Slope Excavation and Parameter Sensitivity Analysis Based on Grey Correlation Method

Zhang Xu and **Tan Zhuoying**

School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China
Corresponding author: Tan Zhuoying
e-mail: markzhy_tan@163.com

ABSTRACT

With the unceasing construction and development of highway, there are a large number of being forming excavation slopes which will due to the hazard of instability. Aimed at a highway roadside slope of Yiba in Hubei province, analyzed the stability under slope excavation scheme, and put forward a measure of prestressed anchor-bolt to control effectively. From the angle of displacement and stress analysis, pointed out the key position that played a leading role in slope stability. Meanwhile, considered sensitivity factors of slope stability coefficient, analyzed the change rule of slope stability and four main impact factors which were the cohesive force *c*, internal friction angle *φ*, unit weight *γ* and gradient *α* by use of grey correlation analysis method. The results reveal sensitivity contribution rate of stability which is due to influence parameters, and it is of certain significance to the slope safety and protective treatment.

KEYWORDS: Slope excavation; Stability control; Support analysis; Grey correlation; Sensitivity

INTRODUCTION

On account of excavated or unsupported slope engineering, it is easy to cause geological hazards, and the slope stability is closely related to geotechnical strength, parameters, etc. Slope parameters selection is the most basic foundation in the design of slope engineering, it should be determined comprehensively based on laboratory test, large in-situ shear test, parameter inversion analysis and existing engineering experience[1]. Sensitivity analysis of slope parameters, namely, analyzes quantitatively the impact generated by the changing various uncertainty factors on slope stability[2]. For a long time, some scholars have been carried out to make some beneficial explorations on slope stability and sensitivity. Bojorque Iñeguez[3] and Xue-wen Zhang[4] respectively carry out the back-analysis of slope failures by numerical techniques and landslide mechanical parameters by sensitive grey correlation method, Li-xiong Feng etc.[5] carry out stability and reliability evaluation for the unstable rocks in Jiaozuo longsi abandoned mine slopes, Tan X.H etc.[6] analyze the reliability and sensitivity of unsaturated soil slopes under rainfall infiltration, Yong-xiang Zheng etc.[7] analyze the influence of material factors on slope stability, Yan-mei Yang etc.[8] research slope deformation by use of grey prediction. Aiming at the research object of excavation slope, this paper will consider geological condition characteristics, structure characteristics, and the variability, correlation, fuzziness of factors affecting the slope stability. Combining the conventional method, grey correlation analysis and numerical limit method to simulate slope excavation and supporting, search sliding surface automatically, obtain the displacement, plastic zone of rock-soil body and failure surface of corresponding points, meanwhile, analyze the stability sensitivity of main slope parameters, so as to reveal the internal relations between parameters and slope stability as well as the differentiation characteristics of parameter contribution rate.

GRAY CORRELATIONAL ANALYSIS METHOD

Examining the micro or macro geometric proximity of factors to analyze and ascertain the influence degree of factors, namely, the influence degree of sub-factors (reference sequence) to main-factors (contrast sequence) in various factors. Ascertaining the influence degree of the identify object to the study object through comparing and sequencing the quantitative correlation degree, so as to measure directly the correlation degree of various factors, and ascertain accurately the relationship(expressed as correlation degree) between change factors and reference factors in the case of limited data. The bigger the correlation degree is, the higher relationship between change factors and reference factors is[9].

All the influence factors are as the reference matrix sequence *X*, $X=\{X_1,X_2,\cdots,X_m\}^{\mathrm{T}}$, the sequence that corresponds to the reference sequence is as matrix *Y*, $Y=\{Y_1,Y_2,\cdots,Y_m\}^{\mathrm{T}}$, and there are multiple values of factors in *X*, *Y*. $X_i=[x_i(1),x_i(2),\cdots,x_i(n)]$, $Y_i=[y_i(1),y_i(2),\cdots,y_i(n)]$ (i=1, 2, ⋯, m). *X*, *Y* are written in matrix form:

$$X=\begin{Bmatrix}X_1\\X_2\\\vdots\\X_m\end{Bmatrix}=\begin{bmatrix}x_1(1)&x_1(2)&\cdots&x_1(n)\\x_2(1)&x_2(2)&\cdots&x_2(n)\\\vdots&\vdots&\ddots&\vdots\\x_m(1)&x_m(2)&\cdots&x_m(n)\end{bmatrix}\tag{1}$$

$$Y=\begin{Bmatrix}Y_1\\Y_2\\\vdots\\Y_m\end{Bmatrix}=\begin{bmatrix}y_1(1)&y_1(2)&\cdots&y_1(n)\\y_2(1)&y_2(2)&\cdots&y_2(n)\\\vdots&\vdots&\ddots&\vdots\\y_m(1)&y_m(2)&\cdots&y_m(n)\end{bmatrix}\tag{2}$$

As the dimensions of the above factors are too different and the orders of magnitude are too inconsistent to be comparable, X_i, Y_i must be transformed numerically. Use the dimensionless processing to eliminate the dimension influence of various factors, and the interval value relativization method is adopted:

$$\begin{cases}x_i'(j)=\dfrac{x_i(j)-\min(x_i(j))}{\max(x_i(j))-\min(x_i(j))}\\[2ex] y_i'(j)=\dfrac{y_i(j)-\min(y_i(j))}{\max(y_i(j))-\min(y_i(j))}\end{cases}\tag{3}$$

The new matrix sequences after dimensionless are:

$$\begin{cases}X_i'=[x_i'(1),x_i'(2),\cdots,x_i'(n)]\\Y_i'=[y_i'(1),y_i'(2),\cdots,y_i'(n)]\end{cases}\tag{4}$$

Formula (5) is used to calculate the difference-information of transformed X'_i and Y'_i, then the difference matrix *Δ* can be formed.

$$\Delta_{ij} = \left| x'_{ij} - y'_{ij} \right| \tag{5}$$

The maximum and minimum value of all elements in difference matrix *Δ* should be found:

$$\Delta_{\max} = \max(\Delta_{ij}), \ \ \Delta_{min} = \min(\Delta_{ij}) \tag{6}$$

Find out the distance between reference points and contrast points through grey correlation degree, as well as the relationship and difference of various factors through holistic approach. The relationship between reference factors and contrast factors is expressed as correlation coefficient, the relational expression is as follows:

$$\gamma_{ij} = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{ij} + \xi\Delta_{\max}} \tag{7}$$

In the formula: ξ represent distinguish coefficient, in order to improve the difference significant of correlation coefficient, $\xi \in [0,1]$, in general, ξ=0.5.

As the value of correlation coefficients are too many and the information is too scattered to compare, calculate average correlation coefficient to be as the correlation degree to compare the relatedness of influencing parameters. The correlation degree can be solved through the type:

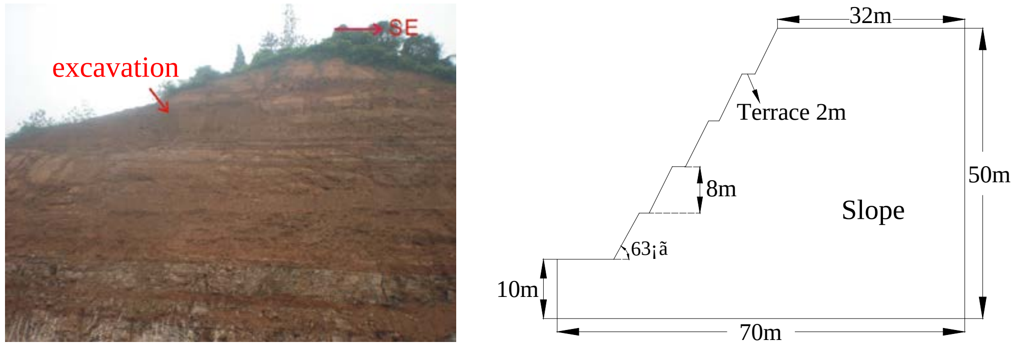
$$A_i = \frac{1}{n}\sum_{j=1}^{n}\gamma_{ij} \tag{8}$$

The value of correlation degree is variable in [0, 1], and reflects the interacted influence of factors. The value of correlation degree itself doesn't represent the contribution of the assessment indexes that the influence factors dedicate to, but the order of correlation degree really reflects the sensitivity essence of influence factors, and the order of A_i is the order of sensitivity. In incidence degree sequence, the relative bigger the correlation degree of influence factors is, the greater influence that the assessment index impacted by the correlation degree is, and the greater the sensitivity is; on the contrary, the smaller the sensitivity is.

STABILITY OF SLOPE EXCAVATION AND SUPPORTING ANALYSIS

Engineering condition and excavation computation

The survey region is along the line section 2 to 4(K11+420~K29+800) of Yiba highway, near Xiaoxi tower to Huanghua town in Yichang city of west-central Hubei province. In the region, the stratum develops well and is one of standard stratigraphic area in our country, the upper Paleozoic Cambrian, ordovician, silurian system, devonian system, Permian, Mesozoic cretaceous and Cenozoic quaternary system are exposed. The lithology distributes from ultrabasic to neutral and acid rock, the neutral and acid rock are the major of all. There are no magmatic rocks outcropped in the studied area, as well as the new tectonic movement is weak, and the level of seismic activity is so low that it can be deduced that it's little possibility of a severe earthquake near ground zone. This paper takes a soil slope in section 3(K23+353~K23+353) for example, according to the slope excavation scheme, dig from top to bottom in turn, and five stages excavation in total, 8 m per stage height, 2 m per slope platform, slope angle 63 ^{o}, as the slope model shown in figure 1. The soil constitutive model is ideal elastic-plastic Mohr-Coulomb, soil parameters are shown in table 1.



(a) (b)

Figure 1: Slope model

Table 1: Parameters value of soil

c/kPa	φ/(°)	γ/(kN·m^{-3})	E/GPa	μ
38	28	23	10	0.3

Use the limit equilibrium method and finite element method to calculate stability coefficient through Slope and Sigma in soft Geo-Studio. The transfixion of plastic zone is taken as the critical instability criterion, and adopt strength reduction FEM to ascertain the safety factor F_s[10]:

$$\frac{c}{c'} = \frac{\tan\varphi}{\tan\varphi'} = F_s \tag{9}$$

In the formula: c, φ are the original strength parameters; c', φ' are the reduced strength parameters.

The reduction factor F_s tends to be a constant when slope damaged, and the yield condition is[11]:

$$\frac{1}{3} I_1 \sin\varphi - (\cos\theta_0 + \frac{1}{\sqrt{3}} \sin\theta_0 \sin\varphi)\sqrt{J_2} + c\cos\varphi = 0 \tag{10}$$

In the formula: I_1, J_2 are respectively the first invariant of stress tensor and the second invariant of stress deviator; θ_0 is stress rude angle; c is cohesive force; φ is internal friction angle.

According to the above excavation scheme, the calculated stability coefficient F_s=0.898<1, slope is instable. So it is need to adopt the prestressed anchor cable to support after considering comprehensively the economy and the construction difficulty.

Analysis of the anchor bolt support

The role of shear force can be considered when supported with anchor bolts so that the evaluation of anchoring slope stability can be more objective, while this is what the limit equilibrium method can't consider. The stiffness matrix $[\boldsymbol{K}_b']^e$ of anchor element in local coordinate system shows in the following form[12]:

$$[\boldsymbol{K}'_{\mathrm{b}}]^{\mathrm{e}} = \begin{bmatrix} \frac{\pi r_{\mathrm{b}}^2 E_{\mathrm{b}}}{L} & 0 & 0 & -\frac{\pi r_{\mathrm{b}}^2 E_{\mathrm{b}}}{L} & 0 & 0 \\ 0 & \frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 & 0 & -\frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 \\ 0 & 0 & \frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 & 0 & -\frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} \\ -\frac{\pi r_{\mathrm{b}}^2 E_{\mathrm{b}}}{L} & 0 & 0 & \frac{\pi r_{\mathrm{b}}^2 E_{\mathrm{b}}}{L} & 0 & 0 \\ 0 & -\frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 & 0 & \frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 \\ 0 & 0 & -\frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} & 0 & 0 & \frac{\pi r_{\mathrm{b}}^2 G_{\mathrm{b}}}{L} \end{bmatrix} \quad (11)$$

In the formula: E_{b} is elastic modulus of anchor; G_{b} is transverse shear modulus of anchor; r_{b} is anchor radius; L is anchor length.

The axial stress-strain constitutive relation of anchor is:

$$\sigma'_{\mathrm{b}} = \begin{cases} E_{\mathrm{b}}\varepsilon'_{\mathrm{b}} & (|\varepsilon'_{\mathrm{b}}| \le \sigma_{\mathrm{bp}} / E_{\mathrm{b}}) \\ \sigma_{\mathrm{bp}} & (|\varepsilon'_{\mathrm{b}}| > \sigma_{\mathrm{bp}} / E_{\mathrm{b}}) \end{cases} \quad (12)$$

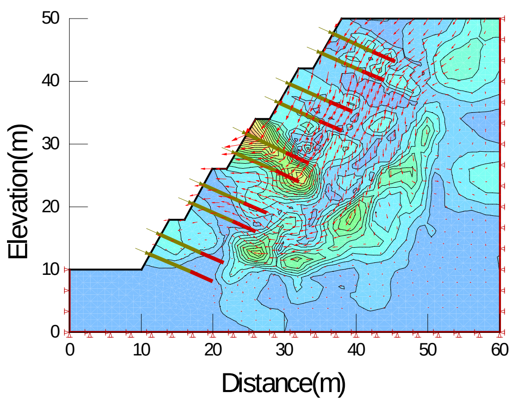
In the formula: σ'_{b} is axial stress; $\varepsilon'_{\mathrm{b}}$ is axial strain; σ_{bp} is yield stress.

The transverse stress-strain constitutive relation of anchor is:

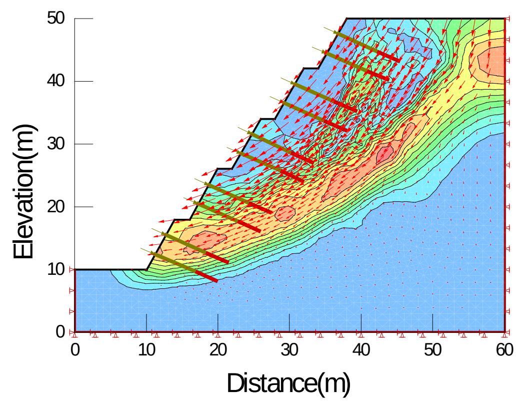
$$\tau'_{\mathrm{b}} = \begin{cases} G_{\mathrm{b}}\gamma'_{\mathrm{b}} & (|\gamma'_{\mathrm{b}}| \le \tau_{\mathrm{bp}} / G_{\mathrm{b}}) \\ \tau_{\mathrm{bp}} & (|\gamma'_{\mathrm{b}}| > \tau_{\mathrm{bp}} / G_{\mathrm{b}}) \end{cases} \quad (13)$$

In the formula: τ'_{b} is transverse shear stress; γ'_{b} is transverse strain; τ_{bp} is yield shear stress.

The bolting parameters of slope under supported by prestressed anchor cable are shown in table 2, calculate the stability through finite element shear strength reduction method after supporting, the maximum shear strain nephogram of slope is shown in figure 2, the displacement vector arrows (as figure 2(b)) show that the plastic zone runs through the entire slope just right, so the safety factor F_{s}=1.09.



(a) F=1.08



(b) F=1.09

Figure 2: The maximum shear strain nephogram

Table 2: Parameters value of anchor

γ/(kN·m^{-3})	E_b/GPa	Bond stiffness/10^8N·m^{-2}	r_b/m	μ	Prestress/kN	L/m	Space/m
78	195	3.0	0.02	0.3	150	9.5	3.4

Analyze the limit sliding failure of slope(as figure 2(b)), draw x-displacement curve of slope surface as shown in figure 3, of which the absolute value increases gradually from top to down of the slope (from right to left in figure 3), the displacement drops sharply and quickly to zero near the slope toe. It indicates that it's good in the effect of bolt supporting and blocking, the whole slope stability has been controlled, and the maximal displacement value is 13.5 mm. Draw the maximum shear stress curve of the sliding surface as shown in figure 4, the maximum shear force value of sliding surface is at the slope center, of about 220 kPa, it's the middle part where should be focused on supporting and controlling. If increasing appropriately the prestress or length of the anchors which locates in middle slope, the support effect will be remarkable.

Figure 3: Displacement of slope surface

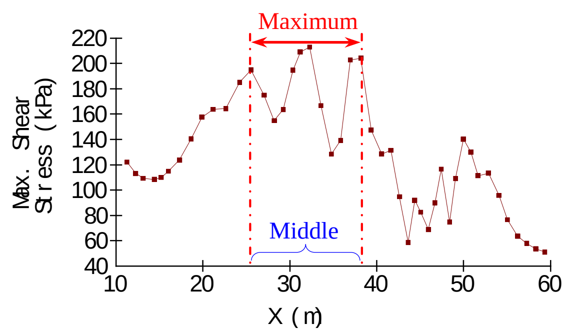


Figure 4: Max. Shear stress of slide surface

PARAMETER SENSITIVITY ANALYSIS

As the factors affecting slope stability are numerous, some slope stability studies by Ying-ren Zheng et al indicate[13]: the elastic modulus E has a certain impact on slope deformation and displacement while impacts on stability coefficient very less; Poisson's ratio μ has no impact on the safety factor, and the safety factors are the same no matter μ=0.1 or μ=0.499. Both E and μ reflect mainly the lateral deformation and unit stiffness of rock-soil mass, and have little impact on the damage of sliding surface, thus the cohesive force c, internal friction angle φ, unit weight γ and gradient α are the emphasis of sensitivity analysis.

When c=29 kPa, φ=24 º, α=63 º, γ=23 kN·m^{-3}, E=10 GPa, μ=0.3, the stability coefficient F=0.728, take multiple value of c in its most possible value range while fixing other parameters value to calculate respectively the corresponding stability coefficient F, as the calculation results shown in table 3. In a similar way, the sensitivity results of φ, γ and α are shown respectively in table 4~6. The sensitivity curves of c, φ, γ and α are shown in figure 5.

Table 3: Sensitivity analysis results of c (φ=24 º, α=63 º, γ=23 kN·m^{-3}, E=10 GPa, μ=0.3)

c/kPa	29	60	90	120	150	200
F	0.728	0.982	1.203	1.399	1.621	1.941

Table 4: Sensitivity analysis results of φ (c=200 kPa, α=63 º, γ=23 kN·m^{-3}, E=10 GPa, μ=0.3)

φ/(º)	24	30	33	35	40	44
F	1.941	2.138	2.200	2.274	2.466	2.642

Table 5: Sensitivity analysis results of γ (c=200 kPa, φ=30 º, α=63 º, E=10 GPa, μ=0.3)

γ/(kN·m^{-3})	19	21	23	25	27	29
F	2.405	2.256	2.138	2.022	1.928	1.852

Table 6: Sensitivity analysis results of α (c=200 kPa, φ=30 º, γ=23 kN·m^{-3}, E=10 GPa, μ=0.3)

α/(º)	30	45	56	63	72	81
F	3.306	2.660	2.319	2.138	1.997	1.804

Figure 5: Relationships of stability coefficient and parameters

From the sensitivity curve of each parameter in figure 5, It is shown that F increases with the increasing c and φ, while decreasing linearly with the increasing γ and α. Among them, the correlation coefficient of F and c, φ, γ, α are respectively 0.9983, 0.9896, 0.9881, 0.9637. They are all linearly correlative with F approximatively, and the linear correlation between F and c is the highest.

Calculate respectively the change rate of F under different influence factors to be shown in table 7, 0.0552>0.0346>0.0289>0.0071, it can be seen that F changes the most fastest with γ, then φ followed, and c is the slowest relatively.

Table 7: Change rate of F along with each parameter

Impact factors	c	φ	γ	α
Average change rate of F ($\lvert\Delta F/\Delta x_i\rvert$)	0.0071	0.0346	0.0552	0.0289

As c, φ, γ, α are sensitive influence parameters, and select the change parameters value to be as reference matrix sequence X; the value of assessment index F are as compared matrix sequence Y. The matrixes are respectively set up as follows:

$$X=\begin{Bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{Bmatrix}=\begin{bmatrix} 29 & 60 & 90 & 120 & 150 & 200 \\ 24 & 30 & 33 & 35 & 40 & 44 \\ 19 & 21 & 23 & 25 & 27 & 29 \\ 30 & 45 & 56 & 63 & 72 & 81 \end{bmatrix}$$

$$Y=\begin{Bmatrix}Y_1\\Y_2\\Y_3\\Y_4\end{Bmatrix}=\begin{bmatrix}0.728 & 0.982 & 1.203 & 1.399 & 1.621 & 1.941\\1.941 & 2.138 & 2.200 & 2.274 & 2.466 & 2.642\\2.405 & 2.256 & 2.138 & 2.022 & 1.928 & 1.852\\3.343 & 2.660 & 2.319 & 2.138 & 1.997 & 1.857\end{bmatrix}$$

Adopt the interval value relativization method to realize dimensionless processing to eliminate the dimension influence of various factors, the new matrix sequences as follows:

$$X'=\begin{Bmatrix}X'_1\\X'_2\\X'_3\\X'_4\end{Bmatrix}=\begin{bmatrix}0 & 0.1813 & 0.3567 & 0.5322 & 0.7076 & 1\\0 & 0.30 & 0.45 & 0.55 & 0.80 & 1\\0 & 0.20 & 0.40 & 0.60 & 0.80 & 1\\0 & 0.2941 & 0.5098 & 0.6471 & 0.8235 & 1\end{bmatrix}$$

$$Y'=\begin{Bmatrix}Y'_1\\Y'_2\\Y'_3\\Y'_4\end{Bmatrix}=\begin{bmatrix}0 & 0.2094 & 0.3916 & 0.5532 & 0.7362 & 1\\0 & 0.2810 & 0.3695 & 0.4750 & 0.7489 & 1\\1 & 0.7306 & 0.5172 & 0.3074 & 0.1374 & 0\\1 & 0.5699 & 0.3429 & 0.2224 & 0.1285 & 0\end{bmatrix}$$

Calculate the difference-information of transformed X'_i and Y'_i to form the difference matrix Δ:

$$\Delta=\begin{bmatrix}0 & 0.0281 & 0.0349 & 0.0210 & 0.0286 & 0\\0 & 0.0190 & 0.0805 & 0.0750 & 0.0511 & 0\\1 & 0.5306 & 0.1172 & 0.2926 & 0.6626 & 1\\1 & 0.2758 & 0.1669 & 0.4247 & 0.6950 & 1\end{bmatrix}$$

Find out the maximum and minimum value of all elements in difference matrix Δ:

$$\Delta_{\max}=\max(\Delta_{ij})=1\,,\quad \Delta_{\min}=\min(\Delta_{ij})=0$$

The relationship between reference factors and contrast factors is representative by correlation coefficient γ, the correlation coefficient matrix is obtained through the difference matrix sequence:

$$\gamma=\begin{bmatrix}1 & 0.9468 & 0.9348 & 0.9597 & 0.9459 & 1\\1 & 0.9634 & 0.8613 & 0.8696 & 0.9073 & 1\\0.3333 & 0.4852 & 0.8101 & 0.6308 & 0.4301 & 0.3333\\0.3333 & 0.6445 & 0.7497 & 0.5407 & 0.4184 & 0.3333\end{bmatrix}$$

Use the average correlation coefficient to be as correlation degree to obtain the correlation sequence:

$$A=\{A_1\ A_2\ A_3\ A_4\}^{\mathrm{T}}=[0.9645\ \ 0.9336\ \ 0.5038\ \ 0.5033]^{\mathrm{T}}$$

From the above sequence, 0.9645>0.9336>0.5038>0.5033, so the descending order of parameters impacted on stability coefficient F is: c, φ, γ, α. The result accords with the principle of Mohr-Coulomb failure criterion, because c and φ are the major parameters which dominate the shear strength of slope.

The interval distribution of influence parameters is considered in sensitivity analysis, and the computational mistakes that due to unreasonable parameter choice can be reduced. It's in line with the spatial variation of actual geologic parameters, and can evaluate the parameters more accurately, reasonably and comprehensively. The sensitive degree calculated by adopting grey relational sensitivity analysis and conventional sensitivity analysis are discrepant, the sensitive factors can be obtained easily by conventional analysis method, but the parameter magnitude and dimension are so inconsonant that may make the changing amplitude of stability coefficient large. The grey relational analysis method can overcome the deficiency of conventional method, and can be logical, more comparable directly, it is of high accuracy and good applicability for evaluating slope stability and parameter sensitivity.

CONCLUSIONS

(1) The strength of soil slope is too low to be unstable according to the original excavation condition, and the bolting scheme proposed should be adopted to control the stability effectively. The displacement of slope toe is small while both the surface displacement and sliding surface shear in the middle part of slope are large relatively, so the effect will be remarkable especially the middle part is supported intensively.

(2) The slope stability coefficient F increases linearly with the increasing internal friction angle φ, and increases slowly with the increasing cohesive force c; F has negative linear correlation with both unit weight γ and gradient α, and changes with γ more quickly.

(3) Analyze and compare the changing trend of four parameters impacting the sensitivity of stability coefficient to conclude that F changes 3.1% with increasing γ by 1 $kN \cdot m^{-3}$, F changes 1.69% with increasing φ by 1 º, F changes 1.17% with increasing α by 1 º, F changes 1.13% with increasing c by 1 kPa. To some extent, F changes greatly with γ, which is due to the soil type and water-bearing condition, etc.

(4) The conventional parameter sensitivity analysis is simplex relatively while the dimension of influence factors are unified and the sensitivity order are consonant by adopting grey relational analysis. It is shown that cohesive force and internal friction angle are the greatest parameters impacting safety coefficient, the shear strength index are crucial in stability analysis.

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REFERENCES

1. Tang Luo-sheng, Yin Kun-long, Li Yuan-yao: “Comprehensive Valuing of Shear Strength Parameters of Zakoushi Landslide” Safety and Environmental Engineering, 2010, 17(3): 10-13.

2. Zhang Chang-liang, Li Tong-lu, Hu Ren-zhong: “Sensibility Analysis of Shearing Strength Parameters of Sliding Surface of Landslide” Journal of Earth Sciences and Environment, 2007, 29(2): 188-191.

3. Bojorque Iñeguez, Jaime: “Back-analysis of slope failures by numerical techniques” *Electronic Journal of Geotechnical Engineering*, 2016, 21(2): 615-625. Available at ejge.com.

4. Zhang Xue-wen, Yang Shi-hao, Wu Shuan-lan, Yi Guang-wei: “Intelligent back-analysis of mechanical parameters for landslide based on sensitive grey correlation analysis”

Electronic Journal of Geotechnical Engineering, 2013, 18(F): 1205-1214. Available at ejge.com.

5. Feng Li-xiong, Ming Yu-hong: “Stability and reliability evaluation of unstable rocks in Jiaozuo longsi abandoned mine slopes” *Electronic Journal of Geotechnical Engineering*, 2015, 20(16): 9637-9647. Available at ejge.com.
6. Tan X.H., Xu Q., Xin Z.Y., Xie Y., Shen M.F.: “Reliability analysis and sensitivity analysis of unsaturated soil slopes under rainfall infiltration” *Electronic Journal of Geotechnical Engineering*, 2014, 19(H): 1635-1646. Available at ejge.com.
7. Zheng Yong-xiang, Liu Jian-jun: “The Influence of Material Factor on Slope Stability” *Electronic Journal of Geotechnical Engineering*, 2016, 21(16): 2379-2388. Available at ejge.com.
8. Yang Yan-mei, Wang Ze-gen: “Grey Prediction Research of Slope Deformation” *Electronic Journal of Geotechnical Engineering*, 2013, 18(G): 1255-1266. Available at ejge.com.
9. Li Yan-yan, Zheng Ying-ren, Kang Nan: “Sensitivity Analysis on Influencing Factors of Tunnel Stability” *Chinese Journal of Underground Space and Engineering*, 2015, 11(2): 491-498.
10. Zhang Xu, Tan Zhuo-ying, Zhou Chun-mei: “Seepage and stability analysis of landslide under the change of reservoir water levels” *Chinese Journal of Rock Mechanics and Engineering*, 2016, 35(4): 713-723.
11. Zhang Hua-qing, Tan Jia-jia, Zuo Dian-jun: “Stability study of unsaturated soft soil slopes under rainfall infiltration” *Port ＆ Waterway Engineering*, 2014(4): 148-153.
12. Wei Lide, Chen Cong-xin, Xu Jian, et al: “Study on strength reduction fem considering seepage and bolt” *Chinese Journal of Rock Mechanics and Engineering*, 2008, 27(Supp.2): 3471-3476.
13. He Jian-ping: “Study on Errors and Sensitivity of Slope Stability with Strength Reduction Method” *Subgrade Engineering*, 2010(1): 64-66.

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