FLAC3D-based slope stability analysis and calculation

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Abstract. Slope stability is related to the normal operation of the project and operational safety, and there have been various methods for evaluating slope stability for a long time, among which the numerical analysis method is the most popular and comprehensive analysis and evaluation method nowadays. In this paper, the numerical simulation is carried out by FLAC3D software to solve the safety coefficient of the slope and the slope stability analysis in combination with the slope of the inverted siphon entry road section at the beginning of Xiaoyuiba, and the conclusions are in line with the actual situation, which shows that FLAC3D software can carry out scientific analysis and evaluation of slope stability and make comprehensive judgement.

Keywords: Slope stability; Numerical simulation; Strength discounting method; Safety coefficient.

1. Introduction

Stability analysis of slopes is a key and complex problem in the field of engineering, and occupies a very important position in geotechnical engineering, which involves a wide range of influencing coefficient s, such as rock physical properties, geological structure, slope height, slope angle and so on. At present, the existing slope stability analysis methods mainly include limit equilibrium method, plastic limit analysis method, numerical calculation analysis method, etc. The first two methods are traditional analysis methods. The first two methods belong to the traditional analysis methods, which have been applied earlier and have a wide range of engineering applications, such as: strip method, Bishop Method, Janbu method, Spencer method and so on. In the information age, with the development of computer hardware and software technology, the numerical analysis method has been greatly developed and gradually become the hot spot of slope stability analysis [1], mainly including: finite unit method, finite unit strength reduction method, DDA method, manifold element method, boundary element method, discrete element method, interface stress element method, etc. [2].

The finite unit method, as a new method for slope stability analysis, has many advantages such as being able to consider the stress-strain relationship of materials, not needing to assume the shape and location of the slip surface, and being able to simulate the joint action of the geotechnical body and various supporting structures. And the finite unit strength discount method combines the finite unit method and the limit equilibrium method in analyzing slope stability, and proposes a safety coefficient, which is an effective tool for complex slope stability analysis.

FLAC3D software is a three-dimensional fast Lagrangian analysis program developed by ITASCA, which is widely used in the fields of geotechnical analysis, groundwater analysis, tunnel design and construction, etc. It is a numerical analysis method based on the three-dimensional explicit finite difference method, which divides the computational area into a number of tetrahedral cells, each of which follows the specified linear or nonlinear eigen structure under the given boundary conditions relations. If the cell stress makes the material yield or produces plastic flow, the cell mesh can be deformed with the deformation of the material, which allows large deformation analysis of continuous media, and is more suitable for the study of damage problems in geotechnical engineering compared to other methods that are limited to small deformation assumptions[3].The FLAC3D software adopts the strength discount method to calculate the slope coefficient of safety, and obtains the slip damage surfaces of the sliding body through model calculation and analysis and strain and stress diagrams, so as to simulate the deformation and destruction of the rock body, until the process of landslides occurring in the rock body of the slope, and thus make a scientific analysis of the stability of the slope.

In this paper, numerical simulation using FLAC3D software is carried out to analyses the stability of the slope and give an eva

2. Principles of calculation

2.1. Basic principle of finite element strength discounting method

The idea of strength discounting was first proposed by Zienkiewicz and others [4] and has been widely studied and applied. The idea of this method to analyse slope stability problems is similar to the traditional limit equilibrium method I. The basic principle is to divide the slope strength parameters: Cohesion c and internal friction angle value φ at the same time divided by the corresponding strength reduction coefficient F_c , F_φ, and usually assume that $F_c = F_\varphi = F$, to get a new set of c',φ' values, and then as a new data parameter input, and then carry out the calculation of the test, when the calculation does not converge, i.e., when the strength of the engineering slope rock body reaches the critical damage state, the corresponding reduction The coefficient F is called the minimum stability safety coefficient of the slope, at this time the slope body reaches the limit state, shear damage occurs, and at the same time, the destructive sliding surface of the slope body can be obtained. The formula is:

$$c' = \frac{c}{F_c} \tag{1}$$

$$\varphi' = \arctan\left(\frac{\tan\varphi}{F_\varphi}\right) \tag{2}$$

In the formula, c is cohesion (Pa) and b is stress (Pa).

The safety coefficient is defined as the ratio of ultimate stress to permissible stress in engineering, and the calculation result is judged as slope stability when$F > 1$; slope instability when$F < 1$; and slope critical stability state when$F = 1$. Considering the actual situation, since when$F < 1$, the slope is already unstable, that is, the slope no longer exists. Therefore, when calculating the example, the result F should not be less than 1.

The form of the definition of the strength discounted finite element stability coefficient is related to the strength yield criterion it uses, and the Mohr-Coulomb yield criterion is usually used to calculate the stability coefficient , and this model is mainly applicable to bonded and loose bulk materials, soils, rocks, etc.[5], which is suitable for conventional engineering studies in reality. The formula is:

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

In the formula, I_1 is the first invariant of the tensor; J_2 is the second invariant of the partial tensor; and ω_b is the stress Rhodes angle.

2.2. Intensity Reduction Method in FLAC3D Software

The algorithm of the strength discount method can be mainly summarised in the following three steps:

(1) Establish the finite element analysis model of the slope, assign different unit material properties to various materials of the slope, and calculate the initial stress field of the slope. Then the stress, strain and displacement changes of the slope under gravity are initially analysed;

(2) Gradually increase the shear strength reduction coefficient F of the soil body of the slope according to a certain step, assign the reduced strength parameters to the calculation model, and carry out the calculation again;

(3) Repeat step (2) and keep increasing the value of F while decreasing the material parameters of the slope body until the calculation does not converge, representing the instability damage of the slope,

then the value of F in the step before the calculation of divergence is the coefficient of safety of the slope.

The functions of FLAC3D software include simulating the mechanical behaviours of 3D soil, rock and other materials, and so on. In the study of slope stability problems, FLAC3D software adopts the strength reduction method to calculate the safety coefficient of slope stability, and the calculation can be carried out in two ways. One is to make use of a command within the FLAC3D software to automatically find the coefficient of safety, i.e., the "solvefos" command [6]. The main idea of this command is to reduce the cohesive force c and internal friction angle b, and use the command to determine the safety coefficient of the slope in the critical damage state by interpolating the approximation, i.e., by repeating the adjustment coefficients, different cohesion and internal friction angles are obtained, which are constantly substituting into the Mohr-Coulomb yield criterion for repeated iterations[7], and when the slope reaches the critical state, the obtained F value is the coefficient of safety for that slope. In addition, it is also possible to use the FISH language within FLAC3D to write a strength reduction procedure and then substitute it into the FLAC3D software to run, which can also obtain the coefficient of safety.

3. Example analyses and calculations

3.1. Project overview

Small fish dam inverted siphon starting point into the field of highway starting point of Anfu highway, the starting point elevation of 1752.32m, the end of the route to the small fish dam inverted siphon inlet section of the excavation slope inlet, the end of the elevation of 1903.18 m, the route length of about 2520km. the project area of geomorphological types are tectonic erosion dissolution canyon mountainous geomorphological area, the highest point of the road section of the elevation of about 2400m, the height of the riverbed about 1744m, the relative height difference of 656m. The project site is located in the ridge part of the bank slope, the terrain slope is generally 30°~45°, and there is local unloading collapse residual dangerous rock steep wall. The whole road is basically located on the large-scale collapse pile (BV-1), the maximum width of the collapse pile can be up to 750m, the composition is mainly siliceous dolomite and greywacke isolated stone, block stone, gravel composition, isolated stone, block stone content of more than 50%, gravel content of about 30%, so the use of FLAC3D in the Mohr-Coulomb model for the calculation is feasible.

In the example section, the largest diameter of the isolated rock is more than 20m, which has some influence on the slope excavation and slope stability of the access road. Other physical geological phenomena are mainly rock dissolution and weathering. According to the exploration results, along the road, the thickness of the rock body with strong dissolution and weathering is generally less than 10m, and the thickness of the rock body with fissure dissolution and weathering is generally more than 30m.

3.2. Numerical model and boundary conditions

According to the slope profile as in Fig. 1, the model is established as shown in Fig. 2, and the mechanical indexes of the rock used for model calculation are shown in Table 1.

Fig 1. Slope profile diagram.

Stratigraphical Soil name	Q4del Gravelly soil	Q4dl+col Gravelly soil	Dolomite (surface dissolution)	Dolomite (fissure dissolution))
Gravity γ(kN/m3)	18	18	22	26.5
Modulus of deformation E(GPa)	0.3	0.36	0.4	2.5
Poisson's ratio μ	0.38	0.38	0.34	0.26
Cohesion *c*(MPa)	0.0125	0.013	0.075	0.25
Internal friction angle φ(°)	17	19	21.7	36.5
Load capacity tolerance value (MPa)	0.17	0.17	0.4	2.0

Table 1. Mechanical parameters of the model material.

The front, back, left and right boundaries of the model are imposed with normal constraints, i.e., the boundary of the model in the east-west direction is displaced to zero along the x-direction, and the boundary of the model in the north-south direction is displaced to zero along the y-direction. The boundary at the bottom of the model is fixed, so the vertical displacements of the model are all zero; and the top of the slope is a free boundary. The model is divided into 1988414 cells, as shown in Fig2.

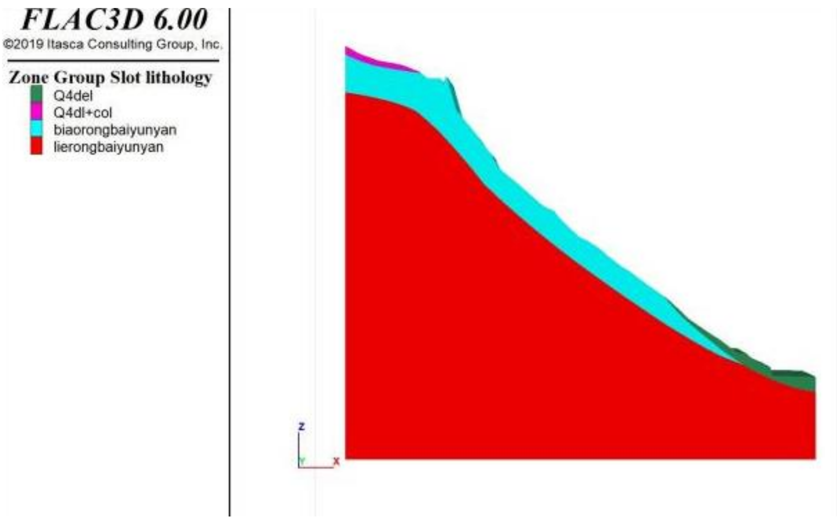

Fig 2. Slope profile model diagram.

3.3. Calculation results of the model

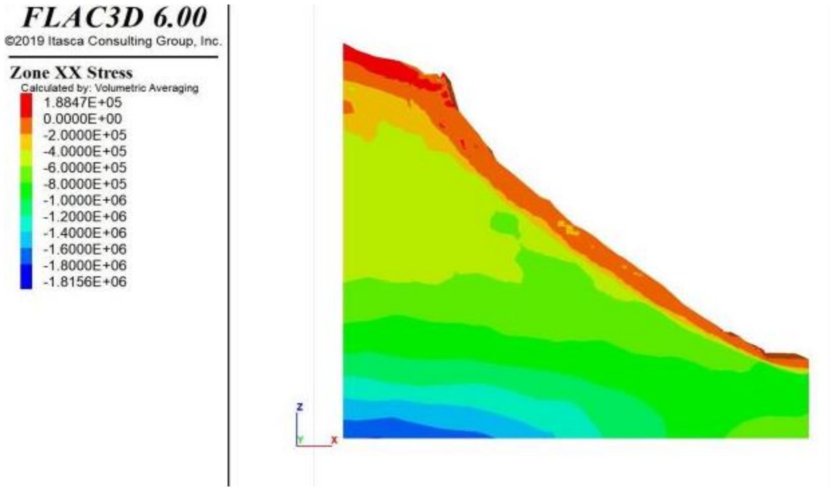

Fig 3. Horizontal stress diagram.

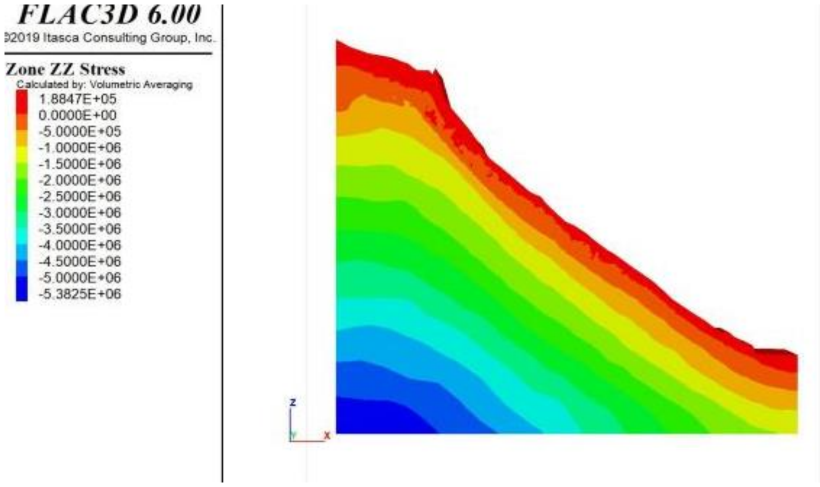

Fig 4. Vertical stress diagram.

As can be seen from Fig. 3 and Fig. 4, the maximum stress values of horizontal and vertical stresses of the slope show tensile stresses with a maximum of 18.8 kPa, and most of the other locations show compressive stresses. As can be seen from Figure 3, the undulation of the rock surface will cause stress changes in the horizontal direction, which has a certain impact on the slope stability, and there is a stress concentration phenomenon in some areas of the slope surface. As can be seen from Figure 4, the vertical stress distribution is close to parallel to the slope surface, and the stress value shows an upward trend with the elevation, and the distribution is basically uniform.

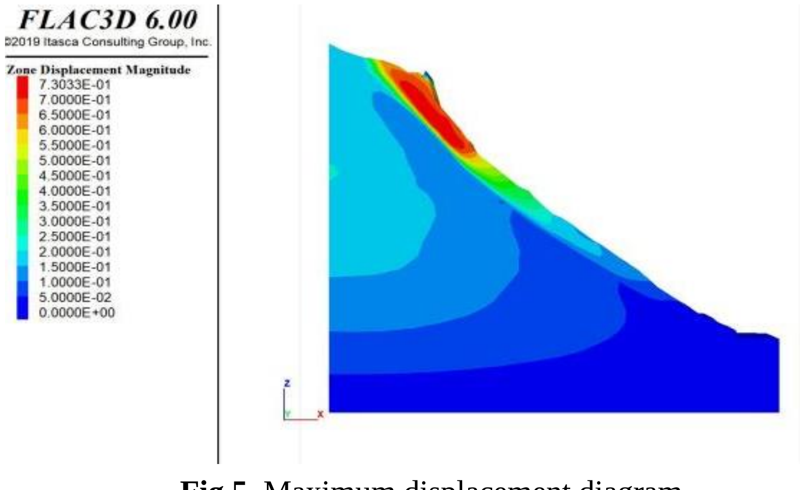

Fig 5. Maximum displacement diagram.

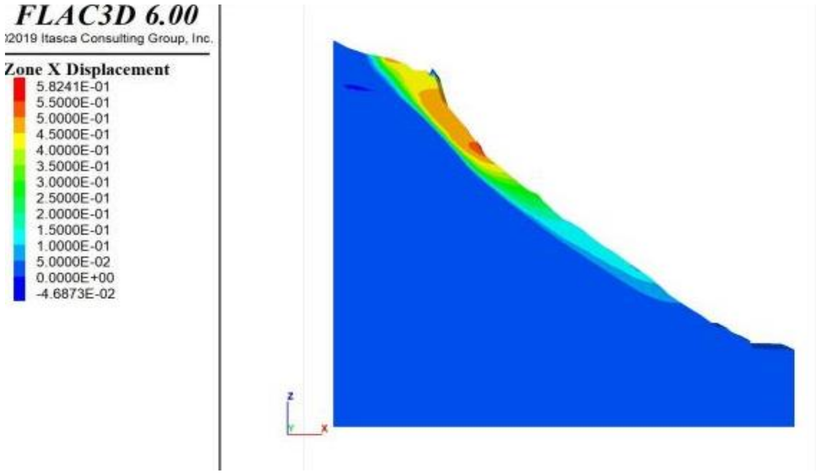

Fig 6. Horizontal displacement diagram.

From Fig. 5 and Fig. 6, it can be seen that the deformation of the slope is more obvious in the upper and central part of the slope surface. From Fig. 5, it can be seen that the maximum displacement of the slope is mainly concentrated in the upper part of the slope surface, which gradually decreases with the decrease of the elevation. From Figure 6, it can be seen that the horizontal displacement and deformation of the slope is mainly concentrated in the upper and middle part of the slope face, and gradually decreases from the leading edge to the trailing edge, which is not conducive to the stability of the slope.

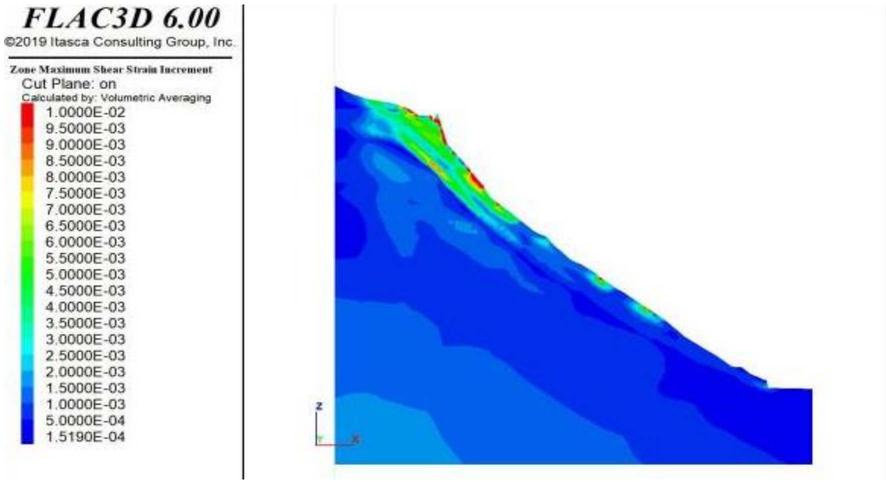

Fig 7. Shear strain increment diagram.

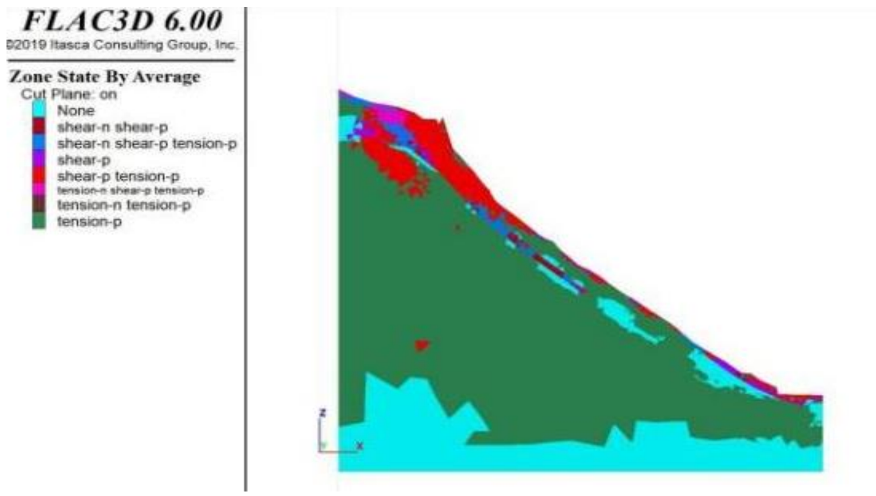

Fig 8. Plastic differential layout.

From Fig. 7, it can be seen that the strain increment generated by the shear on the slope is larger at the upper part of the slope face. From Fig. 8, it can be seen that the cells showing shear- n and shear-p states in the slope are plastic cells, i.e., this part of the cells is in the plastic flow state, and the shear-n part, i.e., the red part of the current cycle that is in the plastic state due to shear, is also mainly concentrated in the upper part of the slope near the top of the slope, which is likely to be undergoing sliding. It can be seen that the upper part of the slope is at a higher risk of destabilisation and that damage may have occurred in some areas.

The calculated slope safety coefficient $F = 1.038$ indicates that when the discount coefficient is 1. 038, the strength of the rock and soil body can no longer maintain the stability of the slope, and the slope will be damaged at this time. That is to say, without the influence of external coefficient s, the slope is currently stable, relative to its critical state of destruction, its stability exists in the space of the safety coefficient of 1.038. This figure is relatively less than the safety value specified in the code, indicating that there is a risk of slope instability and that some reinforcement is desirable.

3.4. Analysis of calculation results

Xiaoyuba inverted siphon starting point access road is the main transportation channel for Caijiacun tunnel exit section and Xiaoyuba inverted siphon inlet section to enter the site, the geological conditions of this access road are complicated, and the physical geological phenomenon is mainly manifested as avalanches, and there is an avalanche accumulation body (BV-1) developed, which means that it exists within the distribution of quaternary avalanche slope deposits. This avalanche accumulation is developed in the middle and lower part of the left bank of the Mantis River, which has the shape of a wide irregular arc, with a volume of about$2100 \times 104m^3$, and belongs to the giant avalanche. The collapse is characterised by the topographical change that the back part is slow and the front part becomes steep, and the weathering is strong, which makes it easy to drop blocks and rocks [8].

It can be seen that the slope at the inlet section is mainly composed of gravel soil, avalanche accumulation of slopes, and the elevation is higher, under the influence of complex geological conditions, it is more prone to local slumping and sliding or the overall sliding force damage, resulting in the deformation of the slope [9]. It is relatively consistent with the small safety coefficient obtained from the calculation, which indicates that the use of FLAC3D to analyse slope stability is a reasonable and feasible method.

4. Discussion

Slope stability has a great impact on production safety, once a landslide occurs, it not only affects production, but also directly threatens the safety of personnel and equipment during operation [10]. Continuous improvement of the slope stability evaluation method is not only conducive to the safe construction of multi-disciplinary projects, but also can bring good benefits to the national economy. Therefore, it is necessary to continuously explore, develop and improve new slope stability analysis methods.

The use of FLAC3D software to build a geotechnical slope model can better simulate its strain phenomenon, so that the calculation results can better reflect the real characteristics of the geotechnical body and be closer to the engineering reality. In this paper, FLAC3D software is used to build a slope model to simulate the strain phenomenon of a high slope section of a motorway, and the calculation results show that the safety coefficient of this slope section is 1. 038, which is smaller than the safety value specified in the specification, indicating that the slope in this section is currently in a stable state, but it is unstable in terms of the safety coefficient, and it should be optimized in design and construction, and the measures such as changing the slope rate and installing slope support structures should be taken to ensure that the slope is in a stable state. The slope should be further optimized in terms of design and construction by changing the slope rate, installing additional slope support structures and other measures to ensure the stability and safety of the slope. In addition, the upper part of the slope and the top of the slope are more unstable than the lower part of the slope and are more prone to destabilization damage, so reinforcement should focus on protecting this part.

From the simulation results in this paper, it seems that it is feasible to calculate the safety coefficient of the slope of the motorway section and analyses the stability of the slope by FLAC3D software using the strength discount method, and the software can provide us with a large amount of analytical data and graphs of stresses and displacements, so that we can understand and analyses the state of the model more intuitively, which shows that the application of FLAC3D software in the evaluation of the stability of the slope is of practical significance, and the calculations are relatively convenient and fast.

References

[1] Griffiths D V, Lane P A. Slope stability analysis by finite elements [J]. Geotechnique, 1999, 49(3):387-403.

[2] Jin Fucheng. Research status and prospect of slope stability analysis methods. West Prospecting Engineering, 2007;19(4):5~8

[3] Peng Wenbin. FLAC 3D practical tutorial [M]. Beijing: Machinery Industry Press, 2007.

[4] ZIENKIEWICZOC, HUMPHESONC, LEWIS RW. Associated and nonassociated visco-plasticity and plasticity in soil mechanics [J]. Géotechnique, 1975, 25(4): 671 –89.

[5] Lowe J,Karaflath L. Stabiliy of earth dams upon drawdown[M] .Proc.lst Panamer Conf.Soil Mech, Mexico City,1960: 537-552.

[6] Itasca Cons ulting Gr oup Inc .FLAC3D manuals. 2006

[7] LIN Honglei, OU Yuan. Slope stability analysis based on strength reduction method in FLAC 3D [J]. Sichuan Construction, 2010, 30, (1): 87-88.

[8] Pei Yangyang, Pu Rui, Guo Yaxin. Management of dangerous rock body of No.1 and No.2 inverted siphon of Xiaoyu Dam in Dianzhong Water Diversion Project [J]. Yunnan Hydropower, 2021, 37(06):48-53.

[9] ZOU Guoqing, PAN Shijiang. Research on safety risk assessment method and application of highway graben high slope construction considering geological classification [J]. Hunan Transportation Science and Technology, 2021, 47(2):66-69.

[10] Zhang Yongxing. Slope Engineering [M]. Beijing: China Ar-chitecture & Building Press, 2008. ZHANF Yongxing. Slope engineering [M].