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Stability of Expansive Soil Slope

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ABSTRACT

The influence of swelling deformation on the stability of expansive soil slope was discussed in this paper. And a limit equilibrium method for calculating slope stability was proposed while considering swelling deformation of expansive soil using the equivalent deformation force. The horizontal deformation force coefficient of expansive soil which was obtained from model test was substituted into Fellini's formula to calculate the safety factor of slope. Taking a high expansive slope in constructing Yun-Gui high-speed railway, safety factor of slope considering horizontal deformation force is reduced by 10.5%. The results show that the limit equilibrium method for slope stability considering horizontal deformation is reasonable and practicable. It is a safe design for supporting structures to determine the safety factor by considering the influence of deformation force.

KEYWORDS: expansive soil; deformation force; indoor test; safety factor; limit equilibrium method

INTRODUCTION

The expansive soil widely distributes in Guangxi and Yunnan province, China. The Nan-Kun railway, the main artery of the southwest region, which was designed and constructed in the 1990s, passes through lots of expansive soil region from Nanning to the Kunming. Since 1998, Nanning Railway Bureau has spent nearly 100 million RMB to mending more than 200 case of expansive soil slope disease [1]. Unfortunately, a similar geological condition exists in Nanning-Baise section of constructing Yun-Gui high-speed railway. There are lots of expansive soil (rock) slope which were inevitably threatened by expansive soil (rock).

Expansive soil, a typical kind of special soil, has a series of special characteristics such as developing fissures and swelling-shrinking. It is very harmful to geotechnical structure since its deformation and strength is sensitivity to climatic conditions. The hazard due to expansive soil is too difficult to deal with and the expansive soil is known as the “cancer” in geotechnical engineering [2]. In particular, the stability of expansive soil slope, known as ‘where there is a cutting slope there is a slide’, is one of the challenge in the field of engineering. Many flat slopes whose slope ratio is 1:6 are still likely to slide [3]. Meanwhile, some expansive soil slopes with ratio of 1: 2 to 1: 2.5 and 15~30 m in height still remain steady after decades of ups and downs [4]. It becomes a puzzling problem to estimate the stability of expansive soil slope exactly.

Most civil scholars pay their main attention to the influence of crack and seepage on slope stability. YUAN [5-6] used numerical simulation methods based on FEM software to analyze the influence of slope topography, fracture location, fracture depth and fracture seepage on slope rainfall infiltration. And the results showed that cracks on the slope had a relatively greater influence on slope infiltration, and the influence is more significant with the increase of crack depth. BAO [7] analyzed the impact of rainfall infiltration and cracks on slope stability based on the expansion soil slope in South-to-North Water Transfer Project, and the mechanism of slope instability and the methods for analyzing slope stability considering crack and rain infiltration were studied. LI [8] discovered that the evolvement behaviors of permeability and the deformation modulus can indirectly describe the developing state of the fissure, and the engineering behaviors of unsaturated expansive soil are objectively influenced by fissure. YIN [9] proposed a method for the stability analysis of expansive soil slope based on the slice method which approximately reflected the influence of crack. The expansive soil slope was divided into three layers with different strength indexes, which were named as the full development fissure layer, inadequate fracture layer and no crack layer respectively. An approximate method for determining the depth of fracture, the interface of each sub-layer, the strength of each layer, and the seepage line of the fracture was presented.

It was obviously inappropriate to ignore the influence of soil swelling deformation on slope stability although it was difficult to establish the stability calculation model while considering swelling deformation. To compensate the above shortcoming, CHEN [10] studied the expansive soil slope stability based on the Middle Route of the South-to-North Water Transfer Project and revealed that the expansive soil slope under the condition of moisture absorption would arouse the instability of shallow layer due to the soil deformation. ZUO [11] put forward the stability calculation method considering the effect of expansive forces.

The volume of expansion soil increases after water absorption, and it decreases after the loss of water as a result of swelling-shrinking characteristic. The expansive soil may crack owing to its low tensile strength when the water gets evaporation. With the increasing times of dry-wet cycles, the cracks both in width and depth of expansive soil slope get larger and larger. The existence of cracks reduces the strength of soil, and provides a channel for water seepage. The slope sliding force becomes larger than the anti-sliding force due to the soil swelling after water absorption. Consequently, the soil swelling after water absorption is an important influence factor on the stability of expansive soil slope. In this paper, a method for calculating slope stability with the consideration of swelling deformation was established using the equivalent deformation force method as it was quite difficult to directly establish the stability calculating model considering swelling deformation. Taking the multistage expansive soil slope in new Yun-Gui high-speed railway for example, the stability of multistage expansive soil slope was analyzed using a limit equilibrium method while considering the influence of swelling deformation.

THE ANALYSIS OF STRESS STATE IN THE EXPANSIVE SOIL

When expansive soil is supposed to be isotropic, major and minor principal stresses are σ_1 and σ_3 respectively ($\sigma_1 > \sigma_3$), as shown in Figure 1 (a). With the water absorbing, the expansive soil obtained swelling potential energy to produce deformation force p, which is restrict by major and minor principal stresses. Three kinds of conditions may occur: ①when deformation force $p<\sigma_3$, the deformation force is too small to deform volume; ②when deformation force $\sigma_3<p<\sigma_1$, horizontal expansive deformation will be occurred; ③when deformation force $p>\sigma_1$; horizontal expansive deformation and vertical expansive deformation will be occurred. The vertical swelling deformation of expansive soil slope only makes the landslide body move upward with a relative small effect on slope stability. However, the horizontal swelling deformation makes the landslide body move or rotates to free face which increases the risk of landslide, and subsequently threatens the stability of slope. So the horizontal deformation force could be used when analyzing the slope stability.

The deformation force is one kind of body force that leads to soil swelling, and it is treated as uniform distribution along the sliding surface, as shown in Figure 2. The horizontal deformation force of expansive soil can be calculated using the following formula:

$$P_h = \beta_h V \tag{1}$$

In which, P_h represents the horizontal deformation force; V is the volume of expansive soil; β_h represents the coefficient of horizontal deformation force which can be determined by the model test, as presented in the next paragraph.

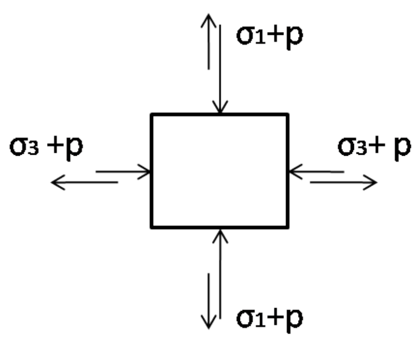


Figure 1: stress state at a point of expansive soil

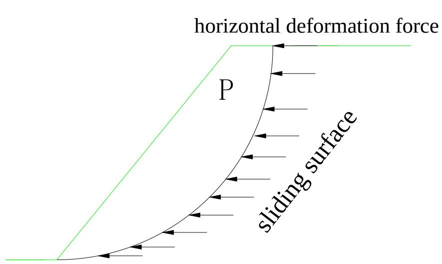
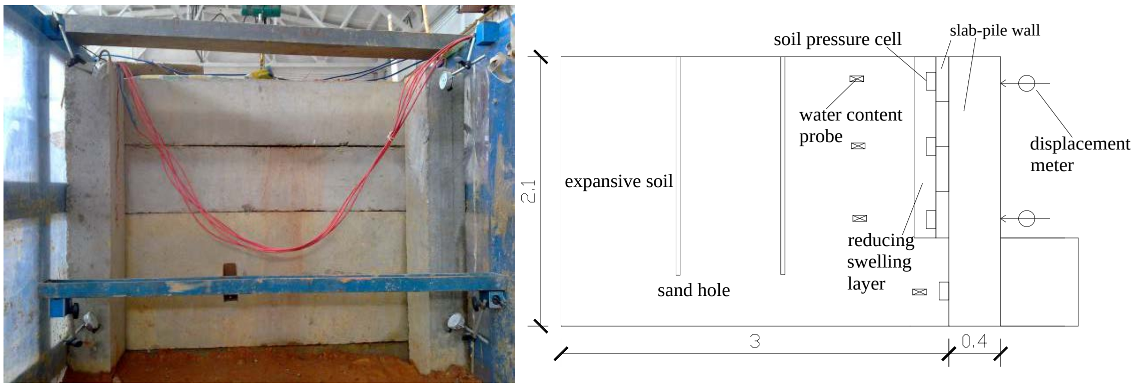


Figure 2: Horizontal deformation force

THE MODEL TEST OF HORIZONTAL DEFORMATION FORCE

Test method

A model test was carried out to determine the coefficient of horizontal deformation force β_h. The test method and components are shown in Figure 3. The size of model box is 4m × 2.1m × 1.5m .The model box is filled with expansive soil in a cutting slope of Yun-Gui high-speed railway. The reducing swelling layer and soil pressure cell are set between the expansive soil and the slab-pile structures. The reducing swelling layer can coordinate with the horizontal deformation of expansive soil. The sand hole is set in the filler to simulate natural crack as well as to accelerate the penetration of water. The distributions of the sand holes, the water content probes and the soil pressure cells are shown in Figure 3(b). When the expansive soil in model box absorbs water, the expansive soil will induce horizontal deformation force. The water is sprinkled at the top of the model box until there is remained water on the surface. The values of horizontal deformation force at different depth, the soil pressure increment and the change of water content can be obtained by soil pressure cell, water content probe etc.



(a) (b)

Figure 3: The horizontal deformation force test of expansive soil

The test results of deformation force are shown in Table 1. The average value of horizontal deformation force is 7.3 kPa, and the filling volume of model box is 3m×2.1m×1.5m. Taking the values of the horizontal deformation force and the filling volume into Eq. (1), the value of β_h can be determined as 0.77kN/m^3.

Table 1: The test results of deformation force.

Depth (cm)	Increment of earth pressure box (kPa)	Increment of moisture content (%)
20	6	11.4
70	8	8.2
120	8	14.1
Average	7.3	-

ESTABLISH METHOD

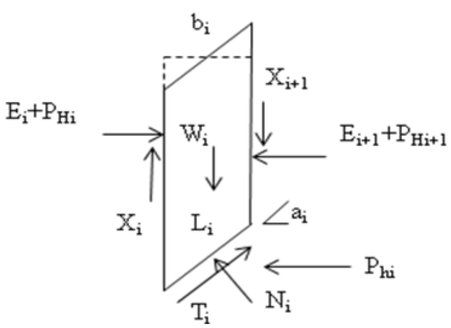
Generally, the slope stability analysis methods, including numerical simulation [12-13], limit analysis [14-18], and limit equilibrium [19-21], were developed and proliferated to be powerful tools for geotechnical engineering design and construction procedure. Limit equilibrium method is widely applied in stability of slope due to its briefness and convenience.

In limit equilibrium slice method, a potential sliding surface is firstly assumed, subsequently, the sliding body is divided into many slices to analyze the force of each slice., The values of safety factor *K* of slope can be obtained by dividing the total resisting force by total driving forces under different sliding surfaces. The potential sliding surface is determined as the one which leads to the minimum value of safety factor *K*.

W.Fellenius put forward the slice method for stability analysis of clay soil slope in 1927, as shown in Fig.4 and Fig.5. Fellenius' simplified formula can be expressed as follow:

$$K = \frac{\sum_{i=1}^{n}(W_i \tan\varphi_i \cos\alpha_i + c_i l_i)}{\sum_{i=1}^{n}(W_i \sin\alpha_i + P_{hi} l_i \cos\alpha_i)} \tag{2}$$

In which, W_i represents the weight of slice i ; l_i represents the arc-length of slice i on sliding surface; b_i represents the width of slice i; α_i represents the inclined angle; P_{hi} represents the horizontal deformation force of slice i; c represents the cohesive force of expansive soil; φ represents the internal friction angle of expansive soil.



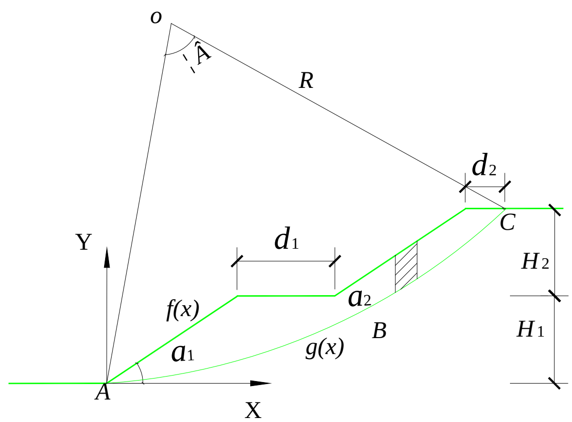


Figure 4: The calculation model of slices method **Figure 5:** The stability analysis of two-stage slope

Taking the Eq.(1) into the Eq.(2).

$$K = \frac{\sum_{i=1}^{n} l_i (\frac{W_i}{l_i} \tan\varphi_i \cos\alpha_i + c_i)}{\sum_{i=1}^{n}(W_i \sin\alpha_i + \beta_h V_i l_i \cos\alpha_i)} \tag{3}$$

Where, both internal friction angle φ and cohesive force c are constant.

Taking $\frac{W_i}{b_i} = \gamma h_i$ and $V_i = b_i h_i = h_i l_i \cos\alpha_i$ into Eq. (3),

$$K = \frac{\sum_{i=1}^{n} l_i (\gamma h_i \tan\varphi \cos^2\alpha_i + c)}{\sum_{i=1}^{n} b_i (\gamma h_i \sin\alpha_i + \beta_h h_i b_i)} \tag{4}$$

When the width of soil slice tends to infinite small, the number of soil slice becomes infinite large. The safety factor (Eq. (4)) can be expressed in integral form.

$$K = \frac{\int_{\widehat{AC}} (\gamma h \tan\varphi \cos^2\alpha + c)ds}{\int_{x_A}^{x_C} (\gamma h \sin\alpha + \beta_h h x)dx} \tag{5}$$

Where, *s* represents the arc-length of ABC.

Taking $\cos\alpha = \frac{1}{1+\tan^2\alpha} = \frac{1}{1+g'^2(x)}$ and $ds = \frac{1}{\cos\alpha_i}dx$ into Eq. (5)

$$K = \frac{\int_{x_A}^{x_C} (\gamma h \cdot \frac{\tan\varphi}{1+g'^2(x)} + c)\sqrt{1+g'^2(x)}dx}{\int_{x_A}^{x_C} (\gamma h \cdot \frac{g'(x)}{\sqrt{1+g'^2(x)}} + \beta_h h x)dx} \tag{6}$$

Where, $g(x)$ is a geometric function related to arc sliding surface in rectangular coordinates, which is shown in Figure 5. γh is the vertical stress of one point [x, $g(x)$] on sliding surface.

The height of soil slice can be determined as,

$$h = f(x) - g(x) \tag{7}$$

Where, $f(x)$ is a geometric function related to slope surface in rectangular coordinates, which is shown in Figure 5.

Taking Eq. (7) into Eq. (6),

$$K = \frac{\int_{x_A}^{x_C} (\frac{\gamma \tan\varphi[f(x)-g(x)]}{1+g'^2(x)} + c)\sqrt{1+g'^2(x)}dx}{\int_{x_A}^{x_C} \frac{\gamma g'(x)[f(x)-g(x)]}{\sqrt{1+g'^2(x)}} + \beta_h[f(x)-g(x)]x dx} \tag{8}$$

Eq. (8) is a common expression of safety factor with the consideration of deformation force. $f(x)$ which is a piecewise function determined by the stage divisions of slope, can be extended to the situations of single-stage slope, double-stage slope and multistage slope. $g(x)$, which is an unknown function determined by the shape of sliding surface, can be extended to the slopes with different sliding surface shapes including circular arc, broken line and logarithmic spiral line. x_A and x_C are the abscissa values of crossover points of function $f(x)$ and function $g(x)$.

The safety factor can be expressed as follow by assuming point A as the origin of coordinate.

$$K = \frac{\int_{0}^{x_c} (\frac{\gamma \tan\varphi[f(x)-g(x)]}{1+g'^2(x)} + c)\sqrt{1+g'^2(x)}dx}{\int_{0}^{x_c} \frac{\gamma g'(x)[f(x)-g(x)]}{\sqrt{1+g'^2(x)}} + \beta_h[f(x)-g(x)]x dx} \tag{9}$$

A four-stage slope is selected for typical study. Sliding surface of slope is supposed as an arc-surface with the centre point of (x_0, y_0) and radius of R. Both the centre point (x_0, y_0) and the radius R are unknown. Subsequently, $f(x)$ and $g(x)$ can be expressed as follows:

$$f(x)=\begin{cases} x\tan\alpha_1; & 0<x\le H_1\cot\alpha_1 \\ H_1; & H_1\cot\alpha_1<x\le H_1\cot\alpha_1+d_1 \\ H_1+(x-d_1-H_1\cot\alpha_1)\tan\alpha_2; & H_1\cot\alpha_1+d_1<x\le H_1\cot\alpha_1+d_1+H_2\cot\alpha_2 \\ H_1+H_2\,; & \cot\alpha_1+d_1+H_2\cot\alpha_2<x\le H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2 \\ H_1+H_2+(x-d_1-H_1\cot\alpha_1-d_2-H_2\cot\alpha_2)\tan\alpha_3\ ; & \\ \quad H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2<x\le H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3 & \\ H_1+H_2+H_3\,; & \\ \quad H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3<x\le H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3+d_3 & \\ H_1+H_2+H_3+(x-d_1-H_1\cot\alpha_1-d_2-H_2\cot\alpha_2-H_3\cot\alpha_3-d_3)\tan\alpha_4\,; & \\ \quad H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3+d_3<x\le H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3+d_3+H_4\cot\alpha_4 & \\ H_1+H_2+H_3+H_4\,; & \\ \quad H_1\cot\alpha_1+d_1+H_2\cot\alpha_2+d_2+H_3\cot\alpha_3+d_3+H_4\cot\alpha_4<x\le x_c & \end{cases} \tag{10}$$

$$g(x)=-\sqrt{R^2-(x-x_0)^2}+y_0 \qquad 0\le x\le x_c \tag{11}$$

Eq. (10) is a piecewise function which is determined by the stage division of slope. Eq. (11) is a function related to arc sliding surface. H_1, H_2, H_3, H_4 are slope heights of different stages of slope. a_1, a_2, a_3, a_4 are the slope angles of different stages. d_1, d_2, d_3 are the platform width of different stages. The minimum safety factor K can be determined based on Eq. (9) by Matlab editing program. Additionally, Eq. (9), Eq. (10) and Eq. (11) can be extended to n-stage (n>4) slope.

ENGINEERING CALCULATION EXAMPLES

Example 1

A typical example of three-stage slope of cohesive soil in Reference [21] is selected to verify the correctness of the formula and program. The results of safety factor K are shown in Table 2. It is seen that the value of safety factor K determined by the proposed method in this paper is nearly the same as that in Reference [22].

Table2: Result Validation of typical examples.

c/kPa	φ/(°)	γ/(kN/m^3)	a_1	a_2	a_3	β_1/(°)	β_2/(°)	β_3/(°)	H/m	Safety factor K	
										Results in reference [20]	Results in this paper
28	25	18.5	1/3	1/3	1/3	45	45	45	12	2.212	2.248

Example 2

The high expansive soil slope, such as four-stage cutting slope, is constructed on the right side of Yun-Gui high speed railway (DK221+700 ~ DK221+820). The parameters of a typical four-stage expansive soil slope in this section are presented in Table 3. In which, c and φ are residual strength parameters of expansive soil while considering the influence of soil cracks. Based on the parameters above, the safety factor *K* can be solved as shown in Table 4.

Table 3: Parameters of four-stage expansive soil slope

d_1(m)	d_2(m)	d_3(m)	a	a_1	a_2	a_3	a_4	β_1(°)	β_2(°)	β_3(°)	β_4(°)	H(m)	γ(kN/m^3)	c(kPa)	φ(°)
3	3	3	0	1/4	1/4	1/4	1/4	33.7	33.7	33.7	33.7	36	18.85	10	25

Table4:calculation results

Calculation method	Centre of sliding surface	Radius of sliding surface	Safety factor *K*	percentage	Deformation force
Traditional slice method	(0.78m,72.65m)	72.6(m）	1.123	1	No
proposed method	(0.78m,72.65m）	72.6(m)	1.005	10.5%	Yes

In Table3, safety factor of this four-stage slope calculated by traditional slice method is 1.123, and it will decrease to 1.005, by 10.5%, when considering deformation force, which is more close to real situation. So slope with reinforcement structure designed with safety factor that considers the influence of deformation force is safer. Parameter of horizontal deformation force got in model experiment is used in this paper, while the real condition of expansive soil mass is far bigger than the parameter of deformation force got in model experiment, which is more unfavorable to slope stability. Result calculated from project example shows that the stability analysis method considering horizontal deformation force is reasonable.

CONCLUSIONS

(1) The model test is carried out to determine the coefficient of horizontal deformation force.

(2) The horizontal deformation force coefficient of expansive soil is substituted into Fellenius' simplified formula to calculate the safety factor of slope. A method based on limit equilibrium theory to analyze slope stability while considering the swelling deformation is obtained.

(3) Taking a four-stage expansive soil slope in Yun-Gui high-speed railway for typical study, a limit equilibrium method is used to determine the safety factor of this slope. The value of safety factor decreases from 1.123 to 1.005 with a reducing ratio of 10.5% while considering the effect of horizontal deformation. The results show that the limit equilibrium method for slope stability with the consideration of horizontal deformation is reasonable and practical. It is safe to determine the safety factor of supporting structure while considering the influence of deformation force.

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REFERENCES

1. FENG Z J, FENG J G, XUE Y, YANG G L, HE X" Application of Flexible Retaining Wall in Protection Engineering on Expansive Soil Slope "[J] *High Speed Railway Technology*, 2012, 3(02): 71-73+78.

2. LU Z H, CHEN Z H, FANG X W, GUO J F, ZHOU H Q" Structural damage model of unsaturated expansive soil and its application in multi-field couple analysis on expansive soil slope" [J] *Applied Mathematics and Mechanics*, 2006, 27(07): 891-900.
3. BAO C G "Geotechnical study series" [M] Wuhan: *Chang Jiang Press*, 2007.
4. LIU T H "The problems of expensive soils in engineering" [M] Beijing: *China Architecture & Building Press*, 1996.
5. YUAN J P, YIN Z Z "Numerical model and simulation of expansive soils slope infiltration considered fissures" [J] *Rock and Soil Mechanics*,2004,25(10):1581-1586.
6. WU J H, YUAN J P, CHARLES W. W. N. "Theoretical and experimental study of initial cracking mechanism of an expansive soil due to moisture-change" [J] *Journal of Central South University*, 2012, 19(05):1437-1446.
7. BAO C G "Behavior of unsaturated soil and stability of expansive soil slope" [J] *Chinese Journal of Geotechnical Engineering*,2004, 26(01):1-15.
8. LI X W, WANG Y, YU J W, WANG Y L "Unsaturated expansive soil fissure characteristics combined with engineering behaviors" [J] *Journal of Central South University*, 2012, 19(12):3564-3571.
9. LIU H Q, YIN Z Z "Research on analytical method of stability of expansive slope"[J] *Rock and Soil Mechanics*,2010, 31(05):1545-1549+1554.
10. CHENG Z L, LI Q Y, GUO X L GONG W B "Study on the stability of expansive soil slope" [J] *Journal of Yangtze River Scientific Research Institute*,2011, 28(10):102-111.
11. ZUO C Q, CHEN J P "The stability analysis of expansive slope in Jing-Yi Expressway" [J] *Journal of Zhejiang University* (Science A), 2007, 8(02):270-274.
12. ABBAS, JASIM M ”Slope stability analysis using numerical method" [J] *Journal of Applied Sciences*, 2014, 14 (9):846-858.
13. LIU F, Zhao J "Limit analysis of slope stability by rigid finite-element method and linear programming considering rotational failure" [J] *International Journal of Geomechanics*, 2014, 13(6):827-839.
14. CHEN J, YIN J H, LEE C F "Upper bound limits analysis of slope stability using rigid finite elements and nonlinear programming" [J] *Canadian Geotechnical Journal*, 2003, 40(4): 742-752.
15. LEE C F, CHEN J, YIN J H "A three-dimensional upper-bound approach to slope stability analysis based on RFEM" [J] *Geotechnique*, 2005, 56(4): 285-286.
16. SUN Z B, LIANG Q "Back analysis of general slope under earthquake forces using upper bound theorem" [J] *Journal of Central South University*, 2013, 20(11): 3274-3281.
17. Hang Lin, Ping Cao "Limit Equilibrium Analysis for the Relationships Among Slope c, φ and Slip Surface"[J] *Electronic Journal of Geotechnical Engineering*,2012,17(B):185 −195.
18. YANG X L "Seismic passive pressures of earth structures by nonlinear optimization" [J] *Archive of Applied Mechanics*, 2011, 81(9): 1195 −1202.
19. Liu Minnan,Liu Fuchen. "Calculation Model of the Earth Pressure on Retaining Wall with Relieving Platform" [J] *Electronic Journal of Geotechnical Engineering*, 2018, 23(02): 477−483.

20. Jia Jin-long, Cao Li-wen "Technology of Large Section Coal Roadway Supporting Based on Limit Equilibrium Method" [J]*Electronic Journal of Geotechnical Engineering* 2014,19(B):413 −424.

21. ZHOU X P, CHENG H "Analysis of stability of three-dimensional slopes using the rigorous limit equilibrium method" [J] *Engineering Geology*, 2013, 160(12):21–33.

22. GAO L S, ZHAO L H, LI Liang "Analysis on Upper Bound of Stability of Multi-stage Slope with Benches" [J] *Journal of Highway and Transportation Research and Development*, 2014, 31(06):1-10.

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