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Evaluation of Rock Slope Stability based on Multi-Dimension Cloud Model

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Abstract. In this paper, slope stability is classified into five grades in terms of very steady, steady, basically steady, unsteady, and very unsteady. Ten indicators of slope height, tendency difference between structural plane and slope, structural plane inclination, etc., were selected. To solve the uncertainty and randomness, multi-dimension cloud model was applied with weights determined by projection pursuit method. The grade of steadiness was determined by maximum subject degree. The method was applied to 34 rock slopes to assess stability. The accuracy of the method reaches 50%, which indicates that the method has higher accuracy, and can be applied to other fields.

1. Introduction

The stability of rock slope is of great significance to the safety of people's lives and property. Since various evaluation indexes affected the rock slope stability, it is essential to determine the index system of rock slope stability scientifically and reasonably. Chen established an evaluation system with 10 indexes including slope height, the difference between structural plane dip and slope tendency, structural plane dip, the difference between structural plane dip and slope dip, rock uniaxial compressive strength, rock quality index, discontinuous plane spacing, structural plane characteristic value, groundwater level condition and slope excavation coefficient [1]. Affected by various fuzzy and random uncertain parameters, Zhu set up five indexes including rock quality, controlled structural plane, structural surface condition coefficient, slope height correction coefficient, and slope excavation method, and evaluated the stability of rock slope by grey correlation analysis method [2]. Wen adopts SAPSO-ELM based on extreme learning machine to select pore water pressure, cohesion, slope height, internal friction angle, weight of rock and slope angle as main indexes to effectively predict slope stability [3]. Based on the weighted least square method and matter element concept, Zhou adopted the evaluation index system for stability evaluation for high and steep rock slope, considering height, slope, rock quality, bulk density, cohesion, internal friction angle, slope aspect and strata occurrence, rock weathering degree, annual maximum rainfall and seismic intensity [4]. Wang established probability density function and membership function of slope safety reserve based on mathematical statistics and fuzzy mathematics, and applied to stability evaluation of bedding rock slope [5]. Li improved the slope stability probability classification (SSPC) method, which can quickly evaluate the stability of hydroelectric rock slope [6].

Since the stability of rock slope is affected by various factors, and uncertainties and randomness exist among the indicators, in this paper multi-dimensional cloud model is applied, which consider the uncertainty and randomness of the evaluation indicators synthetically, and the weights of the evaluation indicators were determined by projection pursuit method. The method proposed can overcome the subjectivity during the process of the weight determination. The method was applied to

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34 rock slope or stability evaluation, and compared with the actual stability of the slope These guidelines, written in the style of a submission to Material Science and Engineering: Conf. Ser., show the best layout for your paper using Microsoft Word. If you don't wish to use the Word template provided, please use the following page setup measurements.

2. Stability Evaluation of Rock Slope Based on Multidimensional Cloud Model

2.1. Evaluation Indicators and Classification Criteria

Based on <Technical Regulations for Engineering Geological Survey of Slopes in Hydropower and Hydraulic Engineering> (DL/T5337-2006), the stability of rock slopes is divided into five grades: very stable, stable, basically stable, unstable and very unstable. According to the revised rock quality classification criterion (CSMR) recommended by the regulations, eight indexes are selected including slope height h (m), difference between structural plane and slope inclination $\Delta\beta$ **(°)**, difference between structural plane inclination and slope angle $\Delta\alpha$ (°), rock uniaxial compressive strength σ_c (MPa), discontinuous plane spacing J_s (cm), structural plane characteristic value η, groundwater level condition C_w, slope excavation method coefficient K_c.The correlation analysis among the indexes indicated that the correlation is small, which proved that the eight indicators van be used to establish the index system to evaluate slope stability. The classification of each evaluation index is shown in Table 1.

Table 1. Grading threshold of rock slope stability evaluation index

Grade	h (m)	$\Delta\beta$ (°)	$\Delta\alpha$ (°)	σ_c (MPa)	J_s (cm)	η	C_w	K_c
very stable	0~10	30~18	10~90	100~2	100~2	25~3	12~1	12~1
stable	10~30	20~30	3~10	60-100	50~10	20~2	9~12	8~12
basically stable	30~60	10~20	-3~3	30~60	30~50	10~2	6~9	4~8
unstable	60~100	5~10	-10~-	15~30	5~30	5~10	3~6	0~4
very unstable	100~100	0~5	-90~-	0~15	0~5	0~5	0~3	-3~0

2.2. Weight Determined by Projection Pursuit Method

Projection pursuit method can avoid the subjective weighting problem in the evaluation process, so projection pursuit method is used to determine the weight of evaluation index. The weighting steps of projection pursuit method are as follows:

First of all, normalize the grading evaluation indicators to obtain $\{x_{ij}^* | i = 1,2,...,n;\ j = 1,2,...,m\}$, where n is the number of samples, m is the number of indicators. For positive indicators,

$$x_{ij}^* = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}} \tag{1}$$

For negative indicators,

$$x_{ij}^* = \frac{x_{j\max} - x_{ij}}{x_{j\max} - x_{j\min}} \tag{2}$$

where x_{ij} is the value of the jth indicator for the ith sample.

Construct projection index function

Assume P is m-dimension unit vector $P = \{P_1, P_2, ..., P_m\}$, and $\sum_{j=1}^{m} P_j^2 = 1$. Then One-dimensional projection pursuit value is

$$z_i = \sum_{j=1}^{m} z_{ij} = \sum_{j=1}^{m} P_j x_{ij}^* \tag{3}$$

Where z_{ij} is the projection component value for the i^th^ sample and the j^th^ indicator. The aim of projection pursuit method is to find the best projection direction to maximize the projection index function $H(P)$.

$$\max H(P) = S_z D_z \tag{4}$$

Where S_z is the standard deviation for projection value z_i, D_z is the local density of the projection value z_i.

$$S_z = \sqrt{\frac{\sum_{i=1}^{n}(z_i - E(z))^2}{n-1}} \tag{5}$$

$$D_z = \sum_{i=1}^{n}\sum_{j=1}^{n}(R - r_{ij}) \times f(R - r_{ij}) \tag{6}$$

Where $E(z)$ is the mathematical expectations of z_i, R is the window width for local density, i.e., density window width, r_{ij} is the distance between samples, $r_{ij} = |z_i - z_j|$, $f(t)$ is step function, When $t \geq 0$, the value is 1.0, and when $t < 0$, the value is 0.

Determine the weights

The weights were determined by

$$w_j = \frac{P_j^2}{\sum_{j=1}^{m} P_j^2} \tag{7}$$

2.3. Multi-Dimension Cloud Model

Cloud model is put forward by Deyi Li, which can transform stochastic and fuzzy problems from qualitative description to quantitative expression. It is widely applied in rock burst prediction, water quality evaluation, slope stability evaluation and other fields [1, 7, 8, 10]. Cloud model uses three parameters to characterize its digital characteristics: mathematical expectation, entropy and hyper-entropy. Among them, E_x is the mathematical expectation of cloud droplets, which refers to the central value of cloud droplets, E_n represents the uncertainty of qualitative concepts, which is determined by the randomness and fuzziness of qualitative concepts, and H_e is the uncertainty measure of entropy, i.e. the entropy of entropy, which is determined by the randomness and fuzziness of entropy. The calculation of three parameters is follows:

$$\begin{cases} E_x = \dfrac{B_{\max} + B_{\min}}{2} \\ E_n = \dfrac{B_{\max} + B_{\min}}{6} \\ He = k \end{cases} \tag{8}$$

Where $B_{\max}$ and $B_{\min}$ are upper and lower thresholds of each evaluation index grade, respectively, k is usually assumed to be 0.1.

Assume the dimensions of cloud model are irrelative with expectations of $E_{x1}, E_{x2}, ..., E_{xm}$, entropy is expressed by $E_{n1}, E_{n2}, ..., E_{nm}$, hyper-entropy is expressed by $H_{e1}, H_{e2}, ..., H_{em}$, then

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$$\mu_i = e^{-w_1 \cdot \frac{(x_i - E_{x1})^2}{2E_{n1}^2} - w_2 \cdot \frac{(x_i - E_{x2})^2}{2E_{n2}^2} - \ldots - w_m \cdot \frac{(x_i - E_{xm})^2}{2E_{nm}^2}} \tag{9}$$

Where $w_1, w_2, \ldots, w_m$ are the weights of m-dimension parameters, μ_i is the complex membership degree of samples.

The rock slope stability grade is determined according to the principle of maximum degree of membership.

3. Application

The multi-dimensional cloud model is used to evaluate the stability of 34 typical slopes [1]. Firstly, the weights of indicators were determined by projection pursuit method to be 0.08, 0.127, 0.126, 0.133, 0.134, 0.138, 0.131, and 0.131, respectively. The membership degree were determined by multi-dimension cloud model, which are shown in Table 2. The slope stability level is obtained according to the principle of maximum membership degree. Since there are only three statuses of unstable, locally unstable, and stable, the status of very unstable and unstable are taken as unstable status, basically stable is taken as locally unstable status, and very stable is taken as stable status.

From Table 2, it can be seen that stability results of 17 slopes in 34 actual slopes are in accordance with the actual stability state. In addition, 11 actual slopes using multi-dimensional cloud model are basically in agreement with the actual status with only one grade difference. Only 6 slopes have a large difference from the actual evaluation results, accounting for 17.6%. However, with CSMR method only 14 evaluation results are consistent with the actual situation, therefore the multi-dimensional cloud model based on projection pursuit can be applied to evaluate the stability of rock slope more accurately, and this method can be applied to other fields, such as water eutrophication assessment, river health assessment, and so on.

4. Conclusion

In this paper, the index system of rock slope stability evaluation is established by correlation analysis. The evaluation grade is divided into five grades: very stable, stable, basically stable, unstable and very unstable. The multi-dimensional cloud model is established by using eight parameters, such as slope height, difference between structural plane, and slope inclination, etc. The weight of the index is determined by projection pursuit method objectively. The proposed method is applied to the stability evaluation of 34 actual slopes. The evaluation results are close to the actual stability state. It indicated that the method can be applied to evaluate the stability of rock slopes and other fields.

Table 2. Comparison of the evaluation results between proposed method and other methods

No.	Slope cases	Results					Method proposed in this paper	CSMR method	Real status
		Very	Stable	Basically stable	Unstable	Very			
1	Tangyan Smooth Slope of Zhexi Hydropower Station	0.107	0.718	**0.733**	0.525	0.153	BS	BS	U
2	1 # slope at Lijiaxia Dam	0.064	**0.543**	0.541	0.377	0.153	S	U √	U
3	2 # slope at Lijiaxia Dam	0.111	**0.505**	0.451	0.288	0.105	S	BS	U
4	West Slope of Tianshengqiao II Hydropower Station	0.035	0.497	**0.685**	0.651	0.410	BS √	U	LS
5	Inlet Slope of Dongfen Hydropower Station	0.058	0.264	**0.327**	0.302	0.201	BS√	BS√	LS
6	Creep Body at Mid-dam Site of Miaojiaba Hydropower Station	0.128	**0.565**	0.557	0.404	0.120	S	BS	U
7	Slope in Shimoling Reservoir Area	0.086	**0.630**	0.605	0.426	0.193	S	U√	U
8	Inlet Slope of Dachaoshan Hydropower Station	0.094	0.640	**0.658**	0.485	0.171	BS	BS√	LS
9	Laxiwa left bank abutment slope	0.093	0.649	**0.671**	0.501	0.214	BS	U√	U
10	Slope of powerhouse of Nanyi Reservoir	0.086	**0.573**	0.524	0.351	0.190	S√	BS	S
11	Spillway Slope of Wohushan Hydropower Station	0.044	0.527	0.649	0.564	0.360	BS√	U	LS
12	Slope in Reservoir Area of Sanbanxi Hydropower Station	0.111	0.539	**0.575**	0.438	0.126	BS	U√	U
13	Slope at the entrance of diversion tunnel of Taipingyi Hydropower	0.073	0.508	0.722	**0.745**	0.341	U	BS√	LS
14	Slope at the entrance of diversion tunnel of Lijiaxia Hydropower	0.077	0.657	**0.820**	0.725	0.330	BS√	U	LS
15	Taipingyi Hydropower Station Taishui Canal Slope	0.205	0.811	**0.845**	0.652	0.200	BS√	BS√	LS
16	Intake Slope of Taipingyi Hydropower Station	0.095	0.636	**0.809**	0.751	0.261	BS	BS	S
17	Three-hole outlet slope of Manwan Hydropower Station	0.091	0.641	**0.827**	0.775	0.316	BS	U√	U
18	Slope of No.2 Tailrace Canal of Ertan Hydropower Station	0.075	0.509	0.718	**0.747**	0.357	U	U	LS
19	ErTan Hydropower Station Hongdong inlet slope	0.065	0.513	**0.653**	0.616	0.308	BS√	U	LS
20	He Jia Landslide of Miaojiaba Hydropower Station	0.100	**0.320**	0.280	0.185	0.100	S	BS	U
21	Wujiangdu Hydropower Station Dahuang Yai slope	0.103	**0.658**	0.650	0.459	0.180	S	U	LS
22	Gushi Group Landslide of Gongboxia Hydropower Station	0.111	**0.611**	0.594	0.416	0.153	S√	U	S
23	Backhill Slope of Powerhouse of Tianshengqiao I Hydropower	0.105	0.768	**0.905**	0.749	0.230	BS	BS	S
24	Spillway Slope of Tianshengqiao I Hydropower Station	0.128	0.746	**0.757**	0.570	0.263	BS	BS	S
25	Shipingtai Landslide of Xiaoxia Shi Hydropower Station	0.143	**0.438**	0.421	0.292	0.087	S√	BS	S
26	Landslide No.6 of Jishixia Hydropower Station	0.180	**0.654**	0.574	0.365	0.079	S√	BS	S
27	Slope of stone yard of Xiangwan Hydropower Station	0.076	**0.613**	0.542	0.345	0.169	S√	S√	S
28	No.1 Landslide of Jishixia Hydropower Station	0.077	0.597	**0.672**	0.538	0.219	BS	U√	U
29	Surge shaft slope of Tianshengqiao second stage hydropower station	0.069	**0.592**	0.549	0.357	0.164	S√	S√	S
30	West Slope and Cliff Slope of Tianshengqiao II Hydropower Station	0.064	0.569	**0.657**	0.531	0.201	BS √	U	LS
31	Right bank wedge of Miaojiaba Hydropower Station	0.290	**0.608**	0.508	0.318	0.074	S√	BS	S
32	Yellow Paraffin Landslide in the Three Gorges of the Yangtze River	0.053	**0.326**	0.313	0.214	0.115	S	U√	U
33	Slope in front of dam of Pubugou Hydropower Station	0.266	**0.650**	0.518	0.301	0.050	S√	BS	S
34	South Slope of Powerhouse of Tianshengqiao II Hydropower Station	0.113	0.283	**0.306**	0.237	0.065	BS√	BS√	LS

Note: S=Stable, BS=Basically stable, U=Unstable, and LS=Locally stable

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