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STABILITY ANALYSIS OF A ROCKY SLOPE CONSIDERING EXCAVATION UNLOADING EFFECT

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ABSTRACT

The rock mass encountered in actual geotechnical engineering usually undergoes long-term digenesis and geological tectonic action, and also subjected to repeated actions of loading and unloading repeatedly. This paper aims to study the influence of excavation unloading on the stability of a rocky slope, and the slope excavation process of Jinping Grade I Hydroelectric Station was selected as a case, and the 2D finite element software PLAXIS was used to evaluate the effect for the slope stability of without considering unloading and considering unloading, including stress, safety factor, plastic deformation zone and slip surface of the slope. The results show that the slope excavation unloading has a significant influence on the stress, stability safety factor, plastic deformation zone and slip surface, the stability of slope with considering unloading is far less than without considering unloading significantly. Therefore, the numerical method used to simulate the excavation of rocky slopes should consider the effect of unloading fully to service the engineering design and ensure the safety of engineering construction.

KEY WORDS

Jinping Grade I Hydroelectric Station, Unloading effect, Slope stability, Finite element

INTRODUCTION

Most of the existed rock masses are damaged and undergone various functions and contain a large number of jointed fissures. When the natural rock mass excavated, the unloading process is the further release process of the residual stress, which could cause the internal stress state of the rock mass to change. Reasonable evaluation of the extent and depth of rocky slope excavation unloading damage could guide engineering design and ensure project safety, and this has become a key technical issue in hydropower project construction.

Haqiuling proposed the concept of unloading rock mechanics 23 years ago, and the basic theory has been accepted by many scholars (HA Qiuling and LI Jianlin 1996; HA Qiuling 2001). In recent years, many experts and scholars have carried out a lot research on the unloading depth of rock excavation. Such as, Zhao Xiaoyan analyzed the distribution range and variation characteristics of the slope excavation relaxation zone in a centrifugal model test, and proposed using the displacement as the criterion to determine the width of unloading zone (Zhao Xiaoyan et al. 2005). The excavation process of a typical rocky slope was used to study the maximum principal stress increment and the mechanical characteristics and distribution law of the plastic deformation zone, and proposed to adopt the variation of the maximum principal stress component as the criterion for the excavation unloading and relaxation zone(Wang Hao and Liao Xiaopin

2007). Based on the qualitative analysis of the unloading relaxation process and mechanism of rocky slope excavation, Feng Xuemin advised using the ultimate tensile strain of rock mass as the criterion for unloading relaxation (Feng Xuemin et al. 2009). According to the basic idea of statistical rock mechanics, Wu Faquan proposed to determine the depth of unloading damage by the magnitude of unloading strain (Wu Faquan et al. 2009).

At present, with the construction of a large number of infrastructures in the world, involving water conservancy, transportation and civil buildings, such as hydropower slope excavation, tunnel construction and foundation pit excavation, all involved a large number of rock mass excavation, inaccurately assess the extent and size of the unloading of rock masses may result in serious safety incidents. Moreover, the analysis of slope rock excavation using unloading rock mechanics theory is mainly based on qualitative analysis, and there is little research on quantitative analysis of rock mass unloading effects. Therefore, in this paper, the slope excavation of Jinping Grade I Hydroelectric Station in China is taken as a study case to analyze the influence of excavation unloading on the stability of slope rock mass quantitatively.

MATERIALS AND METHODS

A large number of engineering practices and theoretical studies have shown that the unloading action is equivalent to apply a reverse tensile stress in rock mass under initial stress (LI Jianlin 2003; DENG Huafeng et al. 2009).Therefore, in the process of numerical analysis, the stress state before unloading of the rock mass can be regarded as the initial stress state, and the unloading stress can be regarded as a kind of tensile stress on the rock mass. The maximum value is $\sigma_0 + R_t$ （$\sigma_0 + R_t$ is called equivalent tensile_strength of rock mass). In this way, the unloading calculation can be divided into two steps: superposition the unloading stress Δσ and the pre-unloading stress σ , as shown in the Figure1:

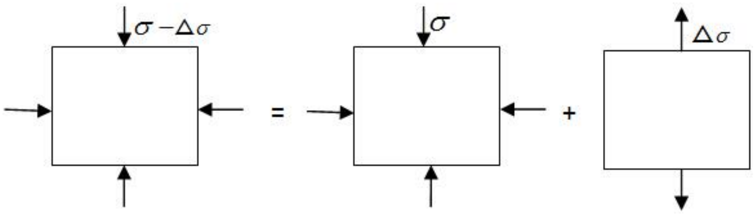

Fig.1 - Schematic diagram of unloading stress

The specific calculation process is as follows:

Firstly, the stress field σ_0 and the displacement field u_0 of the rock mass under the initial stress; then the stress field $\sigma_{\Delta 1}$ and the displacement field $u_{\Delta 1}$ of the rock mass under the unloading stress Δ_σ are calculated; finally, by superposing the stress fields, the stress field σ_1 and the displacement field u_1 with the unloading amount Δ_σ can be obtained.

$$\sigma_1 = \sigma_0 + \sigma_{\Delta 1} \tag{1}$$

$$u_1 = u_{\Delta 1} \tag{2}$$

When calculating the i-th unloading, the stress field $\sigma_{\Delta i}$ of rock mass should be solved first when the i-th unloading $\Delta_{\sigma i}$; later, the stress field σ_{i-1} and the displacement field u_{i-1} of the *i-1*th time are superimposed, and the stress field σ_i and the displacement field u_i at the i-th unloading are calculated.

$$\sigma_i = \sigma_{i-1} + \sigma_{\Delta i} \tag{3}$$

$$u_i = u_{i-1} + u_{\Delta i} \tag{4}$$

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In the slope engineering, under the action of mass excavation and unloading of the rock mass, the stress relaxation and even tensile stress will occur within the influence range, the mechanical conditions of the structural plane in rock mass will change substantially, the quality of rock mass will deteriorate rapidly, and its mechanical parameters will drop sharply. It is indicated that the unloading rock mass mechanics is sensitive to anisotropic and tensile strength of rock mass *Rt*. At present, the division of relaxation zone by excavation unloading in rock mass is mainly calculated by the unloading percentage. The formula is:

$$\text{Unloading percentage}=\frac{\Delta\sigma}{\sigma_0+R_t}\times 100\% \qquad (5)$$

Where the $\Delta\sigma$ is the amount of change in stress before and after unloading. σ_0 is the initial stress before excavation. R_t is the tensile strength of rock mass.

Some different unloading areas are divided according to the degree of unloading percentage, and the deformation modulus of rock mass in different influence areas is reduced appropriately. Based on relevant information, the reduction percentage is shown in the table 1(Yi Qinglin et al. 2009; Yi Changping et al.2005; Li Jianlin and Yuan Daxiang 2001).

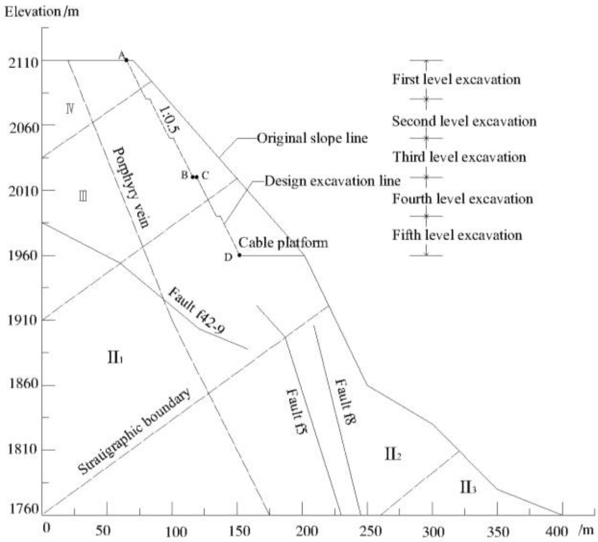
Tab. - 1 Reduction percentage of deformation modulus of slope rock unloading

Unloading percentage/%	Percentage decrease in deformation modulus/%
<30	<10
30～50	10～30
50～80	30～50
80～100	50～80

MODEL AND PARAMETERS

We have selected the slope excavation of cable platform of Jinping Grade I Hydroelectric Station in China as the study case. Lamprophyre veins at the cable platform pass obliquely from the back edge of the slope and buried deep, the f_5、f_8 faults pass through the leading edge of the lower elevation of the cable platform, the $f_{42\text{-}9}$ fault develops deeper inside the f_5, shown in Figure2.

The study range of finite element model: 400m in the horizontal direction and 350m in the vertical direction, the material model is the Mohr-Coulomb elastoplastic model. The slope of the simulated cable platform is excavated at the slope ratio of 1:0.5, and the excavation is carried out in 5 levels. Each level of excavation is 30m height and set a 3m width road, the total excavation height is 150m. In the calculating process, it is necessary to consider the self-weight stress, but ignore the tectonic stress for the initial stress field. We follow the two-dimensional plane strain assumption, and the influence of groundwater is unconsidered due to the groundwater level is deeply buried. And the finite element mesh model of slope and boundary of the slope is shown in Figure 3.



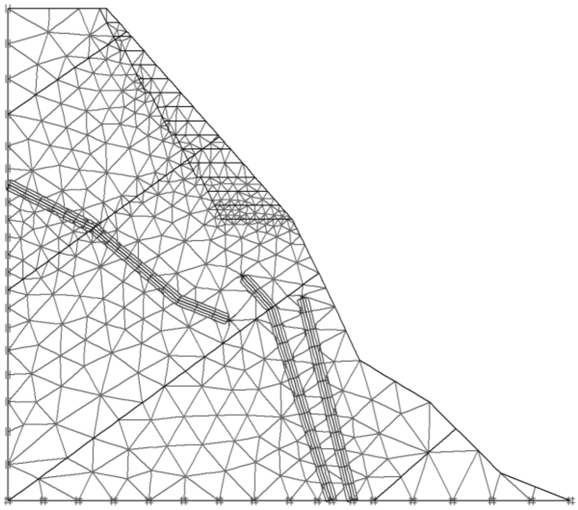


Fig.2 - Sketch diagram of slope excavation for cable crane platform of Jinping I Hydropower Station Fig.3 - Finite element mesh model and boundary of the slope

In the process of finite element calculation, whether the rock mass strength parameters are accurate it has a great influence on the result. Studies have shown that strength of rock mass mechanical parameters in all areas of the unloading rock mass have a decreasing trend, and tend to be stable finally (LI Jianlin 2003). Slope excavation will reduce the rock mass stiffness and strength, such as the elastic modulus, cohesion and internal friction angle and tensile strength decreases, but Poisson's ratio will increase. Based on the unloading rock mass mechanics, the unloading range is obtained by the percentage of unloading amount, and the mechanical parameters of rock mass are obtained by combining and zoning.

The strength parameters of rock mass after excavation are reduced according to the percentage of excavation unloading. In this paper, the reduction is based on the percentage of unloading Table 1. After calculation, the unloading percentage of the rock mass near the excavation is more than 80%, so the original strength parameters of the rock mass are reduced, in this paper, such as the elastic modulus is reduced by about 25%, and other parameters such as cohesion are reduced by about 40%. Thus, the key parameters used are shown in Table 2.

Furthermore, the alternative thickness of rock mass material is determined by the increment of shear strain. The thickness of the first three excavation step is 15m, the fourth excavation is 24m and the fifth excavation is 18m. After each excavation, immediately replace the rock mass material caused by this excavation with the reduced rock mass parameters, and conduct stability analysis, then carry out the next excavation, and then replace the rock mass parameters affected by this excavation stage. After each excavation stage, the stability of rock mass is analyzed with smaller strength parameters, so the stability of rock mass in each stage is reduced, and the sliding fracture surface is also distributed along the replacement depth of rock mass material.

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Tab. .2 - Mechanical parameters of rock mass

Geological material	Elastic Modulus /GPa	Poisson's ratio	Density /kg/m^3	Cohesion /MPa	Internal friction angle/°	Tensile strength/MPa
Type IV rock mass	2.0	0.33	2700	0.6	30	1.01
Type Ⅲ rock mass	3.2	0.30	2700	1.0	35	1.15
Type Ⅱ$_1$ rock mass	4.7	0.25	2700	2.2	42	1.3
Type Ⅱ$_2$ rock mass	10.0	0.23	2700	2.8	50	1.3
Type Ⅱ$_3$ rock mass	6.0	0.23	2700	2.0	40	1.3
Fault f_{42-9}	0.6	0.34	2400	0.1	23	0.3
Fault f_5	0.8	0.35	2400	0.2	23	0.5
Fault f_8	0.8	0.35	2400	0.2	23	0.5
Unloading rock mass1	1.5	0.40	2300	0.22	15	0.84
Unloading rock mass2	2.4	0.39	2500	0.35	17.5	0.97
Unloading rock mass3	3.53	0.37	2700	0.65	20	1.07

Note: The unloading rock mass parameters only consider three rock masses involved in excavation, and the other rock mass parameters keep unchanged.

This excavated simulation takes the following two calculation terms into account:

Calculation term 1: Without considering of unloading effect. The effect of unloading on rock mass is not considered in the whole calculation process, and the initial mechanical parameters of rock mass are used to calculate.

Calculation term 2: Considering unloading effect. Adopting the analytical method which can reflect the nonlinear characteristics of unloading rock mass, the mechanical parameters of unloading rock mass are dynamically selected according to different excavation levels, so that the numerical calculation is basically consistent with the actual stress of rock mass.

RESULTS AND DISCUSSIONS

Stress analysis

In order to analyze the effect of excavation unloading on stress distribution of rocky slope, the major principal stresses of each monitoring point shown in Figure2at different excavation steps and results are listed in Table 3, we stipulate the tensile stress is positive and the compressive stress is negative. It can be found that the major principal stress values of each feature point are negative values under natural conditions, which shows that they are under compression. The stress state of each monitoring point changes continuously along with the excavation of the slope under the two calculation terms.

When the unloading effect unconsidered, the compressive stress at points A and C decreases after excavation of the upper rock mass, which is regard as stress relaxation, and the compressive stress at points B and D increases gradually, which appears as stress strengthening. Since points B and D are located at the foot positions of different steep slopes, they are excavated by the upper right side of the rock mass, resulted in stress releasing and unable to counteract the earth pressure from the left side, so it is under compression.

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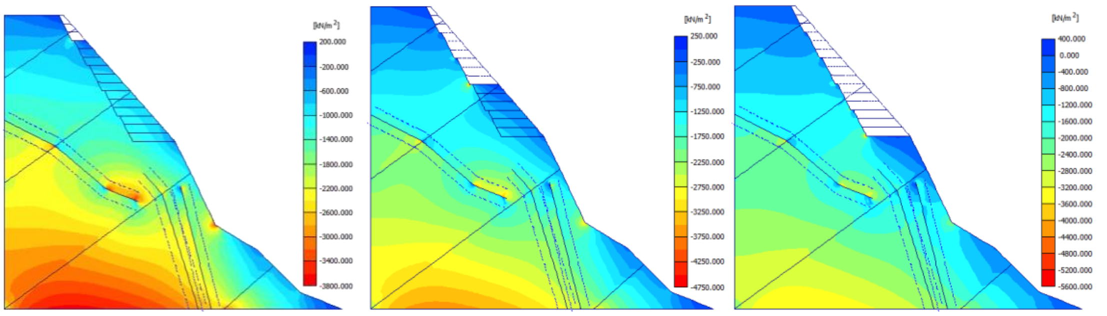
Tab.3 - Main stress of monitoring points in different conditions/MPa

Excavation steps	Calculation terms							
	Regardless of unloading effect				Considering unloading effect			
	A	B	C	D	A	B	C	D
Natural state	-0.26	-2.14	-2.17	-3.01	-0.26	-2.14	-2.17	-3.01
First level	-0.07	-2.03	-2.06	-2.94	-0.03	-2.01	-2.04	-2.91
Second level	-0.07	-1.87	-1.83	-2.78	-0.03	-1.75	-1.72	-2.73
Third level	-0.07	-7.22	-3.09	-2.52	-0.03	-1	-0.98	-2.32
Fourth level	-0.07	-3.9	-0.55	-2.33	-0.04	-0.03	-0.06	-1.88
Fifth level	-0.07	-3.72	-0.52	-7.28	-0.04	0.19	-0.06	-1.46

When considering unloading, the compressive stress of four points is reduced obviously, and appeared relaxation after the excavation completed. The compressive stress value of point D at the foot of slope is particularly different at the two conditions, 7.28 MPa and 1.46 MPa, show all monitoring points appear stress relaxation. In particular, a tensile stress zone will appear near point B, the tensile stress at point B is 0.19 MPa, which could cause adverse effects on the local stability of the slope.

In order to analyze the stress state of rock mass in different excavation stages comprehensively, the average effective stress (σ_m) of rock mass under two calculation terms is shown in Figure 4 and Figure 5 ($\sigma_m = (\sigma_{max}+\sigma_{min})/2$), which is the average value of the maximum and minimum stresses on a certain section of a unit, and the maximum principal stress and the minimum principal stress are considered. Figure 4 shows the average effective stress distribution of the rock mass without considering the unloading excavation slope, yet Figure 5 shows the average effective stress distribution of the rock mass with considering the unloading excavation slope. The unit of σ_m is kN/m^2 (kPa), we also stipulate the tensile stress is positive and the compressive stress is negative.

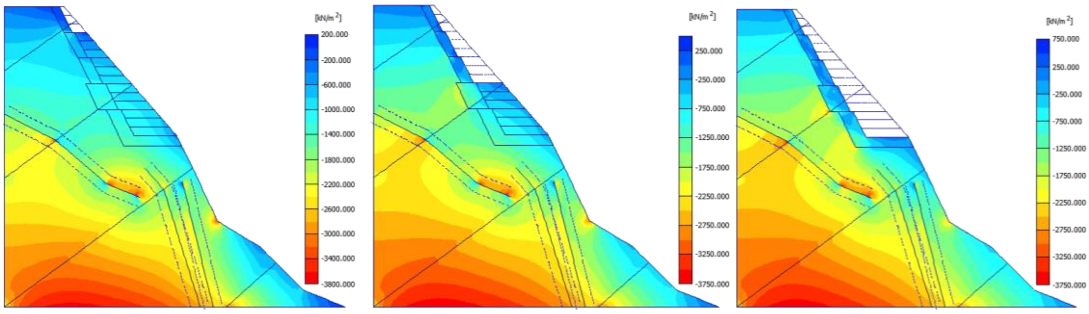


(a) Excavation 30m (b) Excavation 90m (c) Excavation 150m

Fig. 4 - The average effective stress of rock mass without considering unloading

As shown in Figure 4, when the unloading effect is without considering, the average stress near the excavation changes gradually with the increasing of the excavation depth, the average stress of the lower platform rock mass is small due to the empty surface formed by excavation, indicate that most rock mass are under compression and only a small part under tension, it should be noted that the stress concentration phenomenon exists at the foot of the slope after each step of excavation, which is expressed as compression, and the stress relaxation in the rock mass near a certain depth of the excavating surface is not obvious, which is inconsistent with reality. It shows that the software can only consider the load release caused by excavation of the upper rock mass, but it cannot evaluate the unloading effect automatically caused by the excavation. Therefore, it is necessary to carry out artificial calculation and evaluate the impact scope of excavation unloading.

As shown in Figure 5 below, when considering the unloading effect, the average stress near the excavation surface changes obviously and the unloading relaxation effect increased gradually with the increasing of the excavation depth, which is manifested that the tensile stress of the rock mass increases within a certain depth of the excavation surface, however, the compressive stress is reduced gradually. In addition, when the excavation depth reaches 90m, the tensile stress of the local rock mass can reach 250kPa, after the excavation of 150m, the tensile stress of the local rock mass can reach 750 kPa and the range of stress relaxation is further expanded, which indicates that the rock mass under tensile near the excavation face is obvious, and could cause a potential local collapse.



(a) Excavation 30m (b) Excavation 90m (c) Excavation 150m

Fig. 5 - The average effective stress of rock mass with considering unloading

The results above illustrate that comparing with the case without considering unloading effect, the numerical simulation analysis of slope excavation with considering unloading effect can evaluate the stress damage of rock mass caused by excavation and determine the influence range of unloading more accurately.

Slope stability safety factors

In addition, the finite element strength reduction method is used to calculate the safety factor of slope stability during the excavation process. The real shear strength of slope rock mass is divided by a reduction factor F to achieve the purpose of strength reduction until the ultimate failure state reached. According to the elastic-plastic finite element calculation results, the critical slip surface of slope is obtained, and the reduction factor F represents the stability safety factor of slope (Zheng Yingren et al. 2002; Li Rongjian et al.2010; Zhao Chuan and Fu Chenghua 2015). The formulas are as follows:

$$c' = \frac{c}{F} \tag{6}$$

$$\varphi' = \arctan\frac{\tan\varphi}{F} \tag{7}$$

Where c and φ are the real cohesion and internal friction angle of rock mass, c' and φ' are the reduced cohesion and internal friction angle.

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Table 4 shows the stability safety factors of excavated slope at different levels under the two calculation terms. The comparative analysis shows that when unloading is without considering, the safety factor changes little along the excavation steps, even tends to increase. It may be inferred that due to the reduction of the slope sliding force and the improvement of the overall stability of the slope after excavation of the upper rock mass. The safety factor is 1.99 after excavation complete, compared with the safety factor of 1.93 under the initial condition, it increases 0.06, which is inconsistent with the phenomenon that the slope stability will reduce due to the actual excavation.

When the unloading action is considered, the rock mass near the slope is affected by excavation, the strength of rock mass decreases obviously, and the safety factor decreases gradually along with the excavation, and reaches the minimum value 1.32 after the fifth excavation. It can be seen that the change law of slope stability safety factor is different under the two conditions, and the slope stability safety factor is smaller when considering unloading than without considering.

According to the results of the Table 4, it is indicated that the results obtained without considering the unloading effect are pretty unreasonable, and it is also very dangerous for the engineering design when ignore the rock mass relaxation effect caused by excavation to use the results directly obtained without considering the unloading effect.

Tab.4 - Safety factors of rocky slope in different excavation levels

Excavation condition	Gravity	Level 1	Level 2	Level 3	Level4	Level 5
Without considering of unloading effect	1.93	1.93	1.96	1.96	2.00	1.99
Considering unloading effect	1.93	1.77	1.60	1.48	1.40	1.32

Distribution of plastic zone and slip surface

In order to further analyze the plastic deformation zone of the internal rock mass during the excavation of the slope rock mass accurately, Figure 6 and Figure 7 show the plastic deformation zone distribution of the slope in different excavation steps under two conditions (the red point represents the plastic point, and the white point reflects the tensile failure zone). It can be seen from Figure 6 that when the unloading effect unconsidered, the plastic zone distribution range of the slope changes a little along with the increase of the excavation depth, and there is a tendency to decrease. The plastic zones are distributed in the interior of the three faults, mainly appear in fault $f_{42\text{-}9}$, while faults f_5 and f_8 are few relatively. When the excavation reaches 60m and 90m, a few plastic points appear at the foot of the slope formed by excavation. It shows that the rock mass in the structural plane along the strike of the slope is more likely to be destroyed. Because the fault $f_{42\text{-}9}$ terminates in a certain depth of the slope and does not penetrate into the slope surface, the overall slope can remain stable at this time, and the safety factor is 1.99.

As shown in Figure 7, when the unloading effect is considered, the plastic zone distribution range of the slope will increase greatly with the increase of the excavation depth, which is mainly reflected in the unloading rock mass surface formed by excavation. In addition, after excavation depth of 150 m, the red plastic zone almost penetrates the unloading rock mass, which has a great impact on the overall stability of the slope, and the plastic failure is most obvious at the foot of excavated slope. It is well consistent with the analysis results of the stability safety factor.

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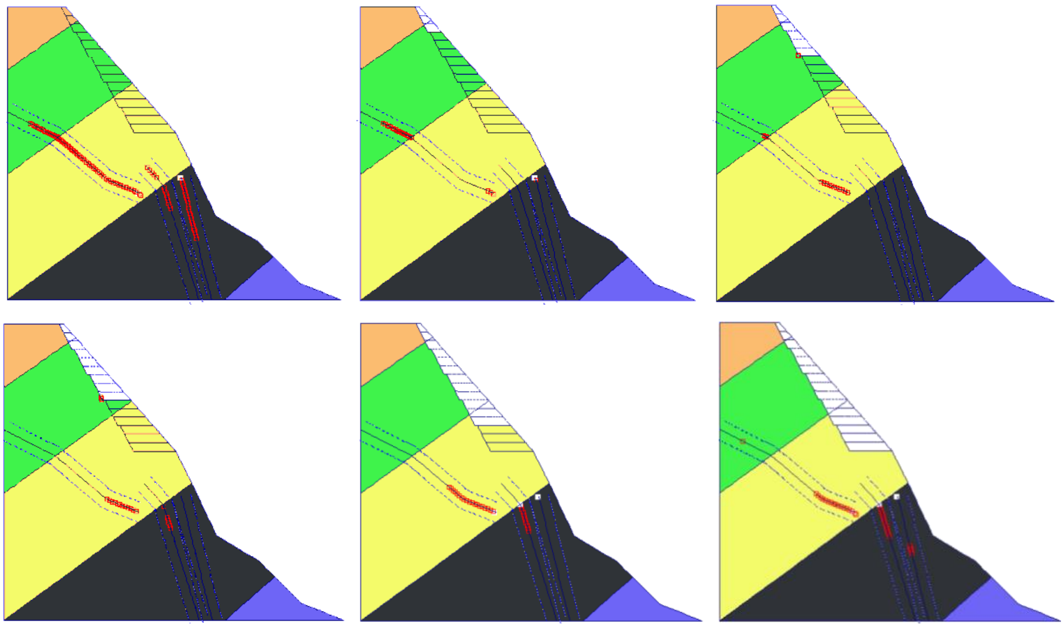

Fig. 6 - The plastic points distribution of rock mass without considering unloading

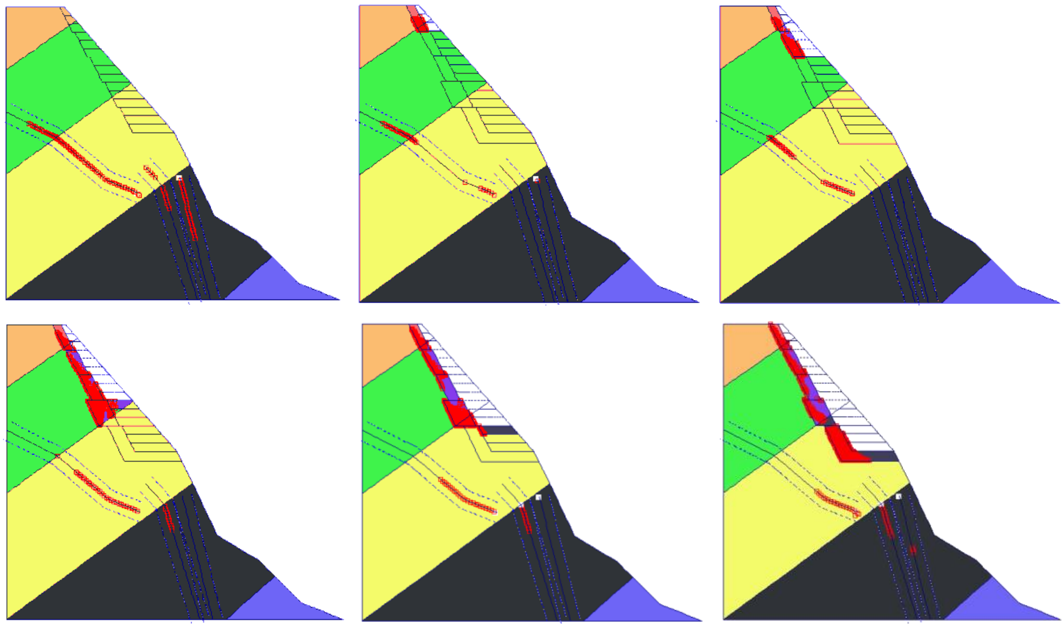

Fig.7 - The plastic points distribution of rock mass with considering unloading

The above analysis of the plastic zone shows that whether the unloading effect is considered it has a great influence on the results of the plastic failure range of rock mass. When unloading is not considered, the plastic point of slope only exists in the fault, but when unloading effect is considered, the plastic point mainly distributes in the rock mass within a certain depth from the excavated slope surface, and forms a large area of plastic point concentration at the foot of the slope.

When the stability of the slope is solved by the finite element strength reduction method, the slope will gradually slide along the critical slip surface with the increase of the reduction factor. In order to analyze the potential slip surface of the slope under different conditions and different excavation heights, the position where the slope may be damaged under the limit equilibrium state is obtained. Figure 8 shows the results without considering the unloading, and Figure 9 indicates results considering unloading effect, and the colour gradually changes to red, indicating that the sliding occurred here is very obvious.

As shown in Figure 8, all the critical slip surface of the slope is deep along the fault $f_{42\text{-}9}$. It is indicated that in the process of excavation, if the unloading effect is not considered, when the slope rock mass reaches the ultimate failure, the position of the slip surface obtained in each excavation stage is the same, which is not consistent with the actual situation.

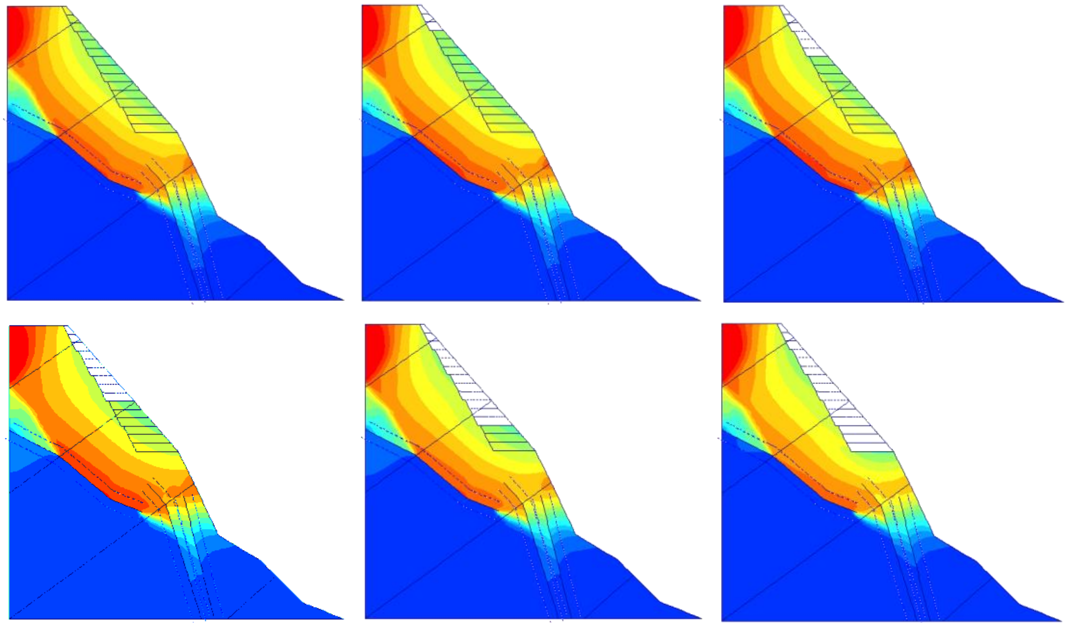

Fig.8 - The slip surface of slope without considering unloading

In order to make a comparative analysis with the above results, the critical slip surfaces with different excavation heights when considering unloading effect are given in Figure 9. The result shows that with the increase of excavation depth, the position of critical slip surface changes gradually, which is very different from that shown in Figure 8 above. Considering the unloading effect, the slip surface is distributed within a certain depth range to form an arc slip shape, and extend downward gradually as the excavation depth increases, the shear foot is formed from the excavation until the excavation is completed. At this time, the volume of potential landslide body is much smaller than that when unloading is not considered, the safety factor of the slope is also smaller. It shows that if the unloading effect of rock mass excavation is reasonably considered, the scope of rock mass damage caused by excavation can be obtained, and the location of possible slope sliding can be determined, which can provide reference for the corresponding reinforcement measures after slope excavation, such as the length and depth of bolt reinforcement in bolting and concreting support, and the size setting of the pre-stress applied.

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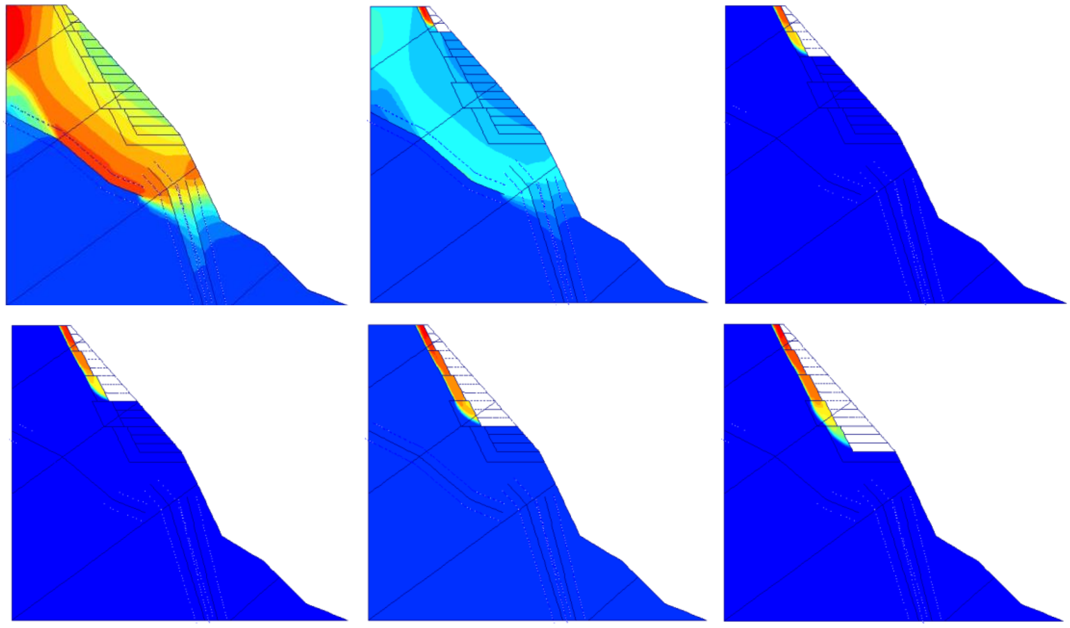

Fig.9 - The slip surface of slope with considering unloading

CONCLUSIONS

In this paper, the excavation process of the high-steep slope of the cable platform of Jinping Grade I Hydroelectric Station is simulated and analyzed by PLAXIS. It is found that whether the unloading effect is considered it has a great influence on the stability analysis along with the slope excavation. When the unloading effect during rock mass excavation is considered, the stress relaxation of slope excavation is more obvious than when the unloading effect is not considered.

Tensile stress will occur in some areas, which is mainly reflected in the internal rock mass stress distribution affected by excavation. With the gradual excavation of the slope, the safety factor of stability does not change much when unloading unconsidered, and ultimately is 1.99. However, the safety factor of the slope decreases gradually with the increasing of excavation depth when unloading effect considered, the safety factor is 1.32 finally after excavation complete. The distribution of plastic zone and critical slip surface is different under the two conditions. When unloading is not considered, the relationship between the scope of slope plastic zone and excavation depth is very small, and mainly concentrated in the interior of three faults, when unloading is considered, the plastic failure zone mainly concentrates in the interior of rock mass near the excavation surface of slope.

There are different critical slip surfaces in the two conditions, and the slope stability is worse when unloading is considered than unconsidered. If the unloading effect is not taken into account, the critical slip surfaces of the slope are the same location along fault $f_{42\text{-}9}$ in each excavation stage. However, when the unloading effect considered, the location of the critical slip surface changes gradually with the increasing of the excavation depth, and it is distributed along a certain depth range of the rock mass excavation unloading affected area, formed an arc slip shape, and extending downward gradually.

Therefore, it is suggested strongly that the deterioration of rock mass caused by excavation should be fully considered for numerical simulation in the future, and the whole excavation unloading process need to be simulated reasonably, so as to provide more accurate reference for engineering design and construction.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] HA Qiuling, LI Jianlin (1996) Study on macroscopic mechanical parameters of unloading rock mass on rock slope. Beijing: China Architecture & Building Press.

[2] HA Qiuling (2001) Simulation analysis for rock mass engineering and rock mass mechanics-The study on anisotropic excavation unloading rock mass mechanics. Soil and Rock Engineering Journal 23(6): 664-668.

[3] ZHAO Xiaoyan, HU Houtian, PANG Liexin (2005) Study on unloading effect and width of unloading zones in excavating of soil-like material slopes. Chinese Journal of Rock Mechanics and Engineering 24(4): 708-712.

[4] WANG Hao, LIAO Xiaopin (2007) Research on the mechanical character of relaxing zone of slopes due to excavation. The Chinese Journal of Geological Hazard and Control 18(sup): 5-9.

[5] FENG Xuemin, CHEN Shenghong, LI Wengang (2009) Research on unloading relaxation criterion of high rocky slope excavation and its engineering application. Rock and Soil Mechanics 30(sup2): 452-456.

[6] Wu Faquan, Liu Jianyou, Liu Tong (2009) A method for assessment of excavation damaged zone (EDZ) of a rock mass and its application to a dam foundation case. Engineering Geology 104: 254-262.

[7] LI Jianlin (2003) Unloading rock mass mechanics. Beijing: China Water & Power Press.

[8] DENG Huafeng, LI Jianlin, YI Qinglin (2009) Research on unloading deformation of soft high slope. Rock and Soil Mechanics 30(6): 1731-1734.

[9] YI Qinglin, DENG Huafeng, WANG Lehua (2009) Study on unloading deformation of one highway slope. Chinese Journal of Underground Space and Engineering 5(1): 139-143.

[10] YI Changping, LU Wenbo, XU Hongtao (2005) Study on effects of dynamic unloading on initial. Chinese Journal of Rock Mechanics and Engineering 24(sup1): 4750-4753.

[11] LI Jianlin, YUAN Daxiang (2001) Basic method for analyzing unloading of rock mass. Journal of China Three Gorges University (Natural Sciences) 23(1):1-6.

[12] ZHENG Yingren, ZHAO Shangyi, ZHANG Luyu (2002) Slope stability analysis by strength reduction FEM. Engineering Science 4(10): 57-62.

[13] LI Rongjian, ZHENG Wen, SHAO Shengjun (2010) Comparison analyses on stability of unsaturated soil slopes by strength reduction FEM and slice method. Journal of Northwest A &F University (Natural Science Edition) 38(9): 207-214.

[14] ZHAO Chuan, FU Chenghua (2015) Stability analysis of slope in a hydropower station with local strength reduction method. Pearl River 18(3): 66-69.