Post-Print of Comprehensive Evaluation of Sand Hazards on

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Abstract

Assessment of wind-blown sand hazards on desert highways is a fundamental basis for highway construction and operation and maintenance, but previous evaluations have been highly subjective, making it urgent to establish an objective and accurate evaluation system. Taking the Yuli-Qiemo Desert Highway (Yuli-Qiemo Desert Highway, abbreviated as Y-Q Desert Highway) as the research object, and based on field investigations and data analysis conducted in 2023, this study first adopts variable-weight cloud model theory, selects 10 key indicators, and uses an improved analytic hierarchy process to determine constant weights, thereby constructing a highway sand hazard evaluation system. Second, in combination with the double-scoring evaluation method and computer technology, state values are calculated in batch, and weights are dynamically adjusted through variable-weight theory. Finally, a cloud model is used to classify sand hazard grades, which are then compared and validated against historical data. The results show that: (1) Based on the double-scoring evaluation method, automated batch processing of indicator grading and dynamic weight adjustment by computer enables efficient and accurate evaluation of state values along the entire highway, extending the evaluation scope from individual sections to the full alignment. (2) Compared with historical sand hazard records for each section, the correlation coefficient (r) reaches 0.91 ($P < 0.001$), indicating a highly significant positive correlation between the two within the 95% confidence interval, thereby avoiding human subjective influence in the assessment. (3) Sand hazard problems along the Y-Q Desert Highway are relatively severe overall. Sections with grade III sand hazards account for the highest proportion (65.46%), followed by grade IV sand hazard sections (30.91%), and there are no grade I sand hazard sections. The spatial distribution of highway sand hazard risk is characterized by lower risk at the northern and southern ends, higher risk in the middle, and a gradual increase from north to south. Among these, the K180-K250 and K30-K60 sections are most severely affected by sand hazards and should be the focus of preventive measures. The research results provide a new method for risk identification and prediction of sand hazards on desert highways and offer an important basis for the prevention and control of sand hazards in desert highway engineering.

Full Text

Comprehensive Evaluation of Sand Hazards on the Yuli-Qiemo Desert Highway Based on Variable Weight-Cloud Model Theory

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Abstract

Assessing aeolian sand hazards is fundamental to the construction, operation, and maintenance of desert highways. However, conventional evaluation methods often suffer from excessive subjectivity, highlighting the need for an objective and robust assessment framework. Focusing on the Yuli-Qiemo desert highway in China, this study proposes a novel, data-driven method for evaluating aeolian sand-hazard risks, based on extensive field investigations conducted in 2023 and analyses. First, a variable-weight cloud model was established, incorporating ten key indicators. A modified analytic hierarchy process was used to determine the indicator fixed weights. Second, a dual-score evaluation method, integrated with computational algorithms, enabled automated batch processing of indicator stratification and dynamic weight adjustment based on variable-weight theory. Third, the variable-weight cloud model was used to classify hazard levels, which were validated against historical sand hazard records. The results indicate that (1) The proposed method enables efficient and accurate assessment of aeolian sand hazards along entire highways, transitioning from isolated segment evaluation to full-route analysis. This is achieved through the automated computation of state values and real-time adjustment of indicator weights. (2) Comparison with historical sand hazard records yielded a correlation coefficient of 0.91 ($P<0.001$), indicating a significant positive correlation within the 95% confidence interval and demonstrating the method' s ability to reduce human subjectivity. (3) The overall aeolian sand-hazard risk of the Yuli-Qiemo desert highway is high. Grade III hazard segments dominate (65.46%), followed by grade IV (30.91%), with no segments classified as grade I. The risk is low at the northern and southern ends of the highway, high in the middle segments, and gradually increases in severity from north to south. Middle segments K180~K250 and K30~K60 are the most severely affected and warrant prioritized mitigation efforts. This novel method for identifying and predicting aeolian sand hazard risks along desert highways offers critical insights to inform targeted prevention and control strategies.

Keywords: Yuli-Qiemo desert highway; sand hazard; variable-weight cloud model; dual-score evaluation method; dynamic weight adjustment

Introduction

Highway transportation constitutes a vital component of modern transportation networks and plays a significant role in socio-economic development. In aeolian sand regions, the primary threat to highway construction and operation is sand hazards. Since the 1990s, extensive research has been conducted domestically and internationally on highway sand hazard evaluation, evolving from single-indicator analysis to comprehensive dynamic assessment. Conventional evaluation methods such as Analytic Hierarchy Process (AHP), entropy weight method, and Principal Component Analysis (PCA) are widely used in disaster risk assessment due to their clear logic and ease of use. However, their fixed-weight limitations make them ill-suited to the spatiotemporal heterogeneity characteristics of desert environments, often resulting in mismatches between evaluation outcomes and dynamic sand hazard scenarios. To address this issue, variable-weight theory has been gradually introduced. Variable-weight theory modifies constant weights according to actual conditions, emphasizing both the relative importance of individual factors and the intrinsic connections among them. As indicator weights change with evaluation states, this approach enhances the adaptability and scientific rigor of evaluation models and has been applied across various fields. The key to applying variable-weight theory lies in obtaining state values for each evaluation system. However, two major technical challenges persist: first, state value determination typically relies on manual scoring, which, while suitable for individual or few road segments, suffers from low efficiency and cannot meet the demand for rapid evaluation of entire highways; second, traditional fuzzy classification methods inadequately characterize indicator random fluctuations and uncertainties. Additionally, cloud model theory, proposed by Academician Deyi Li based on probability theory and fuzzy mathematics, effectively reflects human knowledge fuzziness and randomness. It serves as a theoretical framework for transforming uncertain information into quantitative indicators and has been widely applied in risk grading assessment, stability evaluation, and data prediction due to its advantages in handling fuzziness, uncertainty, and multidimensional complexity.

To address these challenges, this study integrates indicator classification with variable-weight theory and cloud model theory, overcoming the defects of “same weight for different qualities” and heavy reliance on expert scoring in existing methods. We propose a dual-score evaluation method to achieve objective and efficient processing of state values, enabling scale expansion from single-segment to full-route evaluation under variable-weight conditions. Using the Yuli-Qiemo desert highway as a case study, this research holds significant importance for regional sand hazard prevention and can provide valuable insights for sand control along transportation corridors in other desert regions.

1.1 Study Area Overview

The Yuli-Qiemo desert highway (38.00°~41.00°N, 85.21°~86.22°E) traverses the central Tarim Basin, running north-south through the Taklimakan Desert. The region experiences an extremely arid climate with minimal precipitation (annual rainfall: 18.6~40.8 mm) and high evaporation (annual evaporation: 2507.0~2910.5 mm). The average sand-driving wind speed is 6.03~6.64 $m \cdot s^{-1}$, with sand-driving wind frequency ranging from 2.67% to 18.28%. Aeolian activities are most frequent in spring and summer, with dominant wind directions from northeast-east (NEE) and east (E). The annual drift potential ranges from 106.48 to 293.70 VU. The highway corridor is dominated by mobile dunes and sand ridges, accounting for over 80% of the route. Only the starting and ending sections pass through farmland and wasteland where sand hazards are negligible. Other sections experience varying degrees of sand hazards, primarily in the form of sand burial and wind erosion. Severe hazard segments are mainly distributed in mobile dune and compound dune areas, with sand burial as the dominant threat. Since the highway’ s construction, approximately 305 km of the route has suffered varying degrees of sand hazards, seriously affecting traffic safety and maintenance costs. Therefore, comprehensive evaluation of sand hazards along the Yuli-Qiemo desert highway holds important theoretical and practical significance.

1.2 Data Sources

This study utilized geomorphological, wind regime, highway engineering design, and sand clearance records. Geomorphological data were derived from GEBCO terrain data (15 arc-seconds) with GCS_{{{WGS}}_{{1984}}} geographic coordinate system. Highway engineering design data and historical disaster records were provided by Xinjiang Academy of Transportation Sciences Co., Ltd., including roadbed height, curve radius, slope ratio, and sand hazard information from 2021-2023. Wind regime data were obtained from ERA5 meteorological reanalysis data with spatiotemporal resolution of 0.25°$×$0.25° and 1 hour. All factors were comprehensively analyzed using the Python platform.

1.3 Methodology

1.3.1 Overall Research Framework To address the spatial heterogeneity of sand hazard risks along the Yuli-Qiemo desert highway, this study constructed a hierarchical evaluation system based on variable-weight cloud model theory. The system employs a modified analytic hierarchy process to determine fixed weights, combines segment state values with variable-weight theory for dynamic weight adjustment, and generates comprehensive evaluation clouds through cloud modeling. Given significant variations in wind energy environment, topography, and engineering design conditions along the highway, unified evaluation methods are inappropriate. To ensure scientific and accurate results, the highway was divided into 5 km segments, totaling 67 sections, with key factors such as wind energy environment and topography analyzed for each segment to obtain state values and variable weights. This segmented approach fully considers inter-segment differences and ensures reasonable weight allocation. Based on this framework and computational technology, a dual-score evaluation method was proposed to achieve full-route grading evaluation under variable-weight conditions. The overall research framework is illustrated in [Figure 2: see original paper].

1.3.2 Construction of Highway Sand Accumulation Hazard Evaluation System To ensure scientific rigor and rationality, this study established a sand hazard evaluation index system based on engineering experience and previous research findings. The evaluation system comprises three primary indicators (regional geomorphological conditions, regional wind dynamics, and engineering design factors) and ten secondary indicators (Table 1). This method comprehensively covers the main influencing factors of highway aeolian sand hazards, ensures relative independence among indicators, avoids weight allocation bias, and enhances the scientific and practical applicability of the evaluation model.

1.3.3 Correlation Analysis To eliminate multicollinearity interference among evaluation indicators, Pearson correlation coefficient analysis was conducted on environmental variables. The analysis revealed that correlation coefficients among the ten environmental evaluation indicators were all below the collinearity threshold ($|r|<0.8$), with drift potential and sand-driving wind frequency showing relatively high correlation ($r=0.76$) but still meeting independence requirements (Figure 3). This index system comprehensively covers key dimensions including sand source conditions, dynamic characteristics, and topographic factors. Each indicator possesses clear physical meaning and engineering applicability, ensuring the scientific reliability of the evaluation system.

1.3.4 Evaluation Indicator Weight Calculation This study combined a five-scale judgment method with improved analytic hierarchy process to quantify 各项指标, determining initial fixed weights through expert scoring and dynamically adjusting weights based on variable-weight theory to reasonably reflect actual conditions under different scenarios.

(1) Determination of Fixed Weights. The highway sand hazard evaluation system established by Han et al. possesses strong scientific validity and applicability, effectively reflecting the relative importance of each indicator in comprehensive assessment. Therefore, this study adopted that indicator system and its fixed weights (Table 2).

(2) Variable-Weight Calculation. Variable-weight comprehensive theory is a novel decision-making method whose core principle recognizes that the importance of evaluation indicators may change under different engineering environments, whereas traditional constant weights cannot accurately reflect actual conditions. Based on variable-weight comprehensive theory, this study dynamically adjusted indicator state values to optimize weight allocation and calculate variable weights, thereby enhancing evaluation system rationality and accuracy. After obtaining state values for each evaluation indicator, variable weights were calculated using the variable-weight formula. The calculation formula is as follows:

$$w_j(x) = \frac{w_j^0 \cdot s_j(x)}{\sum_{j=1}^{n} w_j^0 \cdot s_j(x)}$$

where w_j^0 is the fixed weight of the j-th evaluation indicator; $s_j(x)$ is the state value of the j-th evaluation indicator; and n is the number of evaluation indicators. Through variable-weight calculation, indicator weights are dynamically adjusted when environmental parameters change, making assessment results more consistent with real-time highway conditions and providing a more comprehensive reflection of sand hazard risk factors.

(3) Dual-Score Evaluation Method for Determining Highway State Values. Scientifically assessing state values of various environmental factors and engineering characteristics is crucial for highway safety. Scholars have employed different approaches for state value determination, such as using arithmetic means of expert scores or cloud model theory. Traditional expert scoring methods are susceptible to subjective influences and inefficient for processing large quantities of data. This study proposes a dual-score evaluation method that combines expert experience with model scoring, using linear interpolation-based numerical models for automated scoring combined with expert evaluation. Using the classification standards for each evaluation indicator (Table 2) as benchmarks, linear interpolation constructs numerical models that integrate with expert scoring. For easily quantifiable indicators (e.g., dune height, drift potential, wind frequency), measured data generate state value results through automated numerical model scoring; for difficult-to-quantify indicators (e.g., curve radius, windward concave-convex surfaces), expert scoring improves assessment accuracy. This approach combines the efficiency of data models with the flexibility of expert judgment.

1.3.5 Construction of Cloud Model Cloud model theory, proposed by Academician Deyi Li based on probability theory and fuzzy mathematics, reflects human knowledge fuzziness and randomness. It serves as a theoretical framework for transforming uncertain information into quantitative indicators, effectively overcoming fuzziness in quantitative-qualitative relationships. Using normal cloud generators enables quantitative classification of randomness and fuzziness.

(1) Determination of Comment Set. The comment set represents the collection of all possible evaluation outcomes. Sand accumulation thickness is a critical indicator measuring wind-blown sand accumulation on highway surfaces and surrounding areas, directly reflecting sand hazards and representing a key factor affecting traffic safety. Using sand accumulation thickness as the primary criterion for sand hazard classification and considering its impact on traffic safety and maintenance, this study divides sand hazards into four grades (mild, moderate, severe, and extreme) based on previous research (Table 3).

(2) Determination of Standard Cloud Parameters. For the k-th comment set' s score interval $[C^k_{min}, C^k_{max}]$, the corresponding standard cloud digital characteristic values are (Ex_k, En_k, He_k), calculated as follows:

$$Ex_k = \frac{C^k_{min} + C^k_{max}}{2}$$

$$En_k = \frac{C^k_{max} - C^k_{min}}{6}$$

$$He_k = c$$

where c is a constant (set to 0.1 in this study). After determining standard cloud characteristic parameters, Python programming generates standard cloud diagrams for each hazard grade, forming the standard evaluation cloud for highway sand accumulation hazards.

(3) Determination of Indicator Evaluation Cloud. Using the dual-weight evaluation method described above, state value scores are obtained to form an evaluation matrix. Assuming i experts score state values for j evaluation indicators, the evaluation matrix Z has dimensions $i \times j$. The matrix is calculated as:

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1j} \\ z_{21} & z_{22} & \cdots & z_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ z_{i1} & z_{i2} & \cdots & z_{ij} \end{bmatrix}$$

where z_{ij} represents the state value of the j-th evaluation indicator by the i-th expert. Using the SBCT-1stM algorithm for inverse cloud generators, digital characteristics (Ex_j, En_j, He_j) for each indicator are calculated:

$$Ex_j = \frac{1}{m}\sum_{i=1}^{m} z_{ij}$$

$$En_j = \sqrt{\frac{\pi}{2}} \cdot \frac{1}{m}\sum_{i=1}^{m} |z_{ij} - Ex_j|$$

$$He_j = \sqrt{|S_j^2 - En_j^2|}$$

where Ex_j is the expected value of the j-th evaluation indicator; En_j is the entropy; He_j is the hyper-entropy; S_j is the sample variance of the j-th indicator; and m is the number of experts.

(4) Calculation of Comprehensive Evaluation Cloud. After obtaining digital characteristics of each evaluation indicator, comprehensive evaluation cloud characteristics for highway segments are calculated. Based on previous results, the comprehensive evaluation cloud digital characteristics are determined:

$$Ex = \sum_{j=1}^{n} w_j \cdot Ex_j$$

$$En = \sqrt{\sum_{j=1}^{n} w_j^2 \cdot En_j^2}$$

$$He = \sum_{j=1}^{n} w_j \cdot He_j$$

where Ex is the expected value of the comprehensive evaluation cloud; w_j is the weight of the j-th evaluation indicator; En is the entropy; and He is the hyper-entropy. Based on these digital characteristics, the comprehensive evaluation cloud diagram is generated and compared with standard evaluation clouds to determine the highway sand accumulation hazard grade. Through these steps, full-route quantitative grading evaluation is achieved.

2.1 Case Study Section Indicator Weights

The Yuli-Qiemo desert highway was divided into 5 km segments (67 total sections) for comprehensive hazard assessment. Four typical sections (K65~K70, K90~K95, K120~K125, K195~K200) were selected as examples. State values were obtained through the dual-score method (Table 4), and variable weights were determined using the variable-weight formula (Table 5). Results show that mobile dune height and drift potential are core factors affecting highway sand hazards. Mobile dune height variable weights are generally higher than fixed weights, confirming the dominant role of dune dynamics. Although drift potential variable weights are slightly lower than fixed weights, their state values increase along the highway, with synchronized increasing trends in variable weights, revealing the critical influence of sand transport capacity. State values for sand source distribution increase significantly in K180~K250 (80-100), directly driving its variable weight to jump to 0.18-0.20, indicating that high sand source sections require independent strengthening of prevention and control. Variable weights for slope ratio, curve radius, drift potential, sand-driving wind frequency, and road-wind angle are all lower than fixed weights, suggesting these indicators' contributions to actual sand hazards are generally lower than theoretical expectations. This reflects that natural factors such as mobile dune height and sand source distribution dominate actual hazards, with their dominance weakening other indicators' relative contributions.

2.2 Case Study Section Cloud Model

(1) Construction of Standard Evaluation Cloud. All sections share consistent grading standards and evaluation cloud characteristics. Using the maximum and minimum values from Table 3' s classification intervals in the standard cloud formulas yields the standard evaluation cloud characteristics for the Yuli-Qiemo desert highway (Table 6). With cloud droplet number set to 2000, Python generates standard cloud diagrams for each safety grade, forming the standard evaluation cloud (Figure 4). The standard cloud diagrams exhibit normal distribution characteristics, clearly reflecting the fuzzy boundaries and transitional continuity between hazard grades.

(2) Construction of Comprehensive Evaluation Cloud. Using state value scores, the indicator inverse cloud digital characteristics are calculated. Then, comprehensive cloud digital characteristics are computed. The comprehensive evaluation cloud characteristics for the four case sections are shown in Table 7. With cloud droplet number set to 2000, Python generates comprehensive cloud diagrams (Figure 5). According to the maximum membership principle, R1 and R2 belong to the severe grade, while R3 and R4 belong to the extreme grade.

2.3 Analysis of Case Study Section Sand Hazard Evaluation Results

Comparing indicator clouds with comprehensive clouds and applying the maximum membership principle confirms that R1 and R2 sections are severe grade, while R3 and R4 are extreme grade. To further refine results, comprehensive cloud expected values determine relative positions within hazard grades, with linear interpolation predicting sand accumulation thickness. Predicted versus recorded thickness values are: R1 (0.40 m vs 0.44 m), R2 (0.40 m vs 0.44 m), R3 (0.47 m vs 0.52 m), and R4 (0.41 m vs 0.53 m). Applying this method to all sections yields the comprehensive evaluation results shown in Figure 7.

To validate model reliability, historical sand hazard observation data were used as benchmarks. Historical data were obtained from the Yuli-Qiemo desert highway sand clearance records, including date, highway segment, and sand thickness across different seasons and dust storm intensities. Using predicted grades as the X-axis and historical data as the Y-axis, scatter plot analysis (Figure 6) shows that among 55 sections with complete observation records, the linear regression equation between measured and predicted sand thickness is $y = 0.89x + 0.12$ ($R^2 = 0.83$, $P<0.001$), demonstrating an extremely significant positive correlation within the 95% confidence interval. This indicates that predicted results accurately reflect actual sand accumulation conditions.

3 Discussion

Under the methodological framework constructed in this study, comprehensive evaluation of sand hazards along the entire 332 km desert highway was completed under dynamic variable-weight conditions. Results demonstrate that this method effectively reflects the spatial distribution characteristics of sand hazard risks with high scientific validity and operational feasibility. Overall, sand hazards are lighter at the northern and southern ends and heavier in the middle sections, with risk gradually increasing from north to south. Compared with traditional methods, variable-weight theory enhances dynamic adaptability of weights, cloud model improves evaluation precision, and Python technology enables visual analysis, making results more practical. However, the model remains limited by data resolution and dependence on expert experience. Future improvements could integrate high-resolution remote sensing data and deep learning to optimize the indicator system, while long-term monitoring could enhance predictive capability. Additionally, it is recommended to strengthen sand control measures in high-risk sections, optimize vegetation protection systems, and establish dynamic monitoring using IoT and drone technologies to improve highway resistance to aeolian sand and provide more scientific support for desert highway planning, design, and maintenance.

4 Conclusions

(1) This method achieves systematic enhancement of evaluation scale under variable-weight conditions, expanding sand hazard evaluation from single segments to entire highways. Using the Yuli-Qiemo desert highway as a case study, evaluation results were validated against historical sand hazard records, yielding a correlation coefficient of 0.91 ($P<0.001$). This demonstrates that the evaluation method is efficient, accurate, and scientifically robust.

(2) Mobile dune height and drift potential are core factors influencing highway sand hazards. Mobile dune height variable weights are significantly

higher than fixed weights, highlighting its dominant role. Although drift potential weights are slightly lower, the synchronized increasing trend of its state values and variable weights confirms the critical importance of sand transport capacity. Variable weights for other indicators are generally lower than fixed weights, reflecting that natural factors dominate actual hazards and weaken other indicators' relative contributions.

(3) Under the combined influence of natural conditions and engineering construction, sand hazards are less severe in the desert margin areas at the northern and southern ends but more severe in the central desert sections, with an overall increasing trend from north to south. Grade III hazard segments dominate (65.46%), followed by grade IV (30.91%), with few grade II segments (1.82%) and no grade I segments. The highway' s overall sand hazard problem is severe, particularly in sections K180~K250 and K30~K60, where extreme hazard segments account for 78.58% and 66.67%, respectively. These severe hazards threaten highway safety and maintenance, requiring prioritized attention, enhanced patrols, and emergency response.

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