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Study on Deformation and Failure of Toppling Deformation Slope of Miaowei Hydropower Station under Storage Condition

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Abstract. With the completion and operation of hydropower stations in Southwest China, the stability of reservoir slope is impacted by the change of water level during reservoir storage and operation. It has become an important engineering geological problem in the design and operation of hydropower stations. Taking the Miao River Hydropower Station in Lancing River Basin as the research object, the structural characteristics of the bank slope and the influence of reservoir impoundment are analyzed. The deformation of the slope rock mass in the reservoir area is serious. During the reservoir storage, the stability of the bank slope is outstanding. In order to analyze the influence of the change of water level on the stability and failure mode of the tilting deformable body on the bank slope under the condition of water storage, through the numerical simulation analysis, using UDEC discrete element software after impoundment, it is concluded that after water storage, the strength of rock mass is reduced, and the failure mode changes from sliding failure to collapse and failure, but the stress field of the slope has little change.

1. Introduction

In the mountains and valleys of southwest China, the geological tectonic movement is strong, and various physical and geological phenomena are widely distributed. The slope of the reservoir of Miaowei Hydropower Station contains a lot of toppling deformation body, and there are a lot of natural villages and related infrastructure in the reservoir area, as a result, on the conditions of the water level change in the process of impoundment and operation, the stability of slope which composed of toppling deformation body has become one of most important problems of engineering geology. In addition, in the process of impoundment, the change of water level will reduce the effective stress of the rock, which resulting in a loss of slope stability, and affect the toppling deformation body, which may produce high-speed surge formation to endanger the dam, so the research of the deformation and destruction of toppling deformation body, on the condition of impoundment, is of great significance [1-3].

At present, scholars at home and abroad have made some achievements in the mechanism and evolution of the toppling deformation body. R. e. Goodman and j. w. Bray [4] divide the forms of deformation and destruction into three categories, bending type, rock type and bending-rock type. And they based on limit equilibrium theory to put forward the method of toppling stability, G-B method for short; Han Beechen and Wang Siding [5] believe that the existence of the anti-dumping structure has a decisive control effect on the toppling deformation body of the slope; Li Yuliana [6] come up with the conclusion that the failure mode of slope rock depends on the structure characteristics of the slope rock, and, with the different intensity of deformation, the inside of rock shows the different forms of fracture, the mechanical mechanism and the phenomenon of characteristic deformation; according to Zhang Shisha [7], the toppling deformation body have the deformation characteristics of "crack - toppling - bending - breaking - gravity falling". At present, more mature research results have been made on the damage forms, deformation characteristics and mechanical mechanism of the toppling deformation body, but relatively few studies have been done on the stability of the slope consisted of toppling deformation body on the condition of impoundment. Based on the background of engineering geology of the reservoir area of Miaowei Hydropower Station, the change of stress and strain of slope on the condition of impoundment was analyzed by using discrete element method, and its stability was evaluated. The result has enriched the mode of deformation and destruction of rock slope consisted of toppling deformation body on the condition of impoundment, which has certain theoretical and practical significance.

2. The characteristics of toppling deformation body

2.1. General situation of engineering geology in the research area

Lancing River Miaowei Hydropower Station is located in Yun Long County, Yunnan province. Within the territory, the area is a typical mountain valley landform, and the tectonic activity is obvious and the rock formations are abrupt. Here are the main strata in the reservoir area: the Huakaizuo group (J2h) in the Middle Jurassic, which are deep grey, lime-green kills and mudstone; and the Buzau Road group (J3b) in the Upper Jurassic, which are aubergine mudstone and kills; and Jinxing group in the Lower Cretaceous (K1j), which are interlayer of different thicknesses consisted of greyish-green quartz sandstone and aubergine kills, quartz sandstone and mudstone. The phenomenon of toppling deformation body of the slope is serious, which has obvious effects on the safety of the reservoir.

Miaowei Hydropower Station has developed a quantity of toppling deformation body which mainly distributes in the reach from Aaden Village to Snakeskin River. Through field investigation, and the left bank is from Tue Village to Snakeskin River, and the right bank is from Aaden Village to Well Village. The toppling deformation body is 1.0 ~ 54.6 km away from the dam. This paper took QD9 as an example to study the topography, and its full appearance of slope is shown in figure 1. The toppling deformation body of QD9 is located in the reservoir section between Lengshuichang River and Ouyang River, which is about 20.7 km away from the dam, and the toppling deformation body is distributed on the low-altitude slope. The form of this reservoir section of Lancing River is slightly crooked, and the direction of the river is SE25°~ SN. And the elevation of slope toe in the right bank is about 1340 m, and the top is about 2200 m, and the gradient of upper slope is gentle incline about 30°~ 40°, and the middle to lower part of slope lowest is a bit steep about 50°~ 60°. The slope toe has developed multiple small ditch. Most of the slope surfaces are exposed, and the toppling deformation body is strongly developed under the elevation of 1520 m.

Figure 1. Panorama of bank slope of QD9 toppling

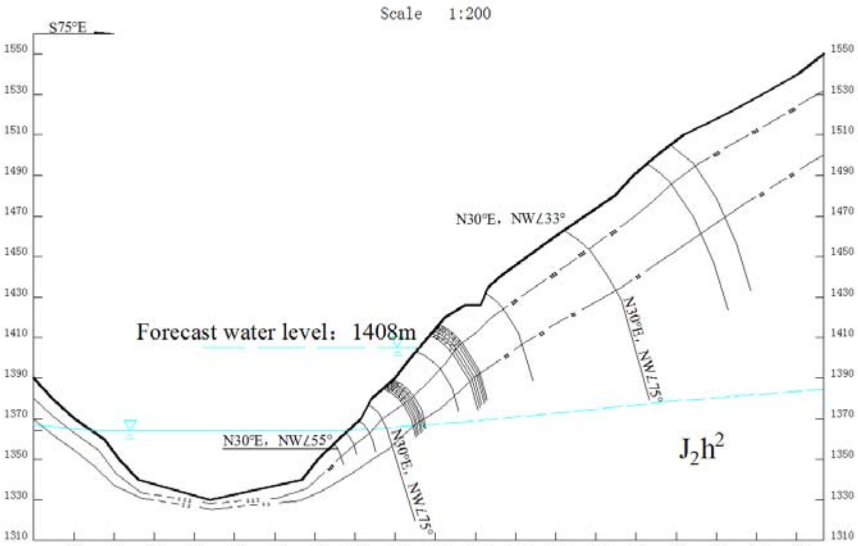

Figure 2. The geological profile of QD9

The bedrock lithology of reservoir bank is the Huakaizuo group (J2h2) in the Middle Jurassic, which are aubergine, greyish-green slate with saltire and packs and, for Jurassic left group (J2h2) purple flowers, green slate clip the powder sandstone, fine sandstone. The toppling deformation body of bedrock has developed strongly, which is highly ~ weakly weathered and is extremely fragmentized, and the occurrence of stratum is N30° ~ 45°E, NW <10°~ 45°; one set of joint in the outside of steep slope has developed, and the occurrence is N15° ~ 20°E, SE < 70° ~ 75°, and the spacing is 20 cm ~ 40 cm. The slope under the highway heaps with gravelly soil artificially, and the part of the slope toe is covered with a little of collapsed cumulate gravelly soil. No flow out point of groundwater was found in the area. The geological profile of the slope is shown in figure 2.

Figure 3. Structure characteristics of bank slope

Figure 4. The dip angle near the riverbank

2.2. The characteristics of slope structure

The structure characteristic of reservoir slope mainly includes two aspects: one aspect is the slope shape, including the slope height and slope angle, and the total length of Miaowei reservoir is about 60 km, the slope heights are above 100 m, except the loose slope. The slope angles are more than 30°, and part of the slope can be up to 40° ~ 60°. The second aspect includes the rock structure types of slope, the relationship between attitude of rock and slope (figure 3) and so on. The slope which develops toppling deformation body is mainly the reverse stratified rock slope and the heterotrophic stratified rock slope, and consequent stratified rock slope has rarely developed the toppling deformation body.

The rock layer obliquity of reverse slope of Miaowei reservoir area is about 70° ~ 85°, closing to the upright, and a group of joint surface which nearly vertical to the layer surface has developed in the rock layer. Because the rock was toppled and deformed, the angle of rock layer becomes to decrease, and apart of them becomes nearly horizontal, and the joints that are near perpendicular to the plane before the toppled are turned into an advantageous structural plane (figure 4, figure 5). The angle of this group structure surface is often close to the slope angle, or even greater than the slope angle, which is the controlling factor of the secondary failure of the toppling deformation body. After reservoir impoundment, on the one hand, the structural plane is full of water, the normal stiffness and the tangential stiffness will reduce greatly. On the other hand, because of the lacking of slope toe caused by bank collapse, the rock of upper slope toe lose the support, and the blocks formed by two groups of structural planes are more prone to slide or collapse.

Figure 5. Rock mass structure of bank slope

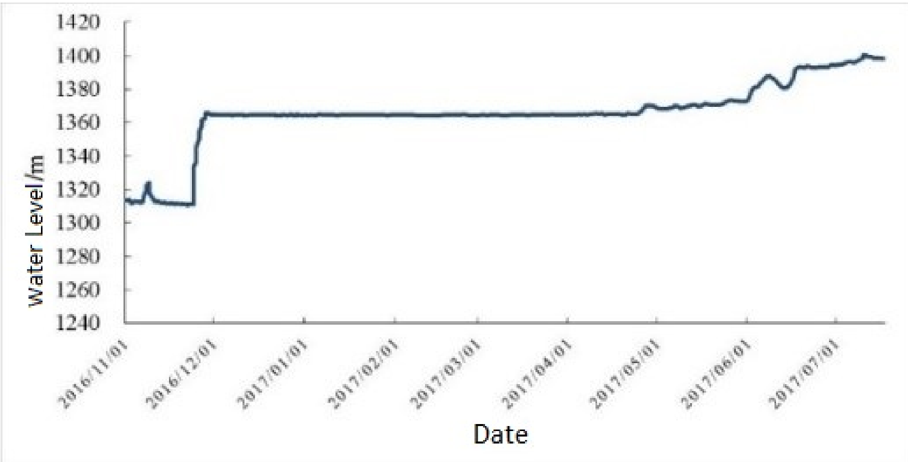

Figure 6. The process of water level change

2.3. The influence characteristics of reservoir impoundment

The Miaowei reservoir began to impound water in November 2016, and the water level of the initial level was 1314 m. By December 2016, the water level had reached 1364 m, and the water level of the reservoir had remained near 1364 m from November 2016 to May 2017. The water level in the third quarter of 2017 reached 1398 m. It was planned to impound water to 1408 m in the fourth quarter, as shown in figure 6.

According to Standard for engineering classification of rock mass (GB/T 50218-2014), in the rock properties of reservoir area, Phyllis, slate, and mudstone are soft rocks, and met sandstone and sandstone are hard rocks, and different combinations of rock properties form different toppling deformation body. According to the results of the laboratory test, the rate of intensity softening of soft rock is 52.81% after 28 days of soaking, and the softening rate of hard rock is 25.51% after 28 days of soaking. Therefore, it is more necessary to study the stability for the toppling deformation body consisted of soft rock on the condition of impounding.

From the beginning of impounding to the water level up to 1364m, the slope of the reservoir has collapsed in many places, and the collapse occurred on the surface, and the slope which occurred collapse was mostly reverse slope. During the period the water level of reservoir up to1 364m, the toppling deformation body of slope toe was scoured, dredged and softened and then lose the bearing capacity, and the upper rock slightly deformed and subsided, and the road surface formed cracks, and the broken rock on surface slid to formed a small collapse bank. The underground water level of the slope rose with the rise of reservoir water level, and the internal rock mass structure deteriorated further after the great fluctuating of reservoir water level. With the further increase of the reservoir water level, the part of rock became saturated and the shearing strength decreased. Under the action of gravity load, the slope body is prone to deform and collapse.

3. Model

3.1. The computational model and boundary conditions

The Discrete Element Method, DEM for short, was firstly proposed by P.A.Cundall [8], which is used to analyze the deformation of discrete media, the motion trend and the problem of rigid or deformable block separation. The Discrete element method is a numerical calculation method which more suitable for the analysis of stability of discontinuous rock, and has been widely used in the studies of mining, high slope, highway, earthquake and blasting [9]. In this paper, Universal Distinct Element Code, developed by Itasca, was used to analyze the stability of the slope in the reservoir area of the Miaowei hydropower station.

This calculation selected the toppling deformation body slope between Longshot River and Ouyang River where located in the right bank of reservoir as the object of numerical simulation. The geometric model referenced to the engineering geological profile, whose the strike direction of profile is N5°W. The elevation of slope toe of the model is 1310 m, and the slope crest is 1550 m. The slope length along the profile is about 290 m. The rock occurrence is 275°<70° ~ 80°, and the depth of toppling is about 25 ~ 40 m. The joint occurrence is 270°<60°. The QD9 model has 1095 blocks and 2644 grids, as shown in figure 7.

This paper selects Mohr-Coulomb model for rock mass, and chooses the contact -Coulomb slip model for the structure surface, and the boundary condition is the displacement constraint. At first, the initial model under the effect of weight is in the equilibrium, and the height above sea level of the initial water level is about 1335m. And then, this paper will predict the deformation trend of the model when the water level reaches 1408m.

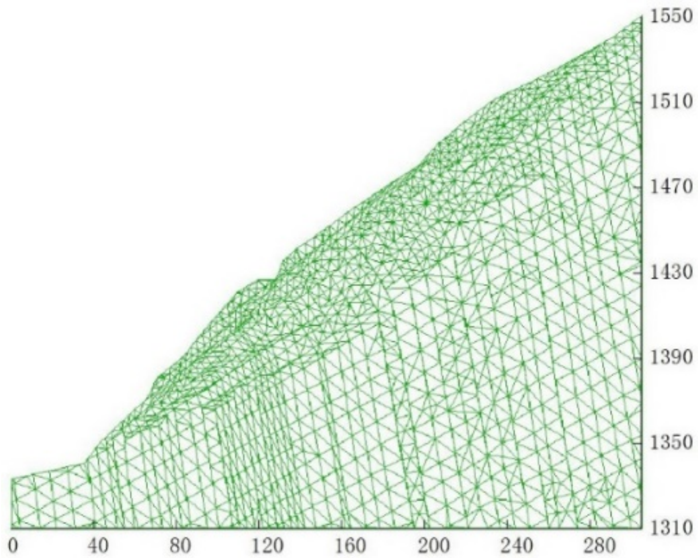

Figure 7. The model of QD9 bank slope (unit: m)

3.2. The parameters of physical mechanics

This numerical simulation is based on the project report of Miaowei Hydropower Station and the Code for engineering geological investigation of water resources and hydropower (GB50487-2008). In the case of impoundment, because of the effect of the connection of structural surface and softening of rock mass, the parameters of rock masses and structural planes should be reduced. The physical and mechanical parameters of rock masses and structural planes used in numerical simulation are shown in table 1 and table 2.

Table 1. The table of parameters of physical and mechanical parameters of rock mass

Rock type	γ(ken/m3)	γ'(ken/m3)	E(GA)	μ	c(MP)	φ(°)	c'(MP)	φ'(°)
strong weathering slate	22.0	23.5	0.5	0.32	0.55	26.6	0.35	21.8
weakly weathered slate	23.5	24.5	0.8	0.30	0.60	28.8	0.45	26.6
slate	24.5	25.0	1.0	0.30	0.68	35.0	0.55	31.0
strong weathering metamorphic sandstone	25.0	25.5	2.0	0.30	0.70	38.7	0.60	35.0
weakly weathered metamorphic sandstone	26.0	26.5	4.0	0.28	0.80	45.0	0.68	38.7
metamorphic sandstone	26.5	27.0	8.0	0.25	0.90	1.20	0.80	45.0

Table 2. The table of mechanical parameters for different structural surfaces

Structural surface type	Ken(GA/m)	Kit(GA/m)	c(MP)	φ(°)	c'(MP)	φ'(°)
joint plane	1.0	0.4	0.10	26.6	0.05	24.6
Strong weathering bedding surface	1.0	0.4	0.10	21.8	0.07	19.8
Weakly weathering bedding surface	1.5	0.8	0.30	26.6	0.21	24.6
Lightly weathering bedding surface	2.0	1.0	0.40	33.0	0.28	31.0
bedding surface of bed rock	5.0	2.0	0.75	45.0	0.50	40.4

4. The analysis of numerical simulation of slope

According to the characteristics of reservoir impoundment, the two working conditions of before impoundment and after impoundment (water level of 1408 m) are selected to analyze. According to the softening test in laboratory, through adjusting the physical and mechanical parameters of rock below the underground water level, this paper simulated the effect of the softened slate that soaked in the reservoir water on the slope stability. The analysis results are as follows.

4.1. Characteristics of slope displacement

The characteristic of the displacement of QD9 before impingement can be seen in figure 8~10. Before impingement, the distributions of horizontal and vertical displacement in the slope are very different, which is due to the uneven deformation of the slope in the course of natural history. At the height of 1360 ~ 1410 m and the horizontal depth is 20 m, and the horizontal displacement reaches a maximum value of 0.015m due to the large angle of the slope. The horizontal displacement is gradually reduced from the superficial part of the slope to the inner part, and the horizontal direction does not have obvious displacement where the horizontal depth reaches about 50 ~ 100 m. At a height of less than 1, 400 m, vertical direction of slope has no apparent displacement. On the contrary, at a height of more than 1400 m, the vertical displacement of the slope is decreased gradually from top to bottom, and the vertical displacement at the top of the slope reaches the maximum value of 0.04 m. The displacement vector of the rock mass below the highway along river points to the outside of slope, indicating that the rock mass below the highway has the tendency of moving outwards, and the potential failure mode of the slope is sliding damage.

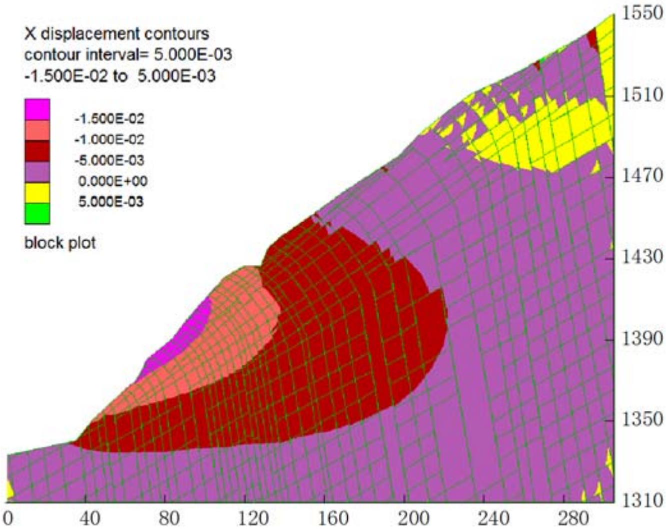

Figure 8. X displacement (natural)

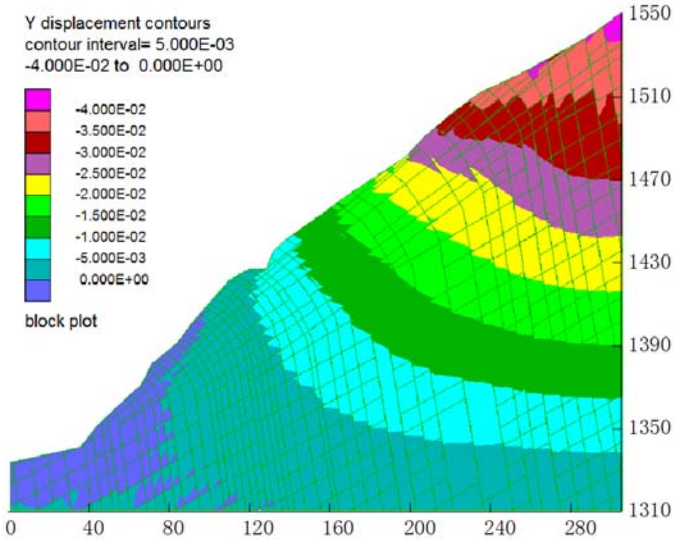

Figure 9. Y displacement (natural)

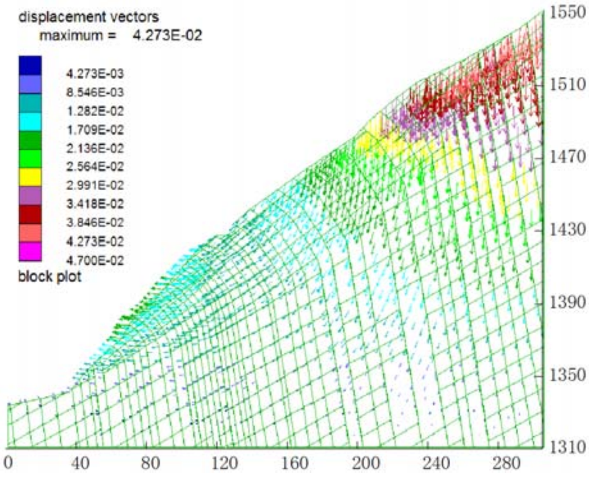

Figure 10. The displacement vectors (natural)

The characteristic of the displacement of QD9 after impingement can be shown in figure 11~13. After the water level reached 1408 m, the slope below the river road within 30 m has obvious displacement, and the horizontal displacement can reach up to 25~30 cm, and the thickness is about 5~10 m; the maximum displacement of the vertical direction is 30~35 cm, and the thickness is about 5~15 m. The slope located in the inside of the highway along river also has a certain displacement, which is 15~20 cm. The displacement area of the slope below the highway along the river is mainly in the superficial part, and the boundary is the structural surface which incline to outside slope, and the trailing edge boundary is composed of the structural surface and the bedding plane, whose occurrence are vertical.

After impingement, great changes have taken place in slope displacement vector, there is no tendency for the rock mass below highway along river to move outwards, but converted to the tendency to move downward, indicating that the damage pattern of slope after impingement is mainly collapse, not sliding. Due to the close of the water level of 1408 m along the river road, the collapse of the slope will affect the road along the river, which may cause the collapse of the highway. Due to the highway is close to the water level of 1408 m, the collapse of the slope will affect the highway, which may cause the collapse of the highway.

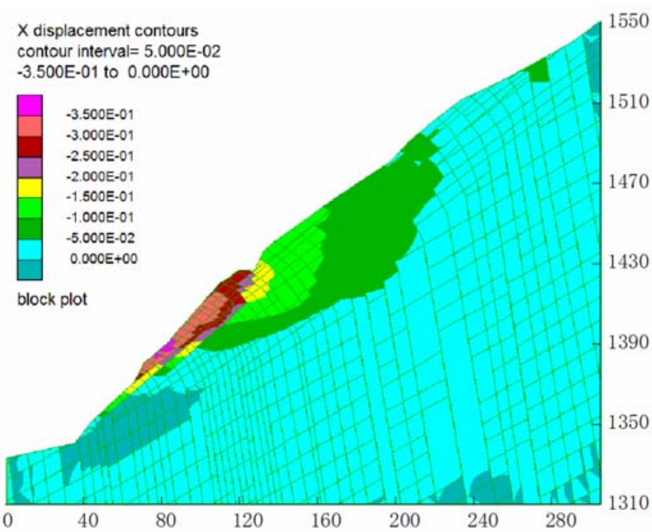

Figure 11. X displacement (impounded)

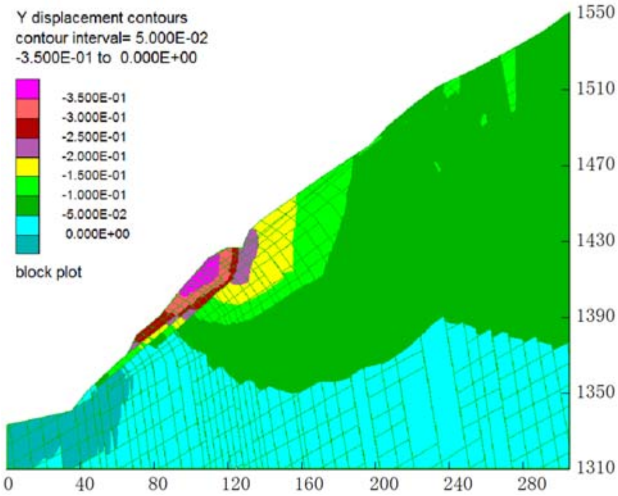

Figure 12. Y displacement (impounded)

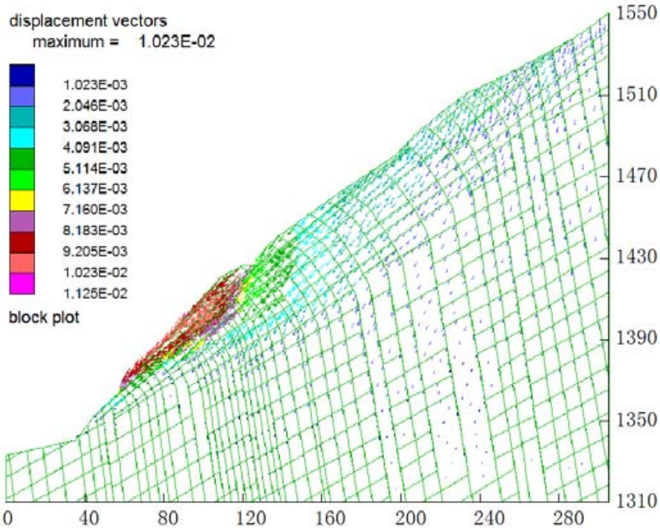

Figure 13. The displacement vectors (impounded)

4.2. Characteristics of stress change of slope

After impingement, the stress distribution of the slope has not changed much, and the stress is gradually increased from the superficial part of the slope to the inner surface. The stress distribution is stratified, which is corresponded to the distribution characteristics of the stress in the southwest region. The maximum principal stress within the 20 m of the superficial slope is 0.5 MPa, and there is no change after impingement. The minimum principal stress value of the superficial slope is unchanged, but the number of blocks whose minimum principal stress value is 0.4 MPa has increased. There is no obvious stress concentration after impingement, and there is no obvious change in stress distribution, indicating that the slope is stable.

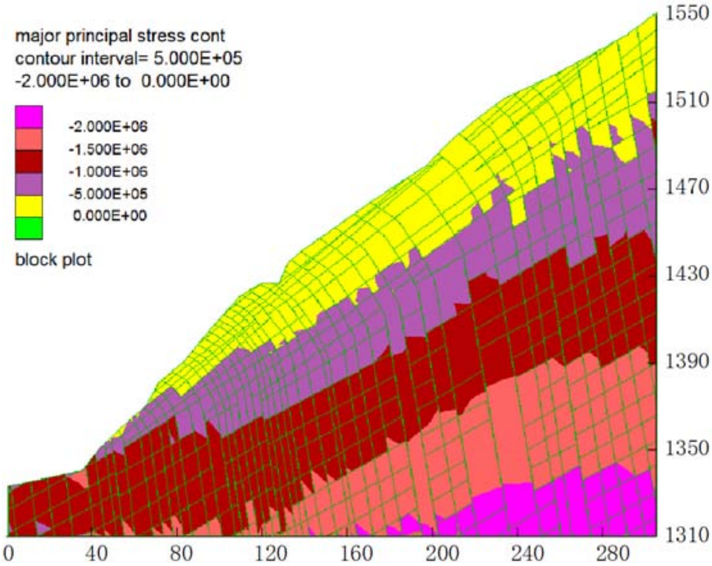

Figure 14. Major Principal stress (natural)

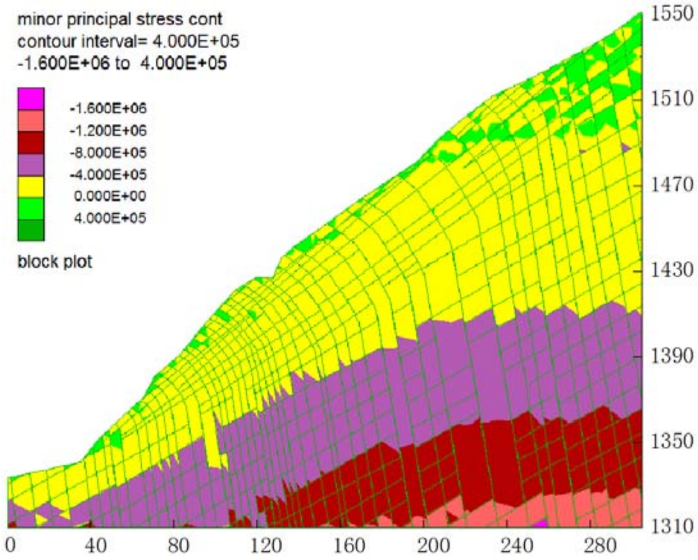

Figure 15. Minor principal stress (natural)

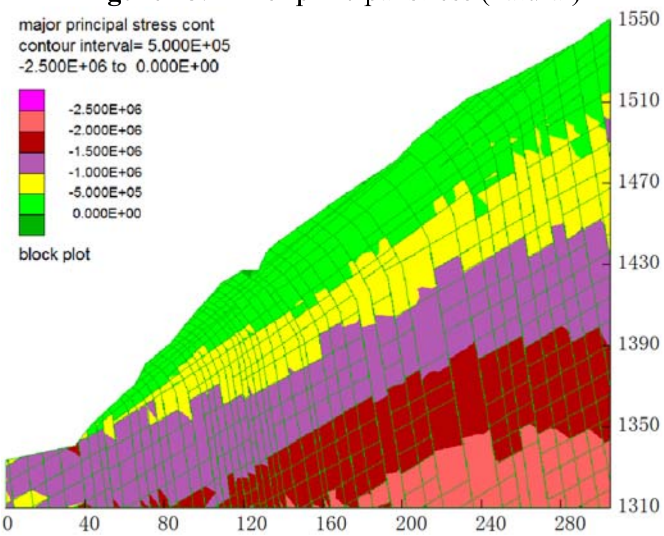

Figure 16. Major Principal Stress (impounded)

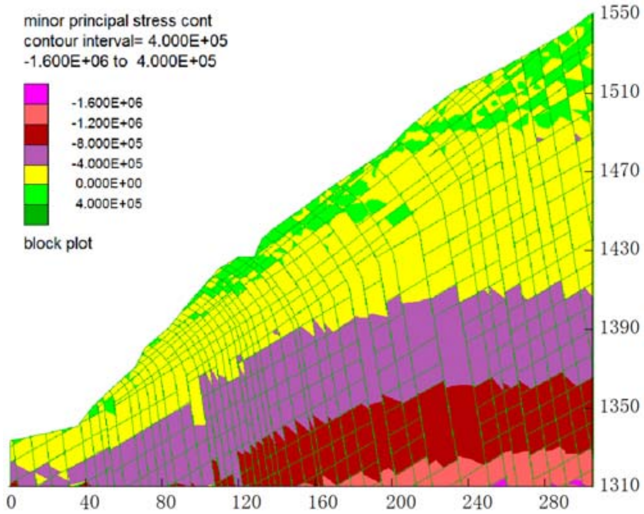

Figure 17. Minor principal stress (impounded)

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5. Conclusion

(1) After the reservoir impoundment, the toppling deformation body is developed strongly, and the rock mass is broken. And a group of joints which are incline to outwards slope are developed, and the intensity of the rock decreases. What`s more, and the deformation of slope is controlled by the structure of the rock body.

(2) By analyzing the changes of the slope displacement field, it can be concluded that the slope which is close to highway has obvious displacement, and the maximum is 30~35 cm, when the water level of reservoir comes up to1 408 m. The slope may be destroyed along the structural surface of the steep slope, and the damage thickness is about 10~ 15m, and there is a tendency for failure plane to develop to inside highway. The failure mode is changed from the sliding failure before the impoundment to collapse failure.

(3) By analyzing the changes of the slope stress field, it is concluded that the impoundment has little influence on the stress field of the slope, and the overall stability of the slope is good, but the partial collapse near the level of 1408 m cannot be excluded.

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