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Abstract

In order to determine the key position of open-pit slope reinforcement and improve the efficiency of slope treatment and slope safety management, the concept of sensitive formation of slope stability is put forward. The stability of an open-pit slope which has 9 formations was analyzed using strength reduction method built-in FLAC3D. The impact on slope safety factor, position of potential slip surface and average node displacement of slide mass was got when weakening cohesion and internal friction angle. Using grey comprehensive correlation degree to evaluate the result, the sensitive formation was determined. The results show that the change of sensitive formation parameters has significant impact on factors which considered in research while other formations have little impact.

Key words: slope stability; sensitive formation; grey correlation analysis; FLAC3D; strength reduction method

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Introduction

Slope stability analysis is an important content of open-pit mine slope safety. There are many literature on the sensitive factors affecting the slope stability: Cheng Dong-xing et al put forward a new method for evaluating the slope stability based on the interaction matrix and information entropy[1];Hu Zhong-quan, Fu Jian-jun et al performed sensitive analysis on factors affecting subgrade slope stability by using grey correlation analysis[2,3]; after using uniform design for slope stability numerical experiment, Chen Gao-feng et al get the sensitive rank of the stability factors affecting homogeneous soil slope or loose and geotechnical slope[4]; Wu Zhen-jun, an professor of CAS, employed reliability analysis method and the random field model in simulating spatial variability of rock or soil property along the slip surface, and then performed sensitive analysis on factors affecting slope stability[5];Li Ke-qing et al used six indicators, which are widely used in slope stability analysis and are respectively slope gravity，cohesion force, friction angle，slope angle，slope height and pore pressure ratio, as discriminant factors to establish a discriminant analysis model for slope stability forecast[6]. The related literature above didn't take the influence of different nature formations on slope stability into consideration, leading it difficult to determine the key position for preventing and controlling slope.

Open-pit mine slope typically contains multiple formations, and general slope stability is decided jointly by all these formations. But the distinction of each formation is relatively large. Because of the different space locations and its own characteristics of different formation, the influence of different formation weakening on general slope stability is different in the same condition. Some formations play an important role on general slope stability. So there must be some formations, whose weakening has a larger influence on general slope stability. This paper called these formations sensitive formation of slope stability, short for sensitive formation. The accurate determination to sensitive formation can enhance the technology of slope monitoring and governing, and is good for slope safety management, and has the significant economic benefits.

Research Method and Principle

Research Method

Different formations have different influence on slope stability, because of their own characteristics and space locations. It will be relatively complicated and error-prone if we determine the sensitive formation by directly geological analyzing the specific influence of formations on slope stability, of which contains multiple formations. This paper will use strength reduction method in FLAC3D to analyze slope stability.

Cohesion force and internal friction angle are decisive strength parameter of slope stability because of Mohr-Coulomb model[7]. Under different external interference, different formations of the same slope are affected by different weakening effect. The physicochemical interaction of groundwater and surface water can decrease the lithology of some certain formations, but can make no difference to others; and some formations fractures are more obvious than others. So this paper only changes the cohesion force and internal friction angle and makes other parameter constant, and can get slope safety factor, slide mass joint displacement in the critical state, the slip surface locations and other parameters. Then using grey comprehensive correlation analysis to evaluate the influence degree of different formations parameters on slope stability, and finally the sensitive formation was determined.

Grey Comprehensive Correlation Analysis

The frequently-used analytical method mainly contains PCA (principal component analysis), regression analysis[8], variance analysis[9] and others. But these methods have deficiency: large sample data is needed, each factor must be independent, samples must be in line with some certain probability distribution and the calculated quantity is very large. Grey correlation analysis can make up the deficiency above. It can find out the critical influence factors under the condition that the sample size is small and the law is not obvious, even not complete[10]. So this paper uses grey comprehensive correlation analysis to determine the correlation degree of each influence factor. Make the system factor for X_i, the observation data on the label k for $x_i(k)$ (k=1,2,…,n), so

$$X_i = (x_i(1), x_i(2), \dots, x_i(n)) \qquad (1)$$

In grey correlation analysis, it is necessary to deal with original data depending on situations. Suppose the zeroing starting point operator for D_1 and initializing operator for D_2, so:

$$X_i D_1 = (x_i(1)d_1, x_i(2)d_1, \dots, \ x_i(n)d_1) \qquad (2)$$

$$X_i D_2 = (x_i(1)d_2, x_i(2)d_2, \dots, \ x_i(n)d_2) \qquad (3)$$

Among them,
$x_i(k)d_1=x_i(k)-x_i(1)$ (k=1,2,…,n); $x_i(k)\mathrm{d}_2=x_i(k)/x_i(1)$ $x_i(1)\neq 0$,(k=1,2,…,n). So X_iD_1 and X_iD_2 is respectively zeroing starting point image and initializing image of D_1 and D_2. Denoted by:

$$X_i D_1 = X_i^0 = (x_i^0(1), x_i^0(2), \dots, x_i^0(n)) \qquad (4)$$

$$X_i D_2 = X_i' = (x_1'(1), x_1'(2), \dots, x_1'(n)) \qquad (5)$$

So, for two equal interval sequence X_i and X_j, if :

$$\varepsilon_{ij} = \frac{1+|s_i|+|s_j|}{1+|s_i|+|s_j|+|s_i - s_j|} \tag{6}$$

Among them, $|s_i| = \left|\sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2}x_i^0(n)\right|$; $|s_j| = \left|\sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2}x_j^0(n)\right|$.

So ε_{ij} is called grey absolute correlation degree of two observed sequence, short for absolute correlation degree. It is related to the geometry-figure similarity of two observed sequence X_i and X_j.

For two equal interval sequence but initial value is not zero X_i and X_j, initializing images are respectively: X_i' and X_j'. If :

$$r_{ij} = \frac{1+|s_i'|+|s_j'|}{1+|s_i'|+|s_j'|+|s_i' - s_j'|} \tag{7}$$

Among them: $|s_i'| = \left|\sum_{k=2}^{n-1} x_i'^0(k) + \frac{1}{2}x_i'^0(n)\right|$; $|s_j'| = \left|\sum_{k=2}^{n-1} x_j'^0(k) + \frac{1}{2}x_j'^0(n)\right|$.

So r_{ij} is called relative correlation degree of X_i and X_j, and it is the closeness degree of the changing rate for the two observed data.

There is no necessary relation between the two grey correlation degrees above. In order to represent the correlation degree of the two sequence more completely and reasonably, grey comprehensive correlation degree is used. For two equal interval sequence but initial value is not zero X_i and X_j, ε_{ij} and r_{ij} are respectively their grey absolute correlation degree and grey relative correlation degree. When $\theta \in [0,1]$,

$$\rho_{ij} = \theta\varepsilon_{ij} + (1-\theta)r_{ij} \tag{8}$$

is grey comprehensive correlation degree of X_i and X_j. It is not only related to the observed data of the sequence, but also the rate of change to the initial point, because it is based on two comprehensive correlation degrees. Different grey comprehensive correlation degrees will be got based on θ, which is related to the absolute amount and rate of change.

Instance Analysis and Numerical Simulation

Slope Instance

Take a mine stope for instance. It is located in Qi-lin Mountain~Huang-mei Mountain tectonic metallogenic belt, which is in the northeast of the middle of fault basin, Ning-wu volcanic rock. The exposed layer is mainly consisted by the pyroclastic rock and marine clastic rock containing volcanic material which is produced by the cycling of jurassic-cretaceous Da-wang Mountain. Its southern slope contains multiple formations, and the change of the formations attitude of each profile is not obvious. A-A′ profile of southern slope is chosen, and it is 251.8m high and slope angle is 32°. This profile has 9 formations, and is mainly consisted by bulk solid, fragmented and massive structure rock. Numerical simulation and grey comprehensive correlation degree are used to discriminate the influence degree of different formations.

Pretreatment slope profile in ANSYS12.0. Build a model of length 628m (x-axis) and height 10m, and make a grid cell of side 12m. Divide the cell into 9 groups, and complete the preliminary modeling. As is shown in Figure1. Then import the model into FLAC3D to make material assignment and analysis, which has 11027cell and 3531 node. Shown in Figure2. Parameters of each formation are shown in Table1.

Figure 1. *Slope Model in ANSYS*

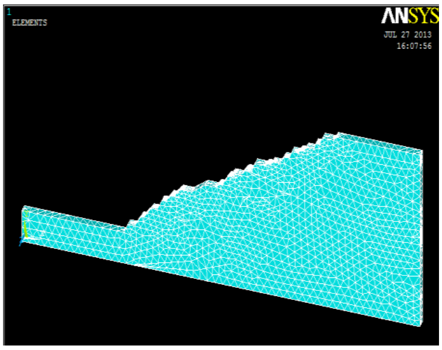


Figure 2. *Model Grouping in FLAC3D*

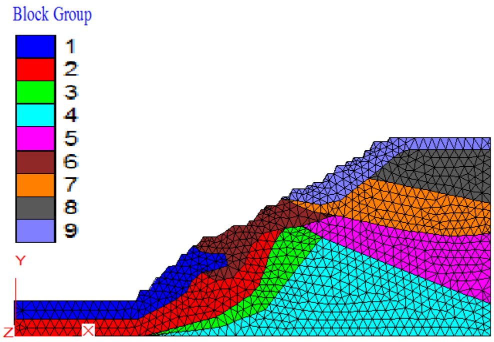


Table 1. *Parameters of Each Group Slope Formations*

group	Density (g/cm^3)	elasticity modulus (GPa)	poisson ratio	cohesion force (MPa)	Internal friction angle (°)
Layered structure breccia magnetite(1)	3280	14.85	0.23	5.21	39.43
Cataclastic texture diorite porphyrite(2)	2590	29.71	0.36	9.11	40.57
Massive texture silicide crystal tuff(3)	2200	19.40	0.23	4.96	41.38
Layered structure of diorite porphyrite(4)	2540	57.64	0.27	10.11	40.75
Cataclastic structure andesite (5)	2300	16.26	0.21	5.77	39.96
Repose of kaolin structure crystal tuff (6)	2040	3.31	0.15	0.65	38.87
massive structure tuff breccia (7)	2600	60.00	0.16	10.0	41.00
Massive texture coarse andesite (8)	2500	45.00	0.16	10.0	40.00
Repose of kaolin structure crystal tuff (9)	2040	3.31	0.15	0.65	38.87

Safety Factor Analysis

In FLAC3D the Mohr-Coulomb model analyzes the slope stability in strength reduction method, mainly on weakening the cohesion and the internal friction angle of formation. In order to find out the sensitive formation of slope, it needs to weaken the cohesion and the internal friction angle in different multiple first, reuse software for simulation analysis. When a formation parameter is in strength reduction, the other formation parameters remain unchanged. According to the results of simulation, the relationship between the different formations reduction ratio and the safety factor Fs of slope is shown in table 2.

Table 2. *The Relationship between the Different Formations Reduction Ratio and the Safety Factor of Slope*

formation multiple of Fs	1	0.9	0.7	0.5	0.25	0.2	0.15	0.1	0.05	0.04	0.03	0.02
X_1(group1)	5.9629	5.9629	5.9629	5.9355	4.9170	4.0010	3.0098	2.0107	1.0059	0.8066	0.6006	0.4033
X_2(group 2)	5.9629	5.9629	5.9629	5.9629	5.9629	5.9629	5.8262	5.0947	4.1240	3.8887	3.6309	3.1973
X_3(group 3)	5.9629	5.9629	5.9629	5.9629	5.9629	5.9355	5.9355	5.9355	5.9082	5.9082	5.9082	5.9082
X_4(group 4)	5.9629	5.9629	5.9629	5.9629	5.9355	5.9355	5.9355	5.2451	4.2881	4.0693	3.8652	3.6309
X_5(group 5)	5.9629	5.9629	5.9629	5.9629	5.9629	5.8809	4.7529	3.2324	1.6289	1.3066	0.9668	0.6475
X_6(group 6)	5.9629	5.6348	4.8896	4.1309	2.0576	1.6523	1.2402	0.8622	0.4131	0.3306	0.2466	0.1653
X_7(group 7)	5.9629	5.9629	5.9355	5.9355	5.7441	5.4365	4.9580	4.0830	2.3037	1.8633	1.4160	0.9629
X_8(group 8)	5.9629	5.9355	5.9355	5.7441	4.6846	3.8184	2.8691	1.9648	1.0020	0.8027	0.5986	0.3994
X_9(group 9)	5.9629	5.5801	4.3428	3.0684	1.5137	1.2129	0.9082	0.6064	0.3032	0.2427	0.1819	0.1213

From Table 2, it has no effects on the safety factor of slope almost when the weakening multiples of parameters is small, but with weakening multiples increase, most of the safety factor of slope change. However, for different formations, the changing trend and degree of slope safety factor are different. In order to determine which one has a greater effect on the stability of the slope, it needs to be evaluated with grey correlation analysis.

According to the data in Table 2, make the reduction ratio sequence for X_0， and the starting point of each sequence for zero by type (2):

$$\begin{aligned} X_i^0 &= (x_i(1)-x_i(1), x_i(2)-x_i(1), \ldots\ldots, x_i(12)-x_i(1)) \\ &= (x_i^0(1), x_i^0(2), x_i^0(3), \ldots\ldots, x_i^0(12)), (i=0,1,2,3,\ldots\ldots,9) \end{aligned} \quad (9)$$

According to the theory of gray correlation analysis ,in order to eliminate the gap of $X^0{}_0$ with other sequence order of magnitude, it needs further processing and makes each one broadly similar for the comparing and analysis with other sequence in 10 times the value. According to the type (6) , the absolute correlation degree of different formation to the impact of the safety factor of slope can be known：

$$\boldsymbol{\varepsilon}_{1i} = (\varepsilon_{11}, \varepsilon_{12}, \ldots\ldots, \varepsilon_{19}) \\ = (0.6883, 0.5599, 0.5051, 0.5534, 0.6389, 0.7728, 0.6246, 0.6939, 0.7959) \quad (10)$$

With the reason, the relative correlation degree can be known from type (7):

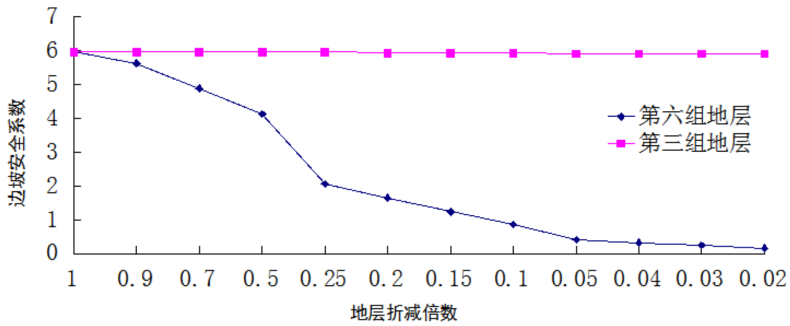
$$\mathbf{r}_{1i} = (r_{11}, r_{12}, \ldots\ldots, r_{19}) \\ = (0.8239, 0.6207, 0.5338, 0.6103, 0.7457, 0.9577, 0.7231, 0.8329, 0.9323) \quad (11)$$

After sorting the absolute and relative correlation respectively, it can be found that the sensitive order of formation are almost the same but slightly different. It is because two kind of correlation are in different considering angles. Due to find out the larger sensitive formation influence on the slope when evaluated with grey correlation analysis, so more attention is put on the trend of rate change than the geometric similar trend. According to the type (8) take θ=0.4, so:

$$\boldsymbol{\rho}_{1i} = \theta\boldsymbol{\varepsilon}_{1i} + (1-\theta)\mathbf{r}_{1i} = (\rho_{01}, \rho_{02}, \ldots\ldots, \rho_{09}) \\ = (0.7697, 0.5964, 0.5223, 0.5875, 0.7030, 0.8837, 0.6837, 0.7773, 0.8777) \quad (12)$$

Sort the comprehensive correlation degree,
so： $\rho_{16} > \rho_{19} > \rho_{18} > \rho_{11} > \rho_{15} > \rho_{17} > \rho_{12} > \rho_{14} > \rho_{13}$. Repose of kaolin structure crystal tuff in Group 6 has the largest influence on the safety factor, while Group 3 has the smallest. The overall safety factor of slope and its respective reduction ratio change trend curve of Group 6 and Group 3 are shown in figure 3.

Figure 3. *Influence Comparison of Slope Safety Factor between Group 6 and Group 3*

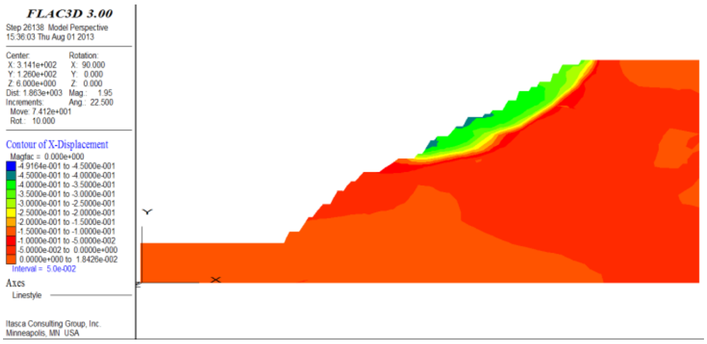


Change in Position of Potential Slip Surface and Displacement Analysis of Slide

In terms of formation influence on slope stability, it is also an important standard for the shape and position of slip surface. And using the reduction method mentioned above, we can see the trend of formation impact of the shape and the position of slip surface. The specific change on the slip surface is related to its relative position, the curve shape and the range. Quantitative characterization of these characteristics is complicated. In addition, to different formations, the slip surface also has its own laws. Because of the grey correlation analysis, this paper focuses on variation trend only. It does not need the description of specific shape and position, nor does the change conform to what law and distribution.

In FLAC3D, analyze the displacement curve contours of x direction. The dense curves equal to the displacement form the arc shape curve and can be regard as a slip surface. The displacement into the curve is significantly greater than the surrounding rock, as shown in figure 4.

Figure 4 *Group 7 displacement nephogram of formation under the reduction ratio 0.25 in x-axis*



On the slip surface curve take a point every 15m in x-axis and add together the sum of the horizontal ordinate , we can get a digital of coordinates information including shape and position of slip surface curve, and so on. According to this, we can get the sum of all coordinates of the points on slip surface of the formations in different reduction coefficients, as shown in Table 3.

Table 3. *The Sum of all Coordinates of the Points on Slip Surface of the Formations in Different Reduction Coefficients*

formation multiple of Fs	1	0.9	0.7	0.5	0.25	0.2	0.15	0.1	0.05	0.04	0.03	0.02
X_1(Group1)	8737	8850	8798	8844	8650	3641	2756	2605	2419	2410	2435	2445
X_2(Group 2)	8737	8840	8844	8862	8849	8462	8868	11186	6324	6149	5807	7442
X_3(Group 3)	8737	8853	8836	8823	8818	8804	8840	8844	8850	8796	8796	8789
X_4(Group 4)	8737	8870	8862	8839	8830	8824	10002	10010	9986	9213	9287	9265
X_5(Group 5)	8737	8875	8888	8890	8900	8797	7008	7109	7209	7234	7239	7300
X_6(Group 6)	8737	8840	8729	7393	4963	4967	4959	4951	4959	4945	4961	4929
X_7(Group 7)	8737	8739	8851	8850	8840	9140	9119	8014	10036	10050	10020	10033
X_8(Group 8)	8737	8846	8848	8852	8859	8472	8868	6909	6899	6973	6987	7010
X_9(Group 9)	8737	8473	6840	6850	6845	6838	6843	6832	6841	6844	6824	6833

According to table 3, the reduction factor should be translate into a numeral of an order of magnitude with the data in the table. Take θ=0.4, with grey relational grade:

$$\boldsymbol{\rho}_{2i}=\boldsymbol{\varepsilon}_{2i}+(1-\theta)\mathbf{r}_{2i}=(\rho_{21},\rho_{22},\ldots,\rho_{29})$$
$$=(0.7883,0.5588,0.5184,0.5279,0.5733,0.7228,0.5194,0.5718,0.6447) \quad (13)$$

the correlation order can be known is： $\rho_{21}>\rho_{26}>\rho_{29}>\rho_{25}>\rho_{28}>\rho_{22}>\rho_{24}>\rho_{27}>\rho_{23}$。

Therefore, group 1 is the most sensitive formation, group 6 takes the second place, and group 3 is the last. For slope stability in different angles, the result of grey correlation order and even sensitive formation can be different. The position of the slip surface change with reduction ratio, and the tendency chart of group1and 3 are shown in figure 5 and figure 6.

Figure 5. *Slip Surface Change of Group 3*

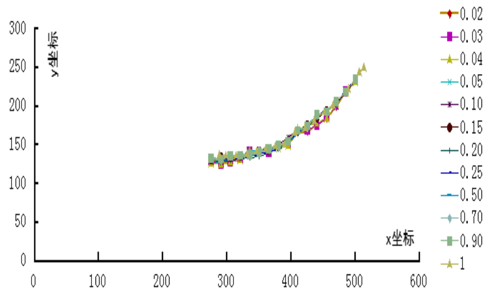
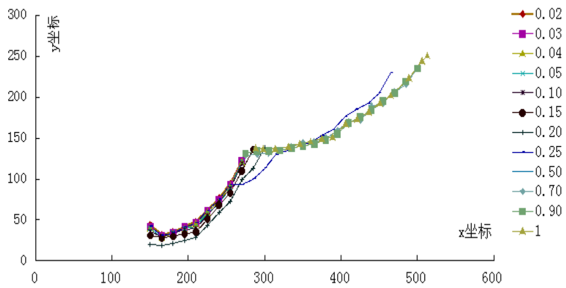


Figure 6. *Slip Surface Changes of Group 1*



As is shown in Table 3 and Figure 5, for the no sensitive formation (Group 3), the reduction of parameters value basically does not affect the position and shape of potential slip surface of slope. And the change of sensitive formation parameters will make the potential slip surface changes a lot with the decrease of the reduction factor.

By the same token, analyze the influence of the reduction of each formation on the average displacements of the nodes of the top of slip surface. Based on the nodes information of FLAC3D, average displacement of slip body of different formation in different degradation situation can be known. Comprehensive correlation analysis are as follows:

$$\boldsymbol{\rho}_{\mathbf{3i}} = \theta\boldsymbol{\varepsilon}_{\mathbf{3i}} + (1-\theta)\mathbf{r}_{\mathbf{3i}} = (\rho_{31}, \rho_{32}, \ldots\ldots, \rho_{39}) \\ = (0.7490,0.6518,0.5318,0.5001,0.4201,0.8359,0.4912,0.4736,0.6553) \tag{14}$$

So the order of correlation is: $\rho_{36}>\rho_{31}>\rho_{39}>\rho_{32}>\rho_{33}>\rho_{34}>\rho_{37}>\rho_{38}>\rho_{35}$.To the influence of displacement of slip surface, group 6 is sensitive formation of largest influence.

The Determination of Sensitive Formation

Based on the analysis of the three aspects of grey relational grade above, and according to (12) (13) (14),we can get the comprehensive correlation matrix is:

$$\boldsymbol{\rho} = (\boldsymbol{\rho}_{\mathbf{1i}}, \boldsymbol{\rho}_{\mathbf{2i}}, \boldsymbol{\rho}_{\mathbf{3i}})^T = \begin{bmatrix} 0.7697,0.5964,0.5223,0.5875,0.7030,0.8837,0.6837,0.7773,0.8777 \\ 0.7883,0.5588,0.5184,0.5279,0.5733,0.7228,0.5194,0.5718,0.6447 \\ 0.7490,0.6518,0.5318,0.5001,0.4201,0.8359,0.4912,0.4736,0.6553 \end{bmatrix} \tag{15}$$

According to the type (15) ,the advantage analysis is:

$$\sum_{i=1}^{3}\rho_{i6} = 2.4424 > \sum_{i=1}^{3}\rho_{i1} = 2.337 > \sum_{i=1}^{3}\rho_{i9} = 2.1777 > \sum_{i=1}^{3}\rho_{i8} = 1.8227 \\ > \sum_{i=1}^{3}\rho_{i2} = 1.807 > \sum_{i=1}^{3}\rho_{i5} = 1.6964 > \sum_{i=1}^{3}\rho_{i7} = 1.6943 > \sum_{i=1}^{3}\rho_{i4} = 1.6155 > \sum_{i=1}^{3}\rho_{i3} = 1.5725 \tag{16}$$

So it is $X_6 \preceq X_1 \preceq X_9 \preceq X_8 \preceq X_2 \preceq X_5 \preceq X_7 \preceq X_4 \preceq X_3$. Repose of kaolin structure crystal tuff of Group 6 is sensitive formation. Group 6 has the greatest influence on the stability of the slope, Group 1 is the second, and Group 3 is the last. So in the process of the governance of slope, more attention should be paid to the formation of Group 6. In order to improve its lithology, the methods such as strengthening governance, grouting, and prestressed anchoring can be taken. The lithology of Group 9 and 6 are the same, but they are different in the degree of influence on the slope. And lithology is not the only reason to the sensitivity of formation. In addition, because of the sensitivity of group 1 is next only to Group 6, it has great impact on the potential position of slip surface, too. It needs to be focused on management.

Conclusions

Grey correlation analysis doesn't need a lot of data and doesn't demand the data obey a mathematical law in determining the sensitive formation of slope. But it uses the relative changes in data to evaluate the degree of correlation between data sequences. It is more convenient in using FLAC3D to search and analyze the sensitive formation of slope.

In the analysis of the slope instances, Repose of kaolin structure crystal tuff of Group 6 is sensitive formation of all the 9 formations. The sensitivity of Group 1 is next only to Group 6, and Group 1 has the biggest influence on the position of slip surface. The lithology of Group 6 and Group 9 are same, but the influence degree of Group 9 on the slope is less than the former.

In the analysis of the slope instances, considering the different factors of the same slope will obtain different sensitive formations: The influence of group 6 on the slope safety factor and the average displacement of slide mass is largest, and the influence of Group 1 on the location of slope slip surface is largest. The advantage analysis of the correlation of different order determines the final sensitive formation.

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