a significant difference relationship for Area I ($P<0.05$), while arrangement distance and porosity did not.

Table 5 provides range analysis of average snow grain volume fraction in Area I. Range values for porosity, fence height, and arrangement distance factors were 3.31\$$\times 10^{\{-2\}, 1.53\times 10}${-1}, *and*7.35×10^{-2}\$, respectively. The three factors can be ranked by sensitivity to deposited snowfall within the influence scope of off-embankment fences as: fence height > arrangement distance > porosity. Thus, fence height was the main factor affecting deposited snowfall in Area I. Porosity and arrangement distance greatly affected distribution patterns and accumulation locations on both sides of snow fences but only slightly affected deposited snowfall in Area I.

Deposited Snowfall at Top Surface of Embankment

Table 6 provides range analysis of average snow grain volume fraction in Area II. Range values for porosity, fence height, and arrangement distance factors were 5.73\$$\times 10^{\{-2\}, 2.81\times 10}${-2}, *and*2.72×10^{-2}\$, respectively. The three factors can be ranked by sensitivity to deposited snowfall in Area II as: porosity > fence height > arrangement distance. Hence, porosity was the main factor affecting deposited snowfall in the pavement area. Fence height and arrangement distance greatly affected off-embankment snow cover distribution and deposited snowfall but only slightly affected snowfall in Area II.

Discussion

Using field surveys to validate remote sensing meteorological data for laboratory simulation tests produces desirable effects in evaluating complex snow disaster prevention and control systems [**?**, **?**, **?**]. ArcGIS, ERA5, and field survey data were combined to reveal the study area's geographical location and wind-snow conditions. Data including snow density, grain size, wind frequency, and wind speed were used for numerical simulation [**?**]. The erosion–accumulation model compared embankment and cutting, revealing significant differences in snow cover distribution characteristics and thickness, with embankments providing more significant protective effects against snow drifts. Embankments should be preferentially built in wind-snow disaster-prone areas when not constrained by economy, space, and construction difficulty. Additionally, snow fences improve embankment snow protection effects [**?**]. The collaborative prevention and control effect of snow fences and subgrade should be considered in fence erection, with protective measures investigated by types for engineering practice [**?**].

This study reveals that analyzing collaborative prevention and control effects of pavements and snow fences with different porosities, fence heights, and arrangement distances shows that erecting snow fences significantly improves embankment snow protection effects. Parametric analysis of the three factors showed fence height affects both sides of snow fences more significantly than porosity. Fence erection should consider snow grain spanning across embankments in short-distance arrangements and prioritize snow deposition on the embankment windward side in long-distance arrangements. Yu et al. [?] simulated and quantified snow fence barrier effects through wind tunnel tests, finding that higher fences provide better barrier effects. Wind protection effects improve as fence height increases from 3.7 to 7.9 m [?]. This study analyzed snow-proof effects at fence heights of 2.1, 3.0, 3.9, and 4.8 m through single-variable tests for the Altay–Zhundong Railway, obtaining optimal effects at 4.8 m, similar to previous results. Ma et al. [?] found that when drifting snow flows through cuttings, eddy currents appear with ranges consistent with snow accumulation positions, verifying the rationality of using streamlined vortices to characterize snow deposition ranges. Li et al. [?] hold that leeward snow cover deposition scope is affected by fence height, similar to orthogonal test conclusions in this study. This study further identified porosity as the main factor affecting pavement deposited snowfall in collaborative prevention and control systems. Additionally, at 20 m arrangement distance, snow deposition acted on pavement with deposited snowfall exceeding that without snow fences, which was unfavorable for pavement snow protection. Therefore, data obtained at 20 m arrangement distance were rejected as accidental errors in pavement snow cover analysis. Existing embankment studies are mostly based on single qualitative or quantitative analysis [?, ?]. By introducing mathematical statistics methods, this study conducted comprehensive analysis based on single-factor and orthogonal tests, ranking the three factors by sensitivity to deposited snowfall in different areas. These results provide theoretical guidance and technical support for predicting snow cover distribution and constructing snow protection facilities along railways.

Railway design parameters and traffic networks limit engineering construction. Snow protection measures are necessary to ensure railway lines successfully pass through extreme climate zones. This study investigated snow cover distribution characteristics and snow fence protective effects by combining field surveys, remote sensing data validation, and laboratory numerical simulation. However, no laboratory wind tunnel tests were conducted due to condition limitations. Future research can use wind tunnel tests to further optimize and validate results. Wind-snow disasters are subject to seasonal changes, and snow fence erection is limited by environment, space, cost, and other factors. To ensure snow fences serve engineering practice efficiently, stably, and economically, research on live snow fences may be the future trend.

Conclusions

This study investigated snow cover distribution characteristics and protective effects of different snow fences along the Altay–Zhundong Railway subgrade using single-factor and orthogonal tests. Field survey data and global atmospheric reanalysis (ERA5) climate data were utilized. Results show that in the absence of snow protection measures, maximum snow cover thickness on the embankment pavement decreased by 12.6% relative to the cutting pavement, suggesting that embankments should be preferentially built in wind-snow disaster-prone areas. Setting snow fences to change flow field distribution around embankments can affect and control the quantity and settlement trend of snow particles transported on the subgrade's windward slope, road surface, and leeward slope.

When porosity increased from 25% to 75%, deposited snowfall on the pavement continuously decreased. A fence height of 4.8 m produced the largest leeward snow cover scope and smallest pavement deposited snowfall. An arrangement distance of 60 m produced the smallest deposited snowfall in front of the embankment and on the pavement. In collaborative prevention and control of snow fences and embankments, the three factors can be ranked by sensitivity to deposited snowfall within the influence scope of fences as: fence height > arrangement distance > porosity. Fence height is the main factor affecting deposited snowfall within the off-embankment fence influence scope.

For embankment protection of the Altay–Zhundong Railway against wind and snow, a snow fence with 75% porosity, 4.8 m height, and 60 m arrangement distance from the embankment produced the best snow control effect.

Conflict of Interest: The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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