Research on Evaluation of Slope Stability of Kunlun Mountain Area Highway Based on Fuzzy-Entropy method

Yinbo Zhang[1,a], Yaoye Li[1,b], Xingbo Zhang[2,c], Rong He[*,1,d]

[1] Xinjiang Communications Construction Group Co., Ltd., Urumqi, Xinjiang 830016, China;

[2] Xinjiang University, China.

[a]1057642630@qq.com, [b]liyaoye512@163.com, [c] 675165829@ qq.com, [d] 64921014@ qq.com

Abstract. To evaluate the stability of rocky slopes in the high-altitude, cold, and High seismic intensity terrain of the Kunlun Mountain region, we analyzed key factors influencing the stability of these slopes in relation to a specific highway project in the area. Four primary indicators, including slope morphology, meteorological and hydrological conditions, rock characteristics, and triggering factors, were selected, along with 16 secondary indicators, as fuzzy evaluation criteria. Based on the entropy weighting-fuzzy theory, we established a stability assessment model for rocky slopes in this region. Finally, taking the rocky slope section K128+540-K128+560 as an example, we used the evaluation model to calculate a 51.71% probability of slope instability. The evaluation results align with the actual on-site conditions, providing valuable insights and practical implications for analyzing and evaluating the stability of similar rocky slopes in this region and other projects.

Keywords: alpine high altitude and High seismic intensity region; highway slope; stability; fuzzy-entropy method; evaluation index.

1. Introduction

For a long time, the stability evaluation of highway slopes has been an important research topic in highway slope engineering and has received increasing attention and emphasis in recent years [1,3]. With the implementation and promotion of the Western Development Strategy and the Belt and Road Initiative, infrastructure construction in Xinjiang has witnessed rapid development. Especially in the high-altitude and cold regions, a large number of highway projects, including slope engineering, have been constructed [4]. The stability of such slopes directly affects the construction projects and the safety of people's lives and properties.

The Kunlun Mountains stretch across Xinjiang, encompassing high-altitude, cold, and high-intensity environments in the mountainous regions. The slopes are mostly exposed rocky ones with severe rock weathering and significantly reduced strength. During the construction process, excavation and blasting cause further fragmentation of rocks and the development of fractures, leading to a decrease in slope stability. Moreover, high-altitude areas have thin soil coverage, low temperatures, and large diurnal temperature variations, making them susceptible to freeze-thaw cycles. In areas with significant joint development and loose rock formations, snowmelt can easily trigger landslides. Seismic activity also adds complexity to some slopes [5]. Such critical nodes become key factors in the success or failure of construction projects, limiting the traffic and safety during operation, and greatly influencing the investment and utility of the construction project. Therefore, the risk assessment of slope stability in these areas holds great practical significance.

Currently, China has conducted extensive research on slope stability evaluation [6, 9]. However, research specific to high-altitude, cold, and high-intensity slopes in the Kunlun Mountains region of Xinjiang is relatively limited. Hence, this paper combines the ongoing project in the high-altitude, cold, and high-intensity regions of the Kunlun Mountains in Xinjiang. Based on previous research findings, a fuzzy-entropy-based analysis of influencing factors and the construction of theoretical models for slope stability are conducted. The ultimate goal is to achieve prediction and evaluation of the risk level for highway slopes in high-altitude, cold, and high-intensity mountainous areas.

2. Construction of Slope Stability Evaluation Model

2.1 The Basic Principles of Entropy Weighted Method

Entropy was originally a physical concept used to describe the degree of energy distribution in space. With the development of information theory, mathematician Shannon introduced it into information theory and applied it to measure system stability and information content [10]. In multi-index decision-making analysis, the entropy weight method is a common algorithm. It is based on the difference-driven principle, which can highlight local differences between indicators. By solving the optimal weight of each sample's actual data, it reflects the importance of the information entropy values of each indicator, so the calculated index weight is more accurate and objective. The basic principle of this method is to determine the corresponding weights of each indicator based on their degree of discreteness, reflecting the relative competition intensity of these indicators. Put simply, if an indicator's value is more discrete or has more information content compared to other indicators, it will be assigned a higher weight in the weight calculation. Conversely, if an indicator's value is more concentrated compared to other indicators, it will be assigned a smaller weight because it contains relatively less information. The entropy weight method is an effective and reliable algorithm that can help decision-makers evaluate various aspects of research objects or decision options' indicators more comprehensively and objectively, providing useful support for practical decision-making [11].

2.2 Establishment of Calculation Model for Entropy Weighted Method

2.2.1 Establishment of Evaluation Index System

Taking into full account the natural factors such as high altitude, coldness, and high intensity in the Kunlun Mountains region where a certain highway construction project is located, adhering to scientific and reasonable basic principles, and establishing a stability index evaluation system for highway slopes in the Kunlun Mountains region.

The first level factor set： $U = (U_1, U_2, \cdots, U_i)$ （1）

The second level factor set： $U_i = (U_{i1}, U_{i2}, \cdots, U_{ij})$ （2）

In the formula, U represents the stability of the slopes of Kunlun Mountain highways; Ui represents the ith subset of slope risk factors of U; Uij represents the jth element in the ith subset of slope risk factors of U.

2.2.2 Establishment of Entropy Weight Method Matrix Model

Construct the evaluation matrix and an m x n order decision matrix X based on the evaluation object of the entropy weight method evaluation index system, as shown in Equation 3:

$$X = \begin{bmatrix} x_{01} & x_{02} & \cdots & x_{0n} \\ x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m-1,1} & x_{m-1,2} & \cdots & x_{m-1,n} \end{bmatrix} \tag{3}$$

In the formula, m represents the assessment grade and n represents the number of assessment indicators.

To address the issue of homogenization of different indicators, the decision matrix is normalized to construct a standardized matrix $Y = (y_{ij})_{m\times n}$ and positive-negative indicator calculation formulas are established to convert the absolute values of the indicators into relative values and calculate the weight values of the indicators, as shown in Equations 4-9:

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \quad (4)$$

$$\text{Positive index:} \ x'_{ij} = \frac{x_{ij} - \min\{x_{1j}, \cdots, x_{nj}\}}{\max\{x_{1j}, \cdots, x_{nj}\} - \min\{x_{1j}, \cdots, x_{nj}\}} \quad (5)$$

$$\text{Negative index:} \ x'_{ij} = \frac{x_{ij} \max\{x_{1j}, \cdots, x_{nj}\} - x_{ij}}{\max\{x_{1j}, \cdots, x_{nj}\} - \min\{x_{1j}, \cdots, x_{nj}\}} \quad (6)$$

$$a_j = \frac{1 + \frac{1}{\ln m} \sum_{i=1}^{m} y_{ij} \ln y_{ij}}{\sum_{j=1}^{n} \left(1 + \frac{1}{\ln m} \sum_{i=1}^{m} y_{ij} \ln y_{ij} \right)} \quad (7)$$

$$\sum_{j=1}^{n} a_j = 1 \quad (8)$$

$$\underline{A} = (a_1, a_2, \cdots a_n) \quad (9)$$

In the formula, $-\frac{1}{\ln m} \sum_{i=1}^{m} y_{ij} \ln y_{ij}$ represents the entropy value of the index, a_j represents the weight value of the index, and $\underline{A}$ represents the weight vector of the index.

2.3 Multilayer Comprehensive Evaluation Based on Fuzzy Theory

According to the basic idea of fuzzy theory and the evaluation object of the evaluation index system in 1.2, and based on obtaining the weight vector $\underline{A} = (a_1, a_2, \cdots a_n)$, a single factor evaluation matrix (10) is established to finally obtain the fuzzy evaluation (11) of the evaluation object.

$$\underline{R} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \quad (10)$$

$$\underline{B} = \underline{AR} \quad (11)$$

Thus achieving step-by-step evaluation from the lowest level factors and obtaining slope stability rating for the highway slopes in Kunlun Mountains area.

3. Engineering Application

The engineering application project in this article is a certain highway in the Kunlun Mountains, which crosses the Inditash Darshan with a maximum altitude of 4950m and a seismic intensity of 8 degrees. It is a typical high-altitude, cold, and high-intensity area. Excavation is the main method along the route, and the geological and topographical conditions are extremely complex. The stability of high slopes is affected by regional geological structures, rock types, rock hardness, and rock structure. In addition, the slope deformation is seriously affected by the geological history. During the construction process, blasting measures were adopted, which resulted in further extension and partial opening of some rock structures. At the same time, there are some downslope sections in individual excavation cross-sections. Some high slopes have the risk of instability, and their instability will cause landslide or landslide disasters, which not only affect the construction safety during the construction period but also pose many safety risks during the later operation period. The stability of high slopes in this section has a significant impact on road safety. In order to grasp the stability of each high slope, control the risks of possible disasters along the line, and reduce the impact of high slope damage on the highway, the slope stability and risk assessment work was carried out using the rock slope from K128+540 to K128+560 section as an example.

3.1 Stability Evaluation Index System

A scientific, reasonable, and complete index system is the basic condition for evaluating slope stability. Therefore, based on field investigations, communication with participating units, expert interviews, and principles such as integrity, hierarchy, and wide applicability, this article establishes a three-level stability evaluation system for the rock slope from K128+540 to K128+560 of a certain highway project in the high-altitude, cold, and high-intensity Kunlun Mountains. The system includes 4 primary indicators and 16 secondary indicators, based on documents such as China's " Specification of risk assessment for geological hazard", " Specification of comprehensive survey for landslide collapse and debris flow ", " Specifications for Design of Highway Subgrades", and " Seismic ground motion parameters zonation map of China", as shown in Table 1.

Table 1. Evaluation System for Highway Slope Stability

Evaluating indicator		Grade steadiness			
Primary indicators	Secondary indicators	stabilize	basically stable	instability	Extremely unstable
Slope morphology U1	Slope height U11	＜20	20 ～50	50 ～100	＞100
	Slope gradient U12	＜20	20～45	45～70	＞70
	Slope excavation method U13/m	Natural Slope	Pre-split Smooth Surface Blasting	Conventional Blasting	Uncontrolled Blasting
Meteorological and hydrological conditions U2	groundwater conditions U21（° ）	Completely Dry	Damp or Moist	Dripping Water	Flowing Water
	Slope drainage conditions U22	Very Good	Relatively Good	Relatively Poor	Very Poor
	freeze-thaw cycle U23（Times/year）	0～10	10～25	25～50	＞50
	diurnal temperature U24（℃）	＜15	15～25	25～35	＞35
Rock Characteristic U3	Structural plane features U31	Slightly Weathered and Unweathered	Moderately Weathered	Heavily Weathered	Completely Weathered
	topographic features U32	Gentle slope, favorable terrain	Gently sloping terrain, relatively good landform	Steep slope, unfavorable terrain	Very steep slope, extremely unfavorable terrain
	Rock mass integrity coefficient U33	1.0～0.75	0.75～0.55	0.50～0.35	≤0.35
	Rock Quality Designation U34/%	75～100	50～75	25～50	0～25
Inducing factors U4	rainfall intensity U41/（mm・d-1）	0～10	10～20	20～50	＞50
	earthquake intensity	＜6	6～7	7～8	＞8

	U42/（°）				
	Affected by seasonal fine water flow U43	Relatively Large	Large	Moderate	No Effect
	Protective measures U44	Reasonable	Relatively Reasonable	Unreasonable	Extremely Unreasonable
	Manual excavation process U45	Minor Disturbance	Moderate Disturbance	Significant Disturbance	Strong Disturbance

3.2 Determination of Weight for fuzzy-Entropy Method Indicators

The weight was determined using the Analytic Hierarchy Process (AHP). A slope stability evaluation indicator scoring group was formed with experts from five different roles, including construction units, supervision units, construction units, university teachers, and scientific research institutes, to compare scores between indicators, and the rationality of the scores was determined through consistency tests. Thus, a discriminant matrix was constructed, and the entropy weight calculation model was used to calculate the degree of superiority of subjective weights for evaluation. Then, a weighted combination of subjective weights and entropy weights was obtained, ensuring reliable indicator weights while considering expert subjectivity and avoiding interference with evaluation results.

To illustrate the weight calculation process for primary indicators, the judgment matrix constructed by expert A is shown below[12]:

$$W=\begin{pmatrix}1 & 1/5 & 1/3 & 1/7\\ 5 & 1 & 2 & 1/3\\ 3 & 1/2 & 1 & 1/2\\ 7 & 3 & 2 & 1\end{pmatrix}$$

Based on the maximum eigenvalue $\lambda_{\max}=4.118$, the normalized feature evaluation indicator vector $B_1=[0.0600\ ,0.2672\ ,0.1836\ ,0.4892\ ]$ is obtained. The consistency ratio CR = 0.044 < 0.1, indicating that the subjective weights are reasonable. By summarizing the scores given by 5 experts, the subjective weights of the primary indicators are obtained, and then the objective weights of the primary indicators are obtained using the entropy weight method in section 1.2, as shown in Table 2. After combining the subjective weights and the entropy weight method weights, the combined weights are obtained and summarized in Table 3.

Table 2. Subjective and objective weights of primary indicators

Indicators or Calculation results	Expert A	Expert B	Expert C	Expert D	Expert E	Weight Type
Slope morphology U1	0.0600	0.0600	0.0596	0.5112	0.1481	Subjective weight
Meteorological and hydrological conditions U2	0.2672	0.1508	0.1563	0.0599	0.0593	
Rock Characteristic U3	0.1836	0.2623	0.2032	0.2698	0.2131	
Inducing factors U4	0.4892	0.5269	0.5808	0.1591	0.5795	
Entropy	0.702	0.654	0.604	0.672	0.603	Objective weight
Weight	0.1687	0.1960	0.2244	0.1857	0.2252	
Level	5	3	2	4	1	

Table 3. Weight values of indicators at each level of the evaluation system

Target layer	Primary indicators	combined weight	Secondary indicators	combined weight
Risk of Highway Slope Stability U	Slope morphology U1	0.1635	Slope height U11	0.0240
			Slope gradient U12	0.0530
			Slope excavation method U13	0.0866
	Meteorological and hydrological conditions U2	0.1342	groundwater conditions U21	0.0152
			Slope drainage conditions U22	0.0424
			freeze-thaw cycle U23	0.0498
			diurnal temperature U24	0.0268
	Rock Characteristic U3	0.2261	Structural plane features U31	0.0637
			topographic features U32	0.0545
			Rock mass integrity coefficient U33	0.0714
			Rock Quality Designation U34	0.0364
	Inducing factors U4	0.4762	rainfall intensity U41	0.0526
			earthquake intensity U42	0.1864
			Affected by seasonal fine water flow U43	0.0398
			Protective measures U44	0.1090
			Manual excavation process U45	0.0883

3.3 Establishment of Membership Degree Matrix for Evaluation Indicators

According to the current situation of the rock slope in section K128+540-K128+560 and the established highway slope stability risk evaluation system, the highway slope stability is divided into 4 levels, forming an evaluation set V = {4,3,2,1}, as shown in Table 4.

Table 4. Accident Probability Level Standards

Degree of impact	grade
Stable	4
marginally stable	3
unstable	2
highly unstable	1

Establish a single-factor fuzzy relationship matrix R from U to V, and obtain the membership degree matrix Ri of the highway slope stability evaluation indicator by expert investigation and review.

$$R_1 = \begin{bmatrix} 0.44 & 0.56 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} R_2 = \begin{bmatrix} 0.8 & 0.2 & 0 & 0 \\ 0 & 0.2 & 0.6 & 0.2 \\ 0.1 & 0.9 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0 & 0.2 & 0.8 & 0 \\ 0 & 0 & 0.8 & 0.2 \\ 0.77 & 0.23 & 0 & 0 \\ 0 & 0.8 & 0.2 & 0 \end{bmatrix} R_4 = \begin{bmatrix} 0 & 0 & 0.72 & 0.28 \\ 0 & 0.5 & 0.5 & 0 \\ 0.4 & 0 & 0.4 & 0.2 \\ 0 & 0 & 0.6 & 0.4 \\ 0 & 0 & 0.8 & 0.2 \end{bmatrix}$$

3.4 Fuzzy Synthesis Calculation of Multi-level Evaluation Indicators

Based on the fuzzy theory and Formula (11), the evaluation matrix is again composed layer by layer using the upper-level evaluation results from the secondary evaluation indicators, and the secondary fuzzy evaluation result is calculated. Specifically:

(1) Fuzzy evaluation of secondary evaluation indicators:

$$B_{11} = [0.0645, 0.082, 0.5295, 0.3240] \quad B_{12} = [0.1276, 0.4199, 0.3394, 0.1131]$$

$$B_{21} = [0.2432, 0.2578, 0.4507, 0.0482]$$
$$B_{22} = [0.0334, 0.1958, 0.5945, 0.1764]$$

(2) Fuzzy evaluation of primary evaluation indicators:

$$B_{1} = [0.0986, 0.2213, 0.5171, 0.1631]$$

3.5 Evaluation Result Analysis

The calculation results show that the probability of instability at this location is 51.71%. Under the influence of inducing factors, the probability of rockfall or landslide disasters is relatively high. Before the highway is put into operation, the construction unit should carry out secondary treatment on the slope, reinforce it or clear the dangerous source to prevent safety accidents from happening.

4. Conclusion

(1) In the special environment of the Kunlun Mountains area with high altitude, coldness, and high intensity, there is great uncertainty in the factors influencing slope stability. This article introduced the fuzzy-entropy weight theory to determine the influencing indicators layer by layer, and established a high-altitude, cold, and high-intensity highway slope evaluation model based on the fuzzy-entropy weight theory, which provides a new idea and method for the subsequent analysis, evaluation, and monitoring of slope stability in this region.

(2) The highway slope stability assessment model based on fuzzy entropy weight theory can use quantitative methods to solve fuzzy and unclear evaluation objects, and it is clear and easy for users to understand its hierarchy.

(3) The evaluation result of this article is an unstable state, which is consistent with the evaluation of the geology department, demonstrating the feasibility of this method.

(4) In order to make the model more practical, there are subjective factors in the selection and assignment of influencing factors, and some less important factors will inevitably be omitted, leading to some degree of deviation in the results. In order to make the model more practical, later research will further study and explore from the angles of selecting influencing factors, expanding expert scorers, and adding some objective data.

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