The deformation and failure mechanism of the toppling slope of the dam reservoir area near Xinlong hydropower station

WU Jian-li[(1)] ， HU Xie-wen[(1,2)] ， LANG Jing-xuan[(1)] ， and LV Jun-lei [(1)]

(1) Engineering Laboratory combined with national and local of spatial information technology of high speed railway operation safety, Southwest Jiaotong university, Sichuan Chengdu 610031,China
E-mail:45117304@qq.com

(2) Key Laboratory of Ministry of education of traffic tunnel , Southwest Jiaotong university, Sichuan Chengdu 610031,China

Abstract

Through field investigation a toppling slope of the dam reservoir area near Xinlong hydropower station, this paper proposed a reasonable planar division and section zonation of the toppling rock mass according to its deformation degree, analyzed the deformation feature and evolutional mechanism of the toppling deformation in the rock near the dam reservoir, and revealed the evolution process of the toppling failure under the action of reservoir water. The results show that the toppling rock mass can be divided into strong or weak group in accordance with the deformation degree of toppling-bending and bending-pulling. After the deformation, the strata inclination of strong toppling slope is 10°-30°, while the weak one is 40°-70°.Under the circumstance of rainstorm or water storage, the strong toppling rock mass will probably creep along the boundary of strong to weak, with a possibility of whole sliding.

Key words: toppling failure; deformation mechanism; planar division; reservoir area

1 Introduction

Toppling failure as a typical failure mode in countertendency layered slopes, was firstly analyzed in the 1970s using the limit equilibrium method proposed by Goodman and Bray（1976,1981）which caused an extensive attention on toppling deformation in geotechnical engineering and engineering geological communities. In the recent 40 years, many geological experts and scholars made a lot of deep researches and analyses on this theory, and the graphical method and numerical computation had made widely development and application in the stability calculation of toppling mass(Ishida T and Chigira M 1987, Hoek E and Bray 1981, Zanbak C 1983, Wyllie DC 1980, GAO Lian-tong, YAN E-chuan 2015).

The Xinlong hydropower station which locates about 6km upstream of Xinlong County, has a storage capacity under normal water level about 0.083 billion m^3 and installed capacity of 240MW, with a dam crest on elevation of 3112.00m, crest length of 250m, maximum dam height of 67m, early prepared normal water level of 3107m, and reservoir backwater length of 26km, There is toppling slopes in reservoir area near the dam on the right bank, the length of which along the river is about 1.4km, and the width across the river is 170m.

From 2011 to 2012, the original selections of dam site, the type of dam, the layout of its hydro project and others were respectively carried out on-site comprehensive survey. The overall planning was based on power plant project area, reservoir area and others with their topographic and geologic conditions, external transport and other conditions, and then in 2013, the relevant geological exploration test work on site of pre-feasibility study stage was carried out, the contents of which including the exploration and investigation of river bed and overburden thickness on both sides, hierarchical structure and spatial distribution feature. Exploration and investigation was made out for river bed and the depth and level of weathering unloading to cross-strait rock, the rock integrity, structural plane development degree and its syntagmatic relation, physical mechanical properties and permeability of rocks, analyzing those impacts to the dam foundation as well as the stability and leakage of rock-mass slope.

Engineering geological survey shows obvious signs of deformation in the slope, and the overall stability of the slope could be endangered if the deformation developed wantonly, thus evaluating the stability of the toppling slope is necessary. Through studying the mechanism of deformation and the stability situation of toppling slope under various conditions, three geophysical profiles and five adits are successively set up in the toppling mass. This paper here studies the deformation mechanism and potential failure mode of toppling slope, and finally makes evaluation on the stability of toppling mass.

2 Geological conditions in the study area

The slope in dam site area locates about 1km upstream of Xinlong County, Dilong Village of the main stream channel segment of Yalong River. The length of the channel segment in dam site area is about 0.5km, and Xinlong gutter imports from the upstream left bank in dam site area. Yalong River flows into the dam site at an azimuth angle of S32°W, turns into S55°W near the dam monolith, and finally flows out the dam site in the direction near "W". Valley in dam site area is the oblique~transverse valley, which is in asymmetric "U" shape, and the valley is deeply cut. The valley is steep on the left bank, with a natural slope angle of 50°~60°, and the height of slope on the verge of rivers 300m~350m; the valley is also steep on the right bank under 3130m, with a natural slope angle of 40°~45°, and the valley above 3130m is gradual, with a natural slope angle of 15°~20°, and the height of slope on the verge of river is 130m~280m (see Fig. 1). By early crustal uplift and unloading of rock, some deformable landslides are embedded near the right bank of the dam.

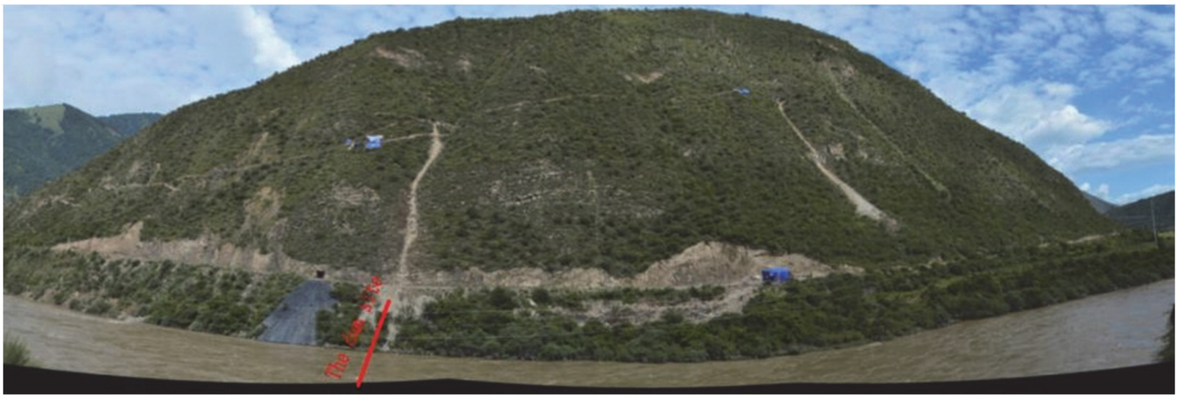


Fig.1 Full view of the slope on the right bank

In order to identify the plane distribution range and geology of deformable landslides, the work to building three geophysical prospecting sections, five adits and multiple drilling is successively set out. The quaternary overburden layer of toppling slope part mainly composes of modern alluvial deposits and rock fall deposits locates on the toe of the valley slope. Bedrock made of slate sandstone of Lianghekou Formation lower section(T_3ln^1) has slightly changed with an overall stable trend, due to the strata steep dip angle, the tendency has slight change (see Fig. 2).

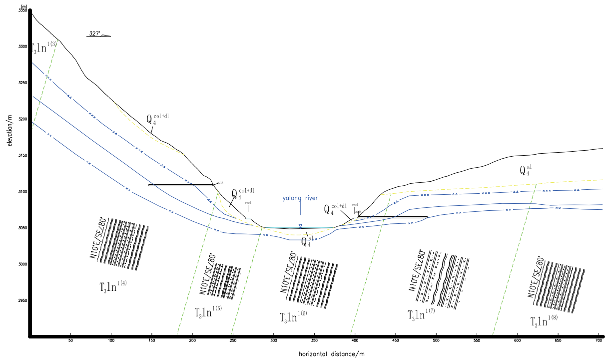


Fig. 2 Geological profile of the dam axis

The slopeis located in the west limb of the multiple anticline of Yalong River, and it is a monoclinal stratum, with a stratum overall occurrence of N10°W~N20°E/NE (or NW) ∠70~90°, while the regional fold deformation is weak. No major fold development is seen in the slope, andthere are only individual small foldssporadically exposed.No mass fault is seen in the slope.

Rock mass unloading is relatively strong in the slope, and fractures in all directions are generally open in strong unloading band, with rock debris and secondary mud filled, most fractures are 2~10cm wide, and top-collapsed phenomenon exists in partial adit.Fractures are less open in weak unloading band, with rock debris filled mainly, and secondary mud filled partially, but the width is generally less than 3cm, and secondary mud has the feature of interval filled, that is the rock masses with more secondary mud and less secondary mud are often distributed alternately . In the strong unloading rock mass, rock debris or secondary mud filled are widespread in the fractures along the slope, and alternately filled exists in weak unloading rock mass.

The groundwater of the toppling slope in front of the dam could be divided into loosely packed layer of pore water and fissure water in bedrock.The loosely packed layer of pore water is distributed mainly in slope wash etc., and the water abundance is often greatly affected by seasonal changes. While thefissure water in bedrock is mainly supplied by atmospheric precipitation, and flows into the Yalong River.

3 Deformation features of toppling mass

3.1 Partition of topplingslope

According to seismic inversion data, stratum is divided into three layers: the first layer is strongly weathered and unloading rock mass, with a covering layer of gravelly soil and residual slope wash mainly, whose wave velocity is between 500m/s~1500m/s; the second layer is the weak rock mass on the top, whose wave velocity is between 1500m/s~2200m/s; the third layer is bottom weak and slightly new rock mass, whose wave velocity is greater than 2200m/s(see Fig. 3). Take profile Z2 in Fig. 3 for example, the entirety of first and second layer shows a fan-shaped distribution from the bed side to the mountain top side. The first layer burial depth is 10~55m, with a minimum burial depth at stake number Z2-65, and the deepest at stake numberZ2-420.The burial depth of second layer of weak unloading rock mass is 20~60m, with a minimum burial depth at stake number Z2-65, and the deepest at stake numberZ2-440.

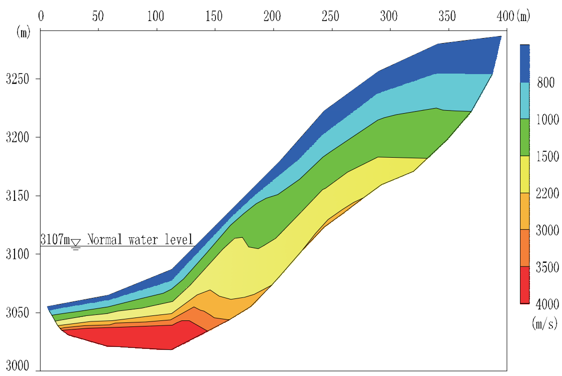


Fig. 3 The geophysical prospecting result map of cross slope Z2 in toppling slope

Combined with adit exploration (Table 1), the first layer above (dark blue) actually represents strong unloading, strong toppling deformable rock mass, and the second layer (light blue) actually corresponds to the weak unloading, part weak toppling deformable rock mass.

Table 1The strong and weak deformable achievements of adit exploration reveal for the toppling slope in Xinlong hydropower station

Parti -tion	Adit number	Adit depth (m)	Adit opening elevation (m)	Covering layer thickness(m)	Deformation degree		Unloading		Weathering		
					Strong	Weak	Strong (m)	Weak (m)	Strong weathering (m)	Top weak (m)	Bottom weak (m)
A1	PD08	99.3	3081	13	30	38.5	38.5	55	38.5	55	90
A2	PD16	118	3137	1	30	72.5	72.5	85	72.5	85	102

According to surface survey and exploration, the division criteria between strong and weak deformation upstream (Table 2) directed at Xinlong hydropower station dam area are revealed, and the planar distribution range and spatial distribution for the strong and weak deformation of toppling slope front of dam are ascertained. According to the development characteristics of toppling slope and current slope stability, three areas of A1, A2 and B can be divided (see Fig. 4～5).

Table 2Simple table about criteria on strong and weak toppling deformation division for the slope near dam at the right bank of Xinlong hydropower Station

Essential feature	Strong toppling deformation	Weak toppling deformation
Rock mass dip angle(reflecting toppling degree)	Dip angle 10~40°	Dip angle 40~70°
Tension fissure developing density between layers	Wedge-shaped tension fissures generally develop,well connectivity	Wedge-shaped tension fissures sporadically develop,poor connectivity
Rock mass loose degree	Rock masses generally loose,poor self-stabilization	Rock masses generally loose,well self-stabilization
Rock mass structure	Cataclastic structure,partially loose structure	Mainly is mosaic structure,partially loose structure

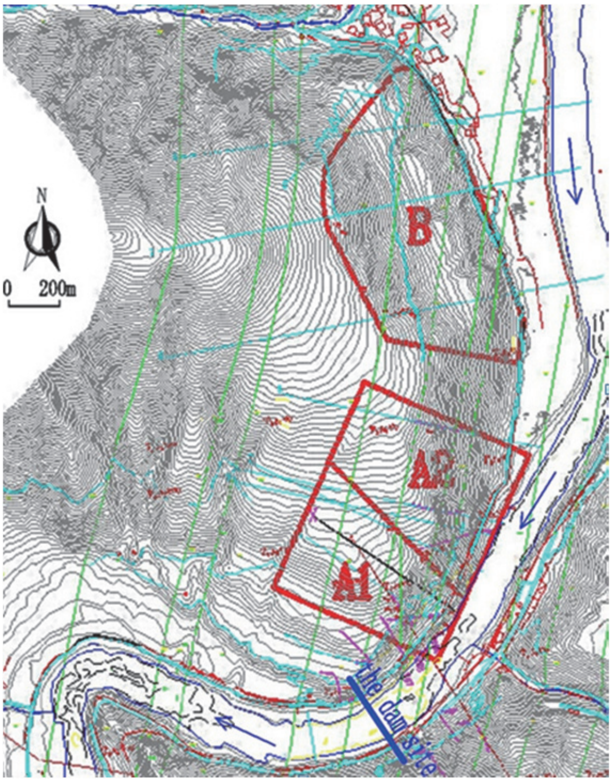
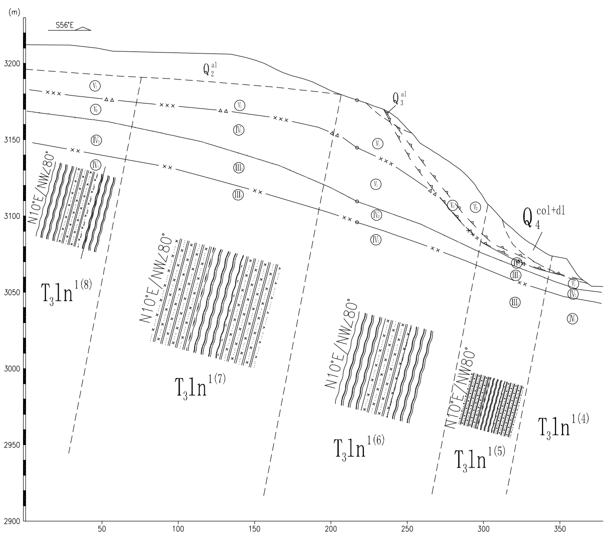
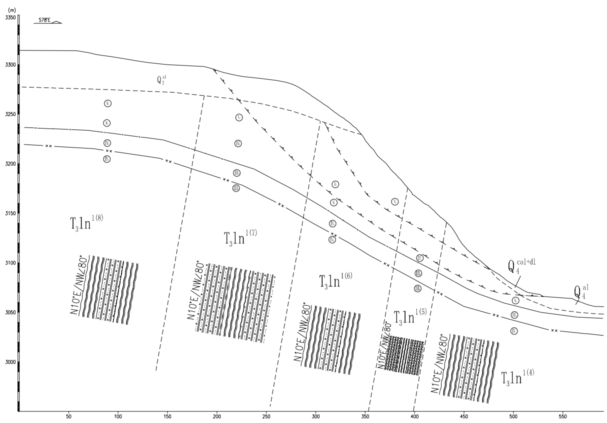


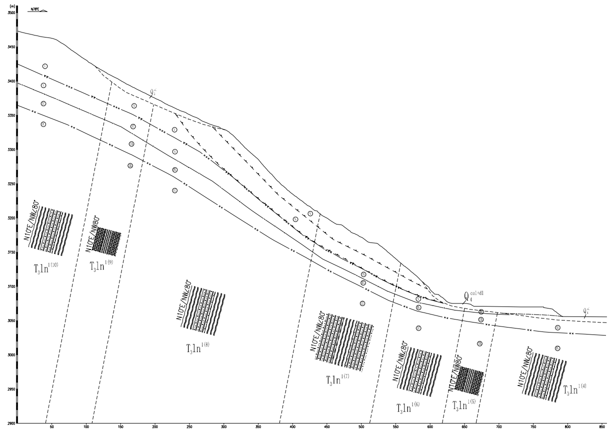
Fig. 4 The engineering geological zoning map for slopeof Xinlong near dam right bank area



a) A1 zone



b) A2 zone



c) B zone

Fig. 5 Cross-sectional view of the toppling slope . a) A1 zone, b) A2 zone, c) B zone

3.2 Essential featuresof zone A1

Zone A1 locates at the downstream segment of the slope, and the length along the river is about 332m.Its main features are as follows: 1) strong deformation occurred on entire slope surface, with the thickness of 18-30m, rock mass crushed severely, and it is nearly horizontal or the angle less than 40°after the stratum topples, with partial granular media form and poor self-stabilization; 2) thickness of weak deformation is maldistributed; 3) topography and geomorphologyis relatively gradual(with a slope angle of 35°~40°), and residual colluvium deposits distribute in the foot of the slope (see Fig. 6).

Fig.6 Downstream side zone A1 of slope

Analysis shows that, this area is actually a residual body of the early strongly toppling rock mass after surface peeling.Strong deformation has spread throughout the slope and residual colluvium deposits distribute in the foot of the slope.The overall stability of slope in zone A1 is generally poor, with poor partial stability, which is unfavorable for the slope engineering.

3.3 Essential features of A2 zone

A2 zone locates in the middle part of the slope, which is 469m in length along the river. Its main characteristics are: 1) Strong deformations distribute on a certain height above the highway instead of the whole surface of the slope, with a thickness of 33-46m. After toppling, the strata are nearly horizontal or in a dip of less than 40°, and the rock is broken in cataclastic structure with general self-stability. 2) Weak deformations are in general distribution with a height of 39-81m. After toppling, the strata are in a dip between 40°-70°, and the rock is in mosaic structure. Part of the strata are in relaxed state due to the impact of weak unloading. 3) Geomorphology of this zone is relatively steep (slope greater than 45°). The bedrocks are uncovered except for those covered by residual colluvium deposits in some certain part of the slope (see Fig. 7).

Fig.7 A2 zone in the middle part of the slope

Analysis shows that, this zone is also the remained mass which was peeled off from surface-layer in strong toppling rock mass in the early period in wider range and larger scale. As a whole, strong toppling rock mass in zone A2 is in a general level of overall stability and low level of local stability, which is a bit better when compared to zone A1. Due to that zone A2 is near the reservoir and dam section, the safe operation of the dams would be threatened by bank caving after the impoundment of reservoirs.

3.4 Essential features of B zone

B zone locates in the upper reaches of the slope, which is 616m in length along the river. A notable distinction to A1 zone and A2 zone is that, terrace accumulation is reserved in the middle part of the slope in this zone. The main characteristics are: 1) Strong deformations distribute on almost the whole surface of the slope, but thin in thickness, which is about 10-20m. After toppling, the strata are nearly horizontal or in a dip of less than 40°, and the rock is broken in cataclastic structure with general self-stability. 2) Weak deformations are in general distribution, the thickness of which is close to that of A2 zone, which is in the range of 35-80m. After toppling, the strata are in a dip between 40-70°, and the rock is in mosaic structure. Part of the strata are in relaxed state due to the impact of weak unloading. 3) In addition to the terrace accumulation in the middle part of the slope, there are residual colluvium deposits at the foot of the slope. The rest parts are also relatively steep (slope angle greater than 40°) (see in Fig.8).

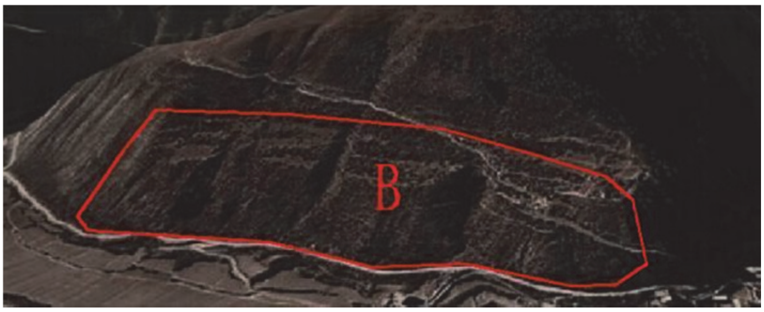


Fig.8 B zone in the upper reaches of the slope

Distribution of earlier terrace accumulation in the middle part of the slope shows that this zone is similar to A2 zone. But after a wide range of slump in early times, alluvial accumulations (IV steps of terrace) is able to accumulate due to the convex bank impact of Yalong River. Consequently the overall stability of the slope becomes better due to pressing foot or pressing slope. Overall stability of the slope is good. As a whole, overall stability of the strong toppling rock mass on the surface of B zone is good, except that the local stability of the slope foot is in a general level, in another way, the overall stability of B zone is better than A2 zone. After impoundment of the reservoir, there could be local bank caving at the foot of the slope, but in limited scale, so the safe operation of the dam would not be threatened.

3.5 Possible instability mode of slope

Slope is mainly located on slates, of which the foliation is extremely developed, the lithology is relatively weak, the spillway rock mass is steep, and the valley trend mainly intersects with stratum strike at small angles. As the Yalong River undercut and earth crust upraises correspondingly, spillway rock mass enters the progress of dumping~bending, bending~cracking and potential slipping surface at bottom formed by bending fracture surface towards free face, and current toppling slope is created (Zhang Zhuoyuan, Wang Shi tian 1994). Simultaneously, the slope could be classified into strong toppling and weak toppling rock mass according to the deformation level of dumping~bending and bending~cracking. The dip angle of strata formed by the dumping~bending procedure of strong formable are about 10°-30° while that of strata formed by the dumping~bending procedure of weak formable are about 40°-70°.

There still are possibilities of surface slip failure of residual slope in these three zones, particularly in A1 zone and A2 zone. The failure mode would be pull-type, in another way, the slip of damaged front locked patches will result in the overall slip of post median part along the fracture surface of strong or weak toppling rock mass. As a consequence, in the stability calculation of toppling slope below, analysis will be conducted according to the slope type -- strong or weak toppling rock mass.

4 Stability analysis of toppling mass

4.1 Parameter selection

In order to obtain the physical and mechanical parameters of ground in field, we carried out 26 group indoor rock physical and mechanical tests and 32 sets of indoor soil physical and mechanical properties tests, testing the rock density, cohesion force, shear strength, compressive strength, modulus of elasticity, softening coefficient and so on.

Parameters for deformable slipping surface are shown in table 3, which are determined by the field and laboratory test results, survey data and the experience analogy.

Table 3 Parameter values of the slope

Types of rock-soil \ Soil parameter		Water immersion state			Water-saturated state		
		C(kPa)	Φ(°)	γ(kN/m3)	C(kPa)	Φ(°)	γ(kN/m3)
Gravelly Soil (col+dlQ4)		0.0	21.0	20.0	20.0	17.0	21.0
Gravel (egg stone) soil (alQ2)		60.0	41.0	21.8	48.0	32.9	22.8
A1 zone	Strong toppling rock mass	150.0	24.2	26.8	135.0	21.8	27.3
	Weak toppling rock mass	200.0	26.6	26.8	180.0	23.9	27.3
A2 zone	Strong toppling rock mass	200.0	26.6	26.8	180.0	23.9	27.3
	Weak toppling rock mass	300.0	28.8	26.8	270.0	25.9	27.3
B zone	Strong toppling rock mass	150.0	26.6	26.8	135.0	23.9	27.3
	Weak toppling rock mass	300.0	28.8	26.8	270.0	25.9	27.3

4.2 Calculation model and working condition

After impoundment of the Xinlong reservoir, the water'splummet of 5m once is taken as the extreme case, that is to say, from the normal storage level of 3107 meters to 3102 meters. Therefore three kinds of water storage working conditions which are used in stability calculation are considered: 1) before impoundment; 2) normal water level of 3107 meters; 3) plummeting 5 meters from normal water level of 3107 meters. And superimposition conditions as follows should be considered in the above conditions: 1) the natural state; 2) the earthquake; 3) continuous rainfall (saturation). The value of seismic influence coefficient is 0.5. X-profile, 5-profile and 70profile are selected as typical profiles of stability calculation in A1, A2 and B zones.

4.3 Result and analysis of stability calculation

Potential sliding surface appeared to be broken line~arc shape, which is determined by strong and weak bottom boundary of the toppling slope. Typical profiles from above three zones are calculated by broken line-sliding surface-transmit-coefficient method. The calculation results are shown in table 4 to table 6.

Table 4 Calculation results on stability coefficient before the impoundment

Profiles	Potentialsliding surface	Working conditions		
		Water immersion	Water immersion +earthquake	Persistent rain
A1 zone	Strong toppling rock mass	1.164	1.045	1.040
	Weak toppling rock mass	1.349	1.196	1.197
A2 zone	Strong toppling rock mass	1.136	1.011	1.009
	Weak toppling rock mass	1.205	1.054	1.061
B zone	Strong toppling rock mass	1.321	1.162	1.173
	Weak toppling rock mass	1.385	1.213	1.229

Table 4 shows that strong and weak toppling rock mass are both stable under water immersion and strong toppling rock mass is understable under earthquake and persistent rainfall before impoundment in A1 zone, which indicates that the stability of slope in A1 zone is poor. Strong toppling rock mass under water immersion is stable, and is understable under earthquake and persistent rainfall in A2 zone; the corresponding weak toppling rock mass is stable all the time, which indicates that the stability of slope in A2 zone is fair. All the slope in B zone is stable under various conditions, which matches the field qualitative analysis results and indicates that the back pressure of terrace in the middle of the slope mass is of significant influence on stability.

Table 5 Calculation results on stability coefficient under normal water level of 3107 meters

Profiles	Potentialsliding surface	Working conditions		
		Water immersion	Water immersion +earthquake	Persistent rain
A1 zone	Strong toppling rock mass	1.132	1.019	1.050
	Weak toppling rock mass	1.279	1.142	1.229
A2 zone	Strong toppling rock mass	1.124	1.000	1.009
	Weak toppling rock mass	1.128	0.990	1.043
B zone	Strong toppling rock mass	1.312	1.154	1.173
	Weak toppling rock mass	1.345	1.179	1.222

Table 6 Calculation results on stability coefficientfrom 3107m plummeting to 3102m

Profiles	Potentialsliding surface	Working conditions		
		Water immersion	Water immersion +earthquake	Persistent rain
A1 zone	Strong toppling rock mass	1.117	1.007	1.032
	Weak toppling rock mass	1.251	1.119	1.202
A2 zone	Strong toppling rock mass	1.121	0.998	1.006
	Weak toppling rock mass	1.121	0.985	1.037
B zone	Strong toppling rock mass	1.308	1.151	1.169
	Weak toppling rock mass	1.340	1.175	1.218

Table 5 shows that strong toppling rock mass is understable under earthquake and persistent rainfall and weak toppling rock mass is always stable under normal water level of 3107 meters, which indicates that the reservoir has some influence on the stability of slope.

Table 6 shows that strong toppling rock mass is understable and weak toppling rock mass is stableunder earthquake and persistent rainfall in A1 zone. It also indicates that water plummet has some influence to A1 zone, especially upstream side in A2 zone, the stability becomes worse. Strong toppling rock mass in A2 zone is in the state of limit equilibrium under earthquake and superimposition of persistent rainfall~ unstable state, and it is probable to have an overall sliding; weak deformation mass is stable under superimposition of persistent rain, but it is in the state of limit equilibrium under earthquake superimposition condition ~ unstable state.

5 Conclusion

Toppling slope are classified into A1 zone, A2 zone and B zone according to the development characteristics of the slope and the stability of current condition of the bank slope.

Before impoundment, the slope are always in stable state under all kinds of working conditions. The slope is overall stable without regard to the impoundment condition.

The results according to Table 5:All zones in the slope are in stable state when the water level reached 3017m. Strong toppling rock mass in A2 zone is mostly influenced. In the condition of normal impoundment combined with rainstorm, its stability would be weaken and there would be high possibility of an overall slide. So attention should be paid to this and reinforcement treatment would be necessary.

The results according to Table 6:After a sharp decrease of 5m of the water level, A1 zone would be influenced to a certain extent. A2 zone would have the worst stability and there would be high possibility of an overall slide, reinforcement treatment should be done in this zone. Strong and weak toppling rock mass in B zone would encounter certain decrease in their stability coefficient, not in minor scale, so the whole zone is in stable state.

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