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Stability analysis of high-steep mining slope based on clustering and unascertained measuring method

Ranging from geological, hydrological to geographical conditions, the influencing factors of the stability of high-steep mining slope involve lots of unascertained information which is difficult to analyze and judge with simple methods. Based on engineering analogy, this paper analyzes the stability of high-steep mining slope by clustering and unascertained measuring method. The clustering center of the various influencing factors of the stability of high-steep mining slope was pinpointed through dynamic clustering, with a large number of historical data as training samples. After using the unascertained measure to evaluate the numerous unascertained information, the authors put forward a new method for stability analysis of high-steep slope mine. The results show that the proposed algorithm can predict the steady state of high-steep mining slope with a hit rate above 90%. All in all, this research sheds new light on rational and rapid analysis of high-steep slope stability.

Keywords: *High-steep mining slope; stability analysis; clustering; unascertained method.*

1. Introduction

With the development and utilization of resources, recent years has witnessed the emergence of deep concave strip mine as a trend in open pit-mining across the globe. As the largest strip mine in the world, the Bingham Canyon copper mine in Utah is 4,000m wide and 1,200m deep, covering an area of 7.7km^2. The Chuquicamata mine in Chile is another largescale copper mine. The current mining depth of 850m is expected to reach 1,100m by 2020. For the Shougang Shuichang iron mine in China, the vertical height of the final slope stands at 760m and the shaft is sunk to the final depth of 540m. The Dexing copper mine, also situated in China, is expected to reach 680m and 465m in slope vertical height and final sink depth, respectively.

During the deep excavation of large strip mines, high-steep slopes are increasingly unstable and less secure under a plurality of complex geological conditions. The landslide of high-steep slopes occurs so frequently that it has become one of the most severe geological disasters in mining. A possible solution to the problem lies in improving the slope angle, which helps to fully recycle resources, reduce production cost, and increase mining benefit for large open pit mines.

According to the statistics [2-4], 66.7% of the open pit mining slopes in China are taller than 100m, and 90.7% of such slopes are designed to exceed the height of 100m. There is a positive correlation between the slope height and the danger of mine production, as a tall mining slope often cuts through various geologically different stratums, involves many uncertain factors of rock mass, and suffers from frequent loss of stability [5-7]. The large and medium-sized slopes in non-coal strip mines are at a serious risk of geological disasters. Statistics show that 42.7% of such slopes are deformed and damaged, 19% are under risk, and 71% are totally ruined.

As above, it is now urgent and difficult to evaluate and predict the stability of high-steep mining slope. Therefore, this paper analyzes the stability of high-steep mining slope by clustering and unascertained measuring method.

2. Literature review

2.1 Overview of slope engineering

Side slopes, i.e. tilted terraces, [8-10] are either natural or artificial. Natural slopes inlcude natural mountain slopes and bank slopes of rivers and lakes; artificial slopes encompass the excavated slopes of foundation pit, slot, culvert, or embankment dam. According to the geotechnical composition, slopes are divided into soil slope, loess slope and rock slope. The rock slope may be destroyed by [11-13]: planar landslide, wedge landslide, circular arc form landslide, toppling landslide, and complex landslide. The landslide is attributable to multiple factors [14-17], both internal and external. The internal factors include but are not limited to the material properties (rock-mass faults, joint fracture, etc.) and structural parameters (slope shape, slope gradient, etc.), while the external factors are mainly stratum lithology, geological structure etc. The external conditions are major inducing factors of landslide. Slope landslide may occur under the joint effect of internal factors and one or more external factors. The

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formation of landslide [18~20] goes through such four phases as creepage, creep sliding, sliding and stoppage. The landslide intensity [21~23] is dependent on the landslide scale, as well as the sliding velocity, sliding distance and the accumulated potential energy of the rock mass. In general, the taller the rock mass, the heavier the sliding mass, the faster the sliding velocity, the further the sliding distance, the more intense the landslide, and the greater the damage. The following are the main factors influencing the landslide intensity: mechanical properties and geological structure of the rock mass, terrain conditions of the slope, and other induced factors.

2.2 Research methods and theories of slope stability

2.2.1 Research progress of slope stability

Taking soil slope as the object, early slope research performed calculation and analysis following the theories of material mechanics, homogeneous elasticity and elastoplasticity. Similar theories were later applied to rock slope stability analysis. Owing to the drastic difference between soil slope and rock slope, the calculated results of rock slope stability deviated greatly from the actual results [24]. Thanks to the development of science and technology, especially the proliferation of computers, the slope stability study entered a new period in the 1980s, as evidenced by the introduction of new calculation theories and numerical simulation technologies, namely, sports biomechanics, discrete element analysis, discrete dipole approximation (DDA), numerical manifold method and the FLAC method. Meanwhile, the rock mass of slope engineering became more and more complex with the increase in project scale. As a result, a variety of analytical approaches were applied to slope stability research, such as random theory, fuzzy mathematics, grey theory, artificial neural network, catastrophe theory, fractal theory and chaos theory.

2.2.2 Research methods of slope stability

Slope stability research has evolved from empirical study to theoretical analysis, qualitative discussion to quantitative measurement, single-object evaluation to comprehensive evaluation, traditional theories and methods to innovative strategies and approaches [25]. It is very meaningful to comb through the previous theories and methods before analyzing the stability of open pit mining slopes. The existing studies roughly fall into three categories.

(1) The traditional limit equilibrium method [26]

Being a common analysis tool for slope stability, the limit equilibrium method stands for a range of numerical analysis methods. It is listed separately as a discrimination approach because of its generality and practicability. Despite the advantage of quantitative and convenient calculation of slope safety factor, this method operates under many assumptions and constraints, and determines stability mainly by experience and subjectivity. Following the shear strength in Mohr-Coulomb theory, the limit equilibrium method divides the landslide slope into several vertical cut sections, builds an equation based on the vertical cutting according to the force balance principle, and then solves the slope safety factor.

Proposed by Peterson in 1916, the method has been constantly improved by Fellenius, Taylor, Bishop, Janbu, Morgenstern, Spencer, Sarma, Chen Zuyu [27] and many other scholars. So far, the rigid body limit equilibrium method has been expanded from 2D to 3D. Several Chinese scholars, including Chen Zuyu, Zhu Dayong [28], and Zheng Hong [29], have made outstanding contributions to the theoretical calculation. Featuring a simple mechanical model and quantitative evaluation of slope stability, the rigid body limit equilibrium method applies well to uniform soil slope, as it focuses on all potentially hazardous sliding ranges without considering the stress-strain state in slope body. The problem is the method has to simplify the landslide boundary conditions and make assumptions about the position, direction and force between blocks. Thus, the calculated results of this method are way different from the actual results for rock slope composed of complex media and boundary conditions. The commonly used limit equilibrium methods are listed below: the Swedish method, the Bishop method, the Sarma method, the Spencer method, the Morgan-Stan price method, and the transfer coefficient method.

(2) The numerical calculation method [30]

With the popularization of computer technology, numerical calculation method has picked up its speed of development. Typical examples are finite difference method, finite element method (FEM), boundary element method (BEM), no-element method, meshfree method, discrete element method (DEM), discontinuous deformation analysis, fast Lagrange's interpolation, and manifold element method. These types of methods have been extensively used in slope stability analysis.

Hereinto, the most popular and mature numerical method FEM was first applied to slope stability analysis in 1967. This method fits well with the needs of deformation and seepage calculation of landslide. For instance, the FEM ascertains the stress-strain relations of landslide, forming a rigorous theoretical system, and simulates the combined action between landslide and supports. However, this method is not suitable for solving problems of large deformation and discontinuous displacement.

Generally, there are two kinds of FEM-based slope stability analysis. One is grounded on the slip surface stress analysis (SSA). This approach integrates the limit equilibrium principle with the finite element calculation results, and uses different optimization methods to determine the most dangerous slide surface based on the FEM stress analysis. The upside of this approach is that the calculation process is simple and easy to implement, while the downside is that it fails to identify the most vulnerable area or reflect the damage evolution process. The other approach is a direct method based on the strength reduction method (SRM), which was created by Zienkiewicz in 1975.

The DEM and fast Lagrange's interpolation were invented by the American scholar Peter A. Cundall. The DEM boasts a broad application prospect in solving discrete, discontinuous and largescale deformation problems. Specifically, the method separates the object into a collection of rigid elements, makes each element satisfy Newton's second law, solves the motion equation of each element by the finite difference method, and obtains the overall movement of the object. Nonetheless, the application of DEM is constrained by the lack of rigorous theoretical basis.

More insights on the slope failure mechanism of instability have been gained with discontinuous deformation analysis, the manifold element, the particle flow code (PFC), the realistic failure process analysis (RFPA) other numerical methods. Among them, the manifold element method is of general significance in that it solves continuous and discontinuous deformation problems with high accuracy, and offers a more natural and simpler solution to engineering problems based on covering technology. Absorbing the advantages of the FEM and the DDA, the manifold element method effectively depicts the evolution of continuous/ discontinuous deformations.

(3) The engineering analogy method

The category of engineering analogy method covers the fuzzy comprehensive evaluation method, the grey clustering evaluation method, the reliability evaluation method, the system clustering evaluation method and the neural network evaluation method [31-35].

Based on fuzzy mathematics, the fuzzy comprehensive evaluation method uses the membership degree to convert qualitative evaluation into quantitative evaluation, and makes an overall evaluation to things or objects restricted by various factors. Featuring clear results and strong systematicity, the method stands out as an effective solution to uncertainty problems that are fuzzy in nature and hard to quantify.

The grey clustering method is originated from the concept of grey system. By the definition given by the Chinese scholar Deng Julong, a grey system means that a system in which part of information is known and part of information is unknown. The grey clustering model clarifies the relationship in such a system, making it possible to take grey forecast and control measures in advance. With this method, one can explain the uncertain influencing factors of slope stability from different sides. The method is easy to implement in actual engineering, but it requires the data from many similar projects.

Essence, the engineering analogy method is a form of clustering analysis that categorizes slope samples by similarity, and determines slope stability in accordance with the principle of similarity. Whereas the traditional clustering method only completed historical data clustering and did not use the clustering results to predict the stability of the similar projects, this paper takes the clustering center of historical data clustering center as the classification standard, establishes the unascertained measure analysis model, and predicts the stability of high-steep mining slope according to the model.

3. Clustering and unascertained measure method

3.1 Clustering

Let there be an object space $R = \{R_1, R_2,..., R_n\}$, where $R_1, R_2,..., R_n$ are the n objects to be classified, and a judgment index space $X = \{x^1, x^2,\dots, x^m\}$, where $x^1, x^2,\dots, x^m$ are the m judgement indexes. Thus, any $R_i \in R(i \le n)$ can be expressed as an m-dimension vector , where $R_i = \{x_i^1, x_i^2, x_i^m\}$ x_i^j is the measured value of the object R_i with respect to the judgment index x_j. Suppose $C_1, C_2,..., C_k$ are the K classification levels of each x_i^j. In the classification space $\Omega = \{C_1, C_2,..., C_k\}$, $C_1 < C_2 <...< C_k$ when the level of k is higher than that of k+1. If $\{C_1, C_2,..., C_k\}$ satisfies $C_1 > C_2... C_k$, or $C_1 < C_2 ... < C_k$, the classification space is called an ordered segmentation class of object space $R = \{R_1, R_2,..., R_n\}$. The classification matrix can be expressed as:

$$R_i = \{x_i^1, x_i^2, x_i^m\} \quad \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_k \\ \hline x^1 & a_{11} & a_{12} & \cdots & a_{1k} \\ x^2 & a_{21} & a_{22} & \cdots & a_{2k} \\ \vdots & & & \vdots & \\ x^m & a_{m1} & a_{m2} & \cdots & a_{mk} \end{array} \quad ... \quad (1)$$

where $a_{jp}(1<j<m, 1<p<k)$ is the clustering center of a class of samples, which meets the classification standard of $a_{j1} > a_{j2} ... > a_{jk}$ or $a_{j1} < a_{j2} ... < a_{jk}$.

3.2 Unascertained measuring method

(1) Calculate the mean of overall index of each class and classification matrix [36]

(2) Calculate the unascertained measuring function of index according to the classification matrix. Please refer to [37-40] for the specific method.

(3) Determine index weight. Let w_j denote the relative importance of index x_j to other indexes, where $0<w_j<1$ and $\sum_{j=1}^{n} w_j = 1$, w_j is the weight of x_i, and $\{w_1, w_2,..., w_n\}$ is the index vector. Assume that the information entropy determined by the unascertained measure μ_{ik}^j is:

$$H_j = \sum_{i=1}^{K} \mu_{ik}^j \lg \mu_{ik}^j$$

Set $v_j = 1+\frac{1}{\lg K}\sum_{k=1}^{K}\mu_{ik}^{j}\cdot\lg\mu_{ik}^{j}$

and $w_j = v_j \Big/ \sum_{i=1}^{n} v_i$,

Considering that w_j reflects the importance of x_i and satisfies $0<w_j<1$ and $\sum_{j=1}^{n} w_j = 1$, it is concluded that w_j is the weight of x_j [47].

(4) Weighted synthetic measure classification vector and multi-index result recognition

Let $\mu_{ik} = \mu(\mu_i \in C_k)$ be the degree of sample R_i under the k-th evaluation class C_k. In this case, the following equation holds.

$$\mu_{ik} = \sum_{j=1}^{m} w_j \mu_{ik}^{j}$$

whereas $0<\mu_{ik}<1$ and

$\sum_{i=1}^{K}\mu_{ik} = \sum_{i=1}^{K}\sum_{j=1}^{m} w_j\mu_{ik}^{j} = \sum_{j=1}^{m}\left|\sum_{i=1}^{K}\mu_{ik}^{j}\right| w_j = \sum_{j=1}^{m} w_j = 1$, μ_{ik} is an unascertained measure.

Denote (μ_{i1}, μ_{i2},..., μ_{ik}) as multi-index weighted synthetic measure classification vector of sample R_i. If $C_1>C_2...>C_p$, introduce the confidence identification principle as follows:

Set λ as confidence coefficient ($\lambda>0.5$, usually 0.6 or 0.7). If $C_1>C_2...>C_p$, there is:

$$k_0 = \min\left\{k : \sum_{l=1}^{k}\mu_l > \lambda, k = 1,2,\cdots,p\right\}$$

Hence, the evaluation factor R belongs to be the k_0-th evaluation class C_{k0}.

4. Case study

This section introduces two cases to illustrate the application of clustering and unascertained measuring method in the stability analysis of high-steep slope.

4.1 Case 1

To obtain the actual stability of high-steep slope, the author selected 36 high-steep slopes of Luanchuan Molybdenum mine, established a model based on clustering and unascertained measuring method for the first 30 slopes, and evaluated the results and predicted the stability of similar samples. The results are shown in Table 1. For comparison, the calculated results of the traditional clustering method and the adaptive simulated annealing method are also listed in the table. It is learnt that the proposed model has a hit rate of more than 90% and makes right predictions on similar samples.

As shown in Table 1, the proposed algorithm, the adaptive simulated annealing method, and the traditional clustering methods shared similar results. However, the proposed algorithm outperforms the other two algorithms because the traditional clustering method only completed historical data clustering and did not use the clustering results to predict the stability of the similar samples. Taking the clustering center of historical data clustering center as the classification standard, the proposed method establishes the unascertained measuring analysis model, and predicts the stability of high-steep mining slope according to the model.

Table 1: Computing results of slope stability

Slope number	Conventional clustering	Adaptive simulated annealing	Our method
	Grade	Grade	Grade
1	III	III	III
2	I	I	I
3	IV	III	III
4	IV	IV	IV
5	IV	IV	IV
6	IV	III	III
7	IV	IV	IV
8	IV	IV	IV
9	VI	VI	VI
10	III	III	III
11	VI	V	V
12	I	I	I
13	I	I	I
14	V	V	V
15	IV	IV	IV
16	V	VI	VI
17	V	V	V
18	III	III	III
19	V	V	V
20	IV	IV	V
21	V	V	V
22	III	II	II
23	III	III	III
24	III	III	III
25	III	III	III
26	III	II	II
27	II	II	II
28	II	II	II
29	II	II	II
30	II	II	II
31*	III	II	II
32*	III	III	III
33*	V	V	V
34*	V	VI	VI
35*	V	VI	VI
36*	V	V	V

TABLE 2: COMPUTING RESULTS

Number	Limit equilibrium method	Our method
1	1	1
2	1	1
3	1	1
4	1	1
5	1	1
6	0	0
7	0	0
8	0	0
9	1	1
10	0	0
11	0	0
12	1	1
13	1	1
14	1	1
15	1	1
16	0	0
17	1	1
18	1	1
19	0	1
20	1	1
21	1	1
22	1	1
23*	0	0
24*	1	1
25*	1	1
26*	0	0
27*	1	1

4.2 CASE 2

27 slopes in Literature [25] were taken to further verify the application of the proposed algorithm in high-steep slope stability analysis. The results are displayed in Table 2.

The proposed algorithm had basically the same results with the limit equilibrium method: the regression estimate accuracy was over 90% and the prediction data were correct. The results demonstrate that the proposed algorithm does well in slope stability analysis.

5. Conclusions

The high-steep slope engineering problems are extremely complex, and difficult to be solved by clustering method alone. The complicated calculation and uncertain information are calling for the introduction of engineering analogy to the judgement of slope stability. In view of this, the authors decide to find the clustering center of the uncertain information through dynamic clustering analysis, and adopt unascertained measuring method to evaluate the slope stability. Hence, a new method was presented to analyze the high-steep slope stability problems. Two engineering examples were introduced to verify the effect of the proposed method in judging the stability of high-steep slopes. The results show that the proposed algorithm has low error rate and high accuracy. Therefore, this research has come up with a novel and effective method for analyzing the high-steep slope stability.

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