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Stability analysis and evaluation of a highway slope in the high and cold mountain area and suggestions for prevention and control

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Abstract

In order to ensure the stability of a rocky slope on a highway in a high cold mountainous area, this paper evaluates the stability of the right high slope in the section from K155+320 to K155+460 using the Chi Ping projection method and the fuzzy evaluation method based on game theory-cloudified object model. Firstly, the geological, geomorphological, hydrological and other natural profile information of the slope is obtained through field investigation, and these indicators are transformed into evaluation indicators for qualitative evaluation using the Chi Ping projection method. Then, the fuzzy evaluation method based on game theory-cloudified object model is used to transform the qualitative evaluation results into quantitative data, taking into account the mutual influence between different factors. The results show that the results obtained by the two evaluation methods are consistent. Finally, based on the stability analysis and evaluation results, it is proposed to use the method of clearing the surface dangerous rocks and applying active protective nets to deal with the slope problem in that area. At the same time, the slope stability analysis and evaluation method and the prevention and control suggestions provide reference for the subsequent slope governance.

Keywords

Stability analysis; Chi Ping projection method; fuzzy evaluation method; prevention and control suggestions.

1. Introduction

In recent years, slope stability evaluation has received increasing attention and importance [1-3]. With the phased success of highway construction in China and the requirements of economic development, reducing the travel distance between two places has become one of the goals of highway construction. However, in western regions such as the Kunlun Mountain area in Xinjiang, slope stability issues have become challenges that cannot be ignored in highway construction and operation. The Kunlun Mountain area is characterized by a high-altitude, cold, and high-intensity environment, with most slopes being exposed rock, and severe weathering of the rock mass leading to a significant reduction in strength. During the construction process, excavation and blasting further fracture the rock and extend existing cracks, thereby reducing slope stability[4]. Additionally, high-altitude regions have thin soil cover, low temperatures, and large temperature differences between day and night, making them susceptible to freeze-thaw effects. Particularly in areas with well-developed joints and loose rock masses, collapses are prone to occur when encountering melting snow. Furthermore, natural forces make some slopes even more complex. Therefore, in order to ensure the safety and smooth operation of highways, it is necessary to conduct stability

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analysis and evaluation of important rock slopes in the Kunlun Mountain area, as well as implement corresponding preventive measures. Geological surveys need to be conducted to determine the geological environmental conditions and characteristics of the slopes. Through stability evaluation analysis, suitable recommendations and measures can be proposed for the prevention and control of slopes, thereby providing a scientific basis for slope treatment.

2. Slope Overview

The slope is located on the right side of the section K155+320 to K155+460 of a highway in Xinjiang and Tian, as shown in Figure 1. The geographical location belongs to the northern foot of the Kunlun Mountains and is located on the northwest edge of the Qinghai-Tibet Plateau. This region is adjacent to the West Kunlun Fold Belt and the Tarim Basin, and strong tectonic movements have caused folding and uplift of the rock layers in the Kunlun Mountain trough. A series of NW-SE trending faults determine the direction and morphology of the mountains and inland depression basins. The past Xishan movement has led to significant uplift of the Kunlun Mountains, while the Tarim Basin has experienced subsidence and accumulated thick sedimentary deposits. The terrain exhibits the characteristic of being high in the southwest and low in the northeast.

Figure 1: Slope Front

3. Natural Geographic Conditions

The slope is located in the Kunlun Mountain area above an altitude of 2500 meters, belonging to the cold temperate continental arid climate zone. According to the natural regionalization, the geographical division where the road is located is the Qilian-Kunlun Mountain area (Ⅶ1) of the Qinghai-Tibetan Plateau alpine region. The climate in this region is cold, with no clear distinction between four seasons, only cold and warm periods, and the cold season is longer. The distribution of precipitation is extremely uneven, with an average annual precipitation of about 300 millimeters, and the growing season (above 0°C) is about 120-150 days. The average annual evaporation is 2458.8 millimeters. The wind speed characteristics in this area are as follows: wind above level 6 occurs more frequently from March to June, with an average of 23 days per year; wind above level 7 occurs more frequently in May and June, with an average of 8 days per year. Westerly winds have the highest speed, with a maximum wind speed of 14-22 meters per second and an instantaneous maximum wind speed of 28 meters per second.

4. Overview of the Slope

4.1. Morphological Characteristics

The slope is a deep-cut roadbed slope with a total length of about 140 meters and a maximum slope height of about 55 meters. The slope is divided into two levels, with a slope platform set in the middle. However, the entire slope surface is uneven, and there are local areas with reverse slopes. The rock type is phyllite, overall gray in color, but locally appears deep green. The rock has a schist structure and phyllite-like structure, with fine texture. It is mainly formed by finely layered sericite, chlorite, and other oriented arrangements. The bedding planes are relatively well developed, and the rock is relatively soft.

4.2. Engineering Geological Conditions

The slope is located in a tectonic erosion area of low to middle mountains, and it is a rocky slope. The main rock type is strongly weathered to moderately weathered Changcheng series phyllite. Groundwater is not developed within the slope range, and there is no special distribution of rock and soil in the deep-cut roadbed. In terms of geological structures, no folds or faults were found.

4.3. Structural Features

The geological formation of the slope mainly consists of Changcheng series (ChP) phyllite, which belongs to a rocky slope. After excavation of the roadbed, the slope surface has an orientation of 163°∠65°. Considering the influence of structures and weathering, joint fissures are relatively well-developed on this slope. Through investigation, it is understood that three main sets of structural surfaces develop in the slope. The attitude of the slope stratum is C: 208°∠75°, and the main structural surface attitude is J1: 54°∠70°, which is closed and partially open, extending 3-5 meters; J2: 310°∠80°, also closed.

5. Slope Stability Evaluation Methods

Slope stability evaluation is an important task in engineering, which involves the safety and reliability of slopes. It provides a comprehensive understanding and analysis of the slope stability. The main methods for slope stability evaluation include: chi-ping projection method, limit equilibrium method, numerical simulation method, fuzzy evaluation method [5-6], empirical method, and monitoring method [7].

(1) Toe Projection Method: This is a commonly used slope stability evaluation method for rocky slopes. It projects the planar shape of the slope on the geological profile, and then calculates the slope's stability safety factor based on the mechanical properties of the rock mass and stability analysis principles. This method is simple and intuitive, suitable for small-scale slopes with relatively simple geological structures. However, it ignores the nonlinear and heterogeneous characteristics inside the rock mass, and the evaluation results for complex slopes may be inaccurate.

(2) Limit Equilibrium Method: This is a slope stability evaluation method based on the principle of mechanical equilibrium. It establishes a mechanical model of the slope, considering factors such as stress on the rock mass, geometric shape of the slope, and mechanical parameters of the rock, to determine whether the slope is in a state of equilibrium, and calculate the slope's stability safety factor. This method is suitable for evaluating the stability of rocky slopes and can consider complex slope structures and groundwater effects. However, it requires accurately determining the mechanical parameters and boundary

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conditions of the slope, and for nonlinear and heterogeneous rock masses, there may be some errors in the calculation results.

(3) Numerical Simulation Method: This is a slope stability evaluation method based on numerical calculations. Commonly used numerical simulation methods include the finite element method, discrete element method, etc. It establishes a three-dimensional model of the slope, considers the nonlinear characteristics of the rock mass, the formation and development of sliding surfaces, etc., simulates the deformation and failure process of the slope, and obtains the slope stability analysis results. This method is suitable for complex slope structures and groundwater conditions, and can provide relatively accurate slope stability evaluation results. However, numerical simulation methods require a large amount of computing resources and longer computation time, and also require high expertise in model establishment and parameter selection.

(4) Fuzzy Evaluation Method: This method introduces fuzzy mathematics theory, combines fuzzy concepts with mathematical models, and evaluates slope stability. It allows for fuzzy partitioning of slope stability indicators and uses fuzzy inference techniques for comprehensive assessment. The fuzzy evaluation method considers the interactions and uncertainties between different parameters and variables, and can better adapt to actual conditions and provide more accurate evaluation results.

(5) Empirical Method: This is a slope stability evaluation method based on engineering practices and empirical summaries. Based on historical data and measured information from similar slope projects, empirical formulas or charts are derived to perform simple calculations and judgments on the geological, geometric, and mechanical parameters of the slope, and assess the slope's stability. This method is suitable for small-scale slopes with relatively simple slope conditions and can quickly evaluate slope stability. However, the applicability of the empirical method has certain limitations, and for complex slope conditions, the evaluation results may not be accurate enough.

(6) Monitoring Method: This is a method to evaluate slope stability by real-time monitoring of slope deformation, stress, and other parameters. By setting up monitoring points and collecting relevant data such as displacement, stress, seepage, etc., monitoring and recording are conducted, and the stability of the slope is judged through analysis of these data. The monitoring method can promptly detect abnormal behavior of the slope and provide measured data to verify the evaluation results. It is suitable for complex slope engineering and situations where high slope stability requirements are needed. However, the monitoring method requires longer monitoring periods and more monitoring equipment, leading to higher costs.

6. Slope Stability Analysis

Based on the basic characteristics of the slope, the Chi-Ping projection method and the fuzzy evaluation method based on game theory-cloudized physical element model are used to qualitatively and quantitatively analyze the stability of the high right slope segment from K155+320 to K155+460, and evaluate its stability.

(1) Chi-Ping Projection Method

The calculation results of the slope using the Chi-Ping projection method are shown in Figure 2.

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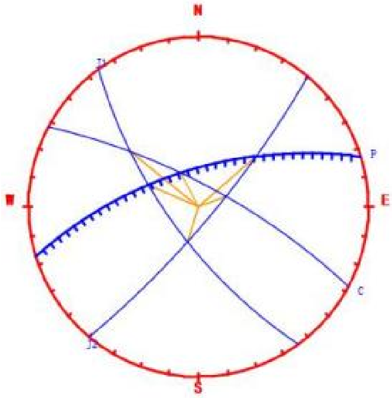

Nnumber	structural surface name	Incline	Angle
P	Slope surface	163	65
C	Structural Plane 1	208	75
J1	Structural Plane 2	54	70
J2	Structural Plane 3	310	80
Combining intersecting edges		Incline	Angle
P-C		152	65
P-J1		114	54
P-J2		229	41
C-J1		129	35
C-J1		250	70
J1-J2		17	66

Figure 2: Slope Horizontal Projection Analysis

After the excavation of the slope in the road cut, the slope surface becomes steep and there are local reverse slopes. The rock mass of the slope has well-developed joints, with block-like to fragmented structure, and unfavorable inclined structural planes. The spacing between structural planes is 0.3m to 1.5m, with 2 to 3 groups of structural planes. There are many detached blocks distributed on the slope surface. The predominant failure mode of the slope is collapse, and the slope is controlled by the structural planes. The overall stability is good, but there are current occurrences of collapse and falling rocks.

(2) Fuzzy Evaluation Method based on Game Theory-Cloudized Physical Element Model

Slope stability evaluation is a complex and critical issue. In order to ensure the accuracy and comprehensiveness of the evaluation, relevant literature and technical specifications were referenced to form a preliminary evaluation index system. It is 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 U_1	Slope height U_{11}	0～20	20～50	50 ～100	100～180
	Slope gradient U_{12}	0～20	20～45	45～70	70～90
	Slope excavation method U_{13}/m	Natural Slope（100～75）	Pre-split Smooth Surface Blasting（75～50）	Conventional Blasting（50～25）	Uncontrolled Blasting（25～0）
Meteorological and hydrological conditions U_2	groundwater conditions U_{21}（°）	Completely Dry（100～75）	Damp or Moist（75～50）	Dripping Water（50～25）	Flowing Water（25～0）
	Slope drainage conditions U_{22}	Very Good（100～75）	Relatively Good（75～50）	Relatively Poor（50～25）	Very Poor（25～0）
	freeze-thaw cycle U_{23}（Times/year）	0～10	10～25	25～50	＞50

	diurnal temperature U_{24}（℃）	＜15	15～25	25～35	＞35
Rock Characteristic U_3	Structural plane features U_{31}	Slightly Weathered and Unweathered（100～75）	Moderately Weathered（75～50）	Heavily Weathered（50～25）	Completely Weathered（25～0）
	topographic features U_{32}	Gentle slope, favorable terrain（100～75）	Gently sloping terrain, relatively good landform（75～50）	Steep slope, unfavorable terrain（50～25）	Very steep slope, extremely unfavorable terrain（25～0）
	Rock mass integrity coefficient U_{33}	1.0～0.75	0.75～0.55	0.50～0.35	≤0.35
	Rock Quality Designation U_{34}/%	75～100	50～75	25～50	0～25
Inducing factors U_4	rainfall intensity U_{41}/（$mm\cdot d^{-1}$）	0～10	10～20	20～50	＞50
	earthquake intensity U_{42}/（°）	＜6	6～7	7～8	＞8
	Affected by seasonal fine water flow U_{43}	Relatively Large（100～75）	Large（75～50）	Moderate（50～25）	No Effect（25～0）
	Protective measures U_{44}	Reasonable（100～75）	Relatively Reasonable（75～50）	Unreasonable（50～25）	Extremely Unreasonable（25～0）
	Manual excavation process U_{45}	Minor Disturbance（100～75）	Moderate Disturbance（75～50）	Significant Disturbance（50～25）	Strong Disturbance（25～0）

Based on the quantitative indicators of the slope, including slope height and slope gradient, 5 experts in this field were selected. Based on the actual conditions of the slope to be evaluated, qualitative indicators such as groundwater conditions and slope drainage conditions were used to score them on a scale of 0 to 100. The average score was calculated and the values of the slope evaluation index system were organized. Then, using the entropy weight method, the subjective and objective weights of the evaluation indicators, as well as the combined weights, were determined. Finally, using the cloudized physical element model, a Python program was developed to determine the comprehensive membership degree using the weighted average method over 100 iterations. According to the principle of maximum membership degree, the stability level of each slope engineering was ultimately determined, as shown in Table 2.

Table 2: Slope Stability Evaluation Level

Slope Pile Number	Stabilize (grade Ⅳ)	basically stable (grade Ⅲ)	Instability (grade Ⅱ)	Extremely unstable (grade Ⅰ)	level determination
K152+700～K152+900	0.0500	0.1268	0.0910	0.1165	Grade Ⅲ

According to Table 2, it can be determined that the stability of the slope is generally stable.

7. Conclusion and Recommendations

This study investigates the actual problems faced by the right high slope of the K155+320~K155+460 section of a highway in a high-cold mountainous area. After analyzing the advantages and disadvantages of six methods including chi-ping projection method, limit equilibrium method, numerical simulation method, fuzzy evaluation method, empirical method, and monitoring method, the chi-ping projection method and the fuzzy evaluation method based on game theory-cloudization object model are selected for calculating and analyzing the stability of the slope. After detailed calculations and analysis, it is concluded that the slope is basically stable. Therefore, it is recommended to use the method of removing surface dangerous rocks and active protection nets to deal with the slope problem at that location. This study provides important scientific evidence for relevant engineering decision-making and risk management. At the same time, it provides a feasible method and evaluation model for similar studies, which is of great reference value for the construction of highways and engineering safety in high-cold mountainous areas.

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