OVERALL STABILITY ANALYSIS OF JINPING I ARCH DAM IN THE INITIAL WATER STORAGE STAGE CONSIDERING THE LEFT ABUTMENT SLOPE DEFORMATION

ZHONG ZHOU, JING ZHANG, DEWEN CAI, ZHONGXU LIU AND LIJUN XUE

Powerchina Chengdu Engineering Co. Ltd., Chengdu, Sichuan,China

ABSTRACT

The 305m-high double curvature concrete arch dam of Jinping I project, ranks the highest in the world. It has undergone 6 times of the normal water level since impoundment in October 2013. On the basis of monitoring data and analysis using 3D nonlinear visco-elastic-plastic rheological model, this paper presents the prediction and evaluation of the long-term deformation of the left abutment slope, and its effect on the arch dam safety, as well as the overall stability analysis of arch dams and foundation, and provides reference for future practitioners.

1. INTRODUCTION

Situated in Liangshan Autonomous Prefecture of Yi minority, Sichuan province, China, Jinping I hydropower station has a controlling reservoir in the lower reaches of the Yalong River, the main tributary of the Yangtze River. The normal water level of the 305m-high dam is at El.1885m. Its underground power plants provide an installed capacity of 3600MW.

Figure 1 : Jinping I Arch Dam

Located in a non-symmetrical deep V-shape canyon with slope of 50°~ 65 ° steep in left bank, 60 °~ 85 ° in right bank, mainly composed of marble, partially of sandstone in left bank above El.1800m.Jinping I dam has an extremely complicated foundation. In sandstone, slope deformation, tension cracks, and stress release are well developed with different intensity, including moderate, strong, and deep class, corresponding to depth of 50m ~ 90m, 100 ~ 160m, and 200 ~ 300m, varying with elevation. Toppling-tension deformation in higher part and toppling deformation in shallow area at lower part were well developed. Main faults in left abutment slope are faults f_2, f_5, f_8, f_{42-9}, and lamprophyre dike X, obliquely crossing the slope from top to bottom, with the strike of N60°~ 80°E, dipping angle of 70°~ 90°, and width of 1.5m~3m, resulting in slope failure modes of shear slip, block slip and wedge shape damage, etc.

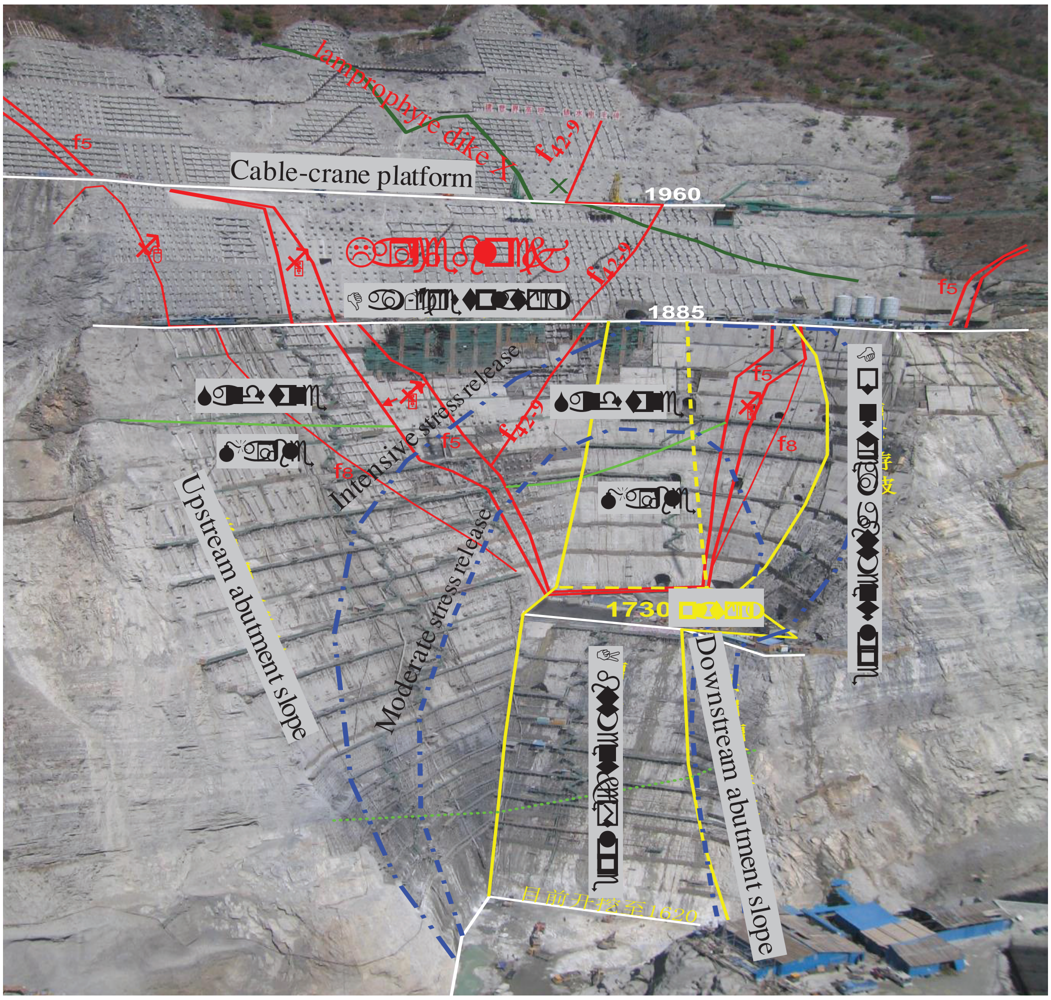


Figure 2 : The left abutment slope during excavation of Jinping I Arch Dam

The stability of the left bank slope is mainly controlled by a large wedge block (referred as "large block") composed of the joint layer SL_{44-1} as the upstream boundary, lamprophyre dike X as the trailing boundary, and the fault f_{42-9} as the downstream and bottom slip plane. After comprehensive reinforcements of rock anchors, rock cables and anti-slide concrete replacement tunnels, stability of the excavation slope of 540m high in left bank has been assured. As the monitoring data indicated, except the slope deformation at high elevation around the excavation line has not yet converged, the slope including the "large block" as a whole is in a stable state.

Excavation of Jinping I arch dam slope started in Sep. 2005 and completed in Aug. 2009, then dam concrete placement completed in Dec. 2013, and then the reservoir impounded to the normal water level 1880m at Aug.24th, 2014. Up to now, undergone 6 times of high water level, the dam has been working well and the slope is stable.

2. DEFORMATION CHARACTERISTICS OF THE LEFT BANK SLOPE

According to deformation data, the left bank slope could be divided into 6 deformation zones, as shown in Figure 3:

Zone 1, Toppling deformation zone at high elevation around the excavation line;

Zone 2, the deformation zone of upstream residual f_5 and f_8;

Zone 3, the upstream abutment slope;

Zone 4, the abutment key slope;

Zone 5, the downstream abutment slope;

and Zone 6, the flood discharge atomization zone above plunge pool. Slope deformation monitors were installed as follows:

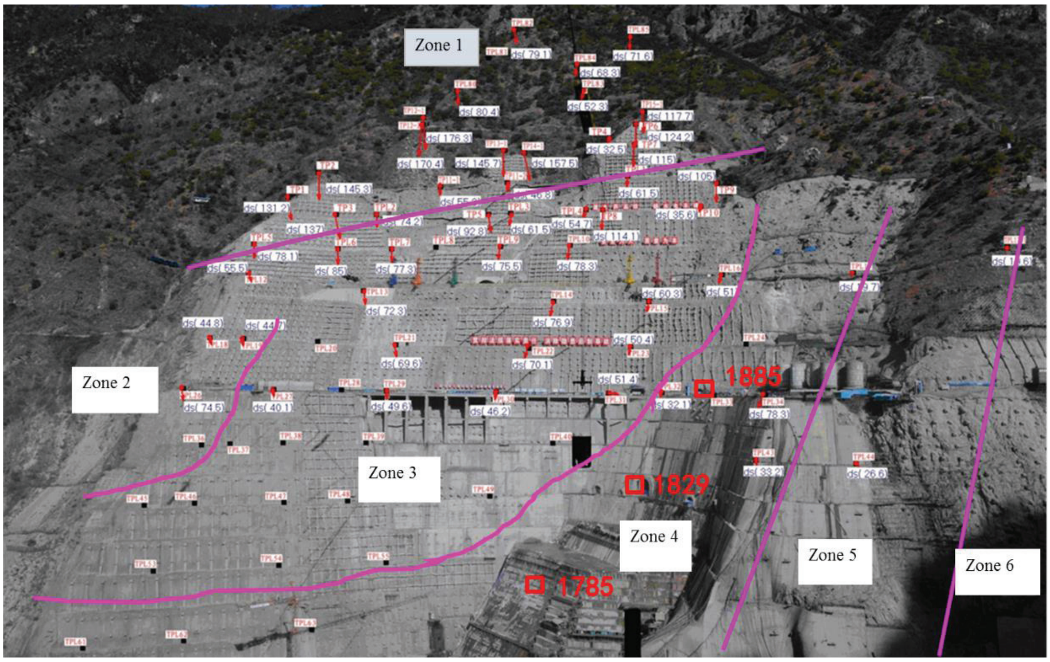


Figure 3 : Slope Deformation Zoning in the left Bank of Jinping I Arch Dam

2.1 Slope shallow deformation

The shallow deformation of the left bank slope is mainly monitored by multi-points extensometers of about 60m deep, the total displacements are between -6.76mm ~ 27.20mm so far. The incremental displacements were between -1.37mm and 26.42mm during the construction stage, -2.87 mm ~ 2.68mm in reservoir impounding to normal water level, and -0.61mm ~ 2.75mm from the normal water level to the present. Slope shallow deformation is small, and by systematic reinforcements including cables, the slope is stable.

2.2 Slope deep deformation

The slope deep deformation monitors have been installed in adit PD_{44}, PD_{42} and the drainage tunnels at El.1915m in the upstream abutment slope, as well as the grouting tunnel at El.1885m, drainage tunnel at El.1829m and El.1785m in the abutment slope, as shown in Figure 4:

(1) As observed in adit PD_{42}, PD_{44} and El. 1915m drainage tunnel, the deep deformations of the upstream abutment slope have not yet converged, continue to deform outward, but the increase rate is small and relatively stable, less than 0.6 mm / month.

(2) As deformation monitored in tunnel at El.1855m, El.1829m, El.1785m, deep deformation at El.1885m is stable, while that of at El.1820m and El.1785m vary with the water level, specifically, decrease corresponding to water level drop, and increase with water level going up.

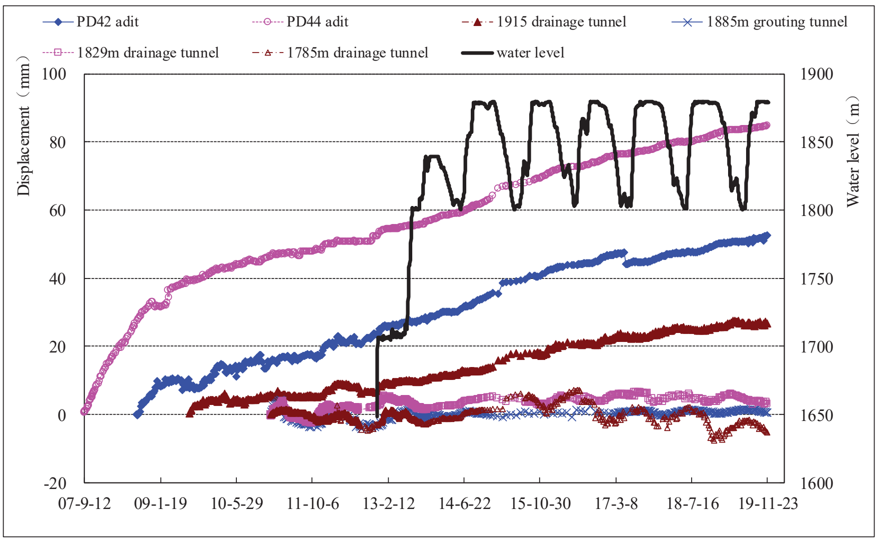


Figure 4 : Deep deformation process line of Jinping I left abutment slope

2.3 Valley deformation

Valley deformation monitors in the upstream abutment slope were installed in tunnels alone river transvers direction. As monitored data shown, upstream valley deformations are generally of shrinkage, and the deformation rates are comparatively large during the excavation period, then get smaller in following stage. The downstream valley deformation is small and getting stable.

2.4 Conclusion on the left bank slope deformation

Mutually verified by the monitored data of the shallow, deep and valley deformation, it could be concluded the deformation in Zone 1 has not yet converged, while Zone 2 is still in the adjustment period, and Zone 3 ~ Zone 6 are in steady state.

Deformations around the fault f42-9 mainly took place in its upper part. In the area under fault f_{42-9}, including the abutment slope and downstream abutment slope, the deep deformation is also small and convergent there, suggesting that the abutment slope and downstream abutment slope has been in a stable state, thus the arch dam long-term safety is guaranteed.

No independent t deformation or the evidence of the overall slip trend of "large block" was observed during in the initial water storage stage. The deformation of the "large block" is mainly comprehensive effects of the water infiltrations into the rock mass of class III2-VI outside of fault f_{42-9} and the lamprophyre dikes X, rather than that of the block slip. The left bank slope as a whole is in a stable state.

3 ANALYSIS OF THE INTERACTION BETWEEN THE SLOPE AND ARCH DAM

According to the characteristics of slope deformation of the left bank, the slope deformation will last for a certain period, therefore, it shall have three stages: the excavation and unloading deformation stage, the adjustment stage while the effective stress adjustment and softening of rock mass take place after be immersed by water during the initial water storage stage, and the stage of long-term deformation convergence. In order to study the effect of left abutment slope deformations on the safety of arch dam, the following procedures had been taken into account:

1. Analysis of geological structures and their rheological parameters, including:

   Analysis of the mechanism of geo-mechanical deformation, study on the influence of reservoir impoundment on slope rock mass and weak fracture zone, rheological test of rock mass of class IV2 and other weak interlayers, analysis of rheological test results and determination of rheological model.

2. Long-term deformation prediction of the slope, including:

   (1) Inversion of rheological parameters and long-term deformation prediction. On the basis of slope monitored data and testing results, rheological model and parameters of the rock mass in left bank were determined by the displacement feedback analysis, therefore, the long-term deformation trend and magnitude of the left bank slope could be analyzed.

   (2) Stability analysis of long-term deformation of the slope. The stability of long-term deformed slope is analyzed by 3D Visco - elastic - plastic finite element method.

3. Analysis of the effects of the long-term deformation on arch dam, including:

   (1) Establishment of FEM fine grid, and parameter inversion of the arch dam and the foundation on the basis of incremental displacement during reservoir impoundment.

   (2) The applying method of loading of Long-term deformation.

   According to the characteristics of the long-term deformation of the left bank slope, and taking the displacement of the profile as the objective function, the displacement loading could be employed on the FEM model boundary, by adjusting displacement loading range and scale.

   (3) The effects of long-term deformation of slope on arch dam. By the above-mentioned load applying method, the stress and stability of the arch dam considering the effects could be studied.

   (4) Long-term deformation overload analysis and study on the bearing capacity of arch dam.

   Taking the predicted long-term deformation of the slope as the base load, then, by magnifying the base load in FEM analysis, the overloading capacity of the left bank slope could be studied.

4. LONG-TERM DEFORMATION PREDICTION AND SLOPE STABILITY ANALYSIS

4.1 Inversion analysis of rheological parameters

According to the results of creep tests of rock mass, a three-parameter (HK) model of stable rheological model is adopted for the left bank slope sandstone and marble, and Moore-Coulomb rule as the plastic yield criterion. The combination of the two is shown in Figure 5.

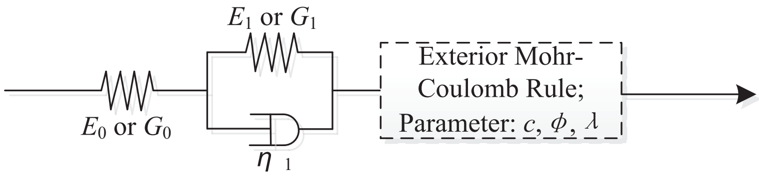


Figure 5 : Three-parameter (H-K) visco-elastic-plastic model

On the basis of the monitored data of displacement across river in each stage of the slope, the rheological parameters are obtained by inversion analysis.

Table 1 : Inversion results of three - dimensional rheological parameters

Sand slate of class III_1		Sand slate of class III_2		Sand slate of class IV_1		Sand slate of class VI_2		Fault f_{42-9}	
Viscoelastic modulus (GPa)	Viscosity Coefficient (×108 GPa·s)	Viscoelastic modulus (GPa)	Viscosity Coefficient (×108 GPa·s)	Viscoelastic modulus (GPa)	Viscosity Coefficient (×108 GPa·s)	Viscoelastic modulus (GPa)	Viscosity Coefficient (×108 GPa·s)	Viscoelastic modulus (GPa)	Viscosity Coefficient (×108 GPa·s)
13.4	**10.0**	**7.6**	**7.0**	**5.0**	**4.0**	**1.2**	**1.0**	**0.7**	**0.8**

4.2 Long-term deformation prediction of the left bank slope

During the span from the slope excavation completion in August 2009 to September 2014, the dam base abutment deformed 0 ~ 22.1mm outside, specifically, 0 ~ 16mm below El.1770m, 16 ~ 22.1mm between El.1770m ~ El.1885m. Since this deformation happened before the completion of dam concrete placement and joints grouting, this slope deformation had little effect on the arch dam.

By the 3D Visco-elastic-plastic FEM, the long-term slope deformation is predicted to be between 0 mm ~ 21.5mm in the span from April 2014 to September 2034, that is, 0 mm ~12.3mm below El.1770m, 12.3 mm ~21.5mm between El.1770m ~ 1885m.

In general, the subsequent long-term deformation is small, may not has significant effect on the dam overall stability, but requires further evaluation.

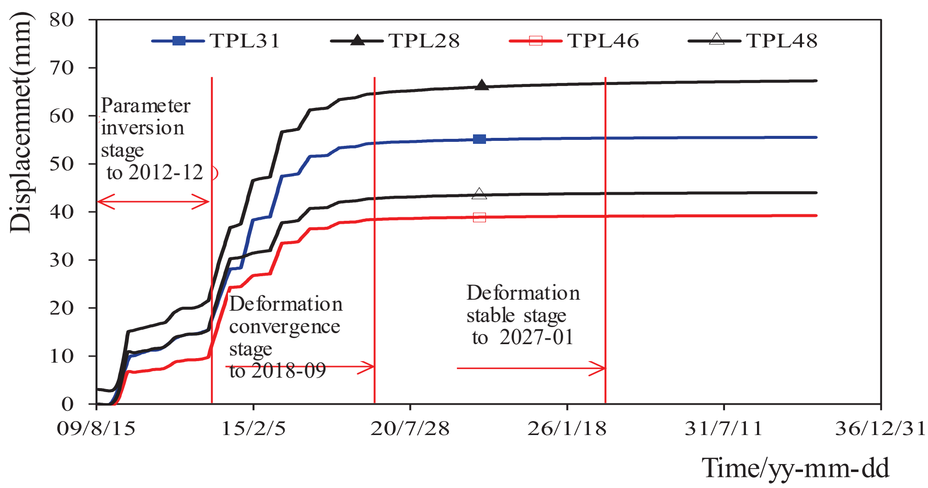
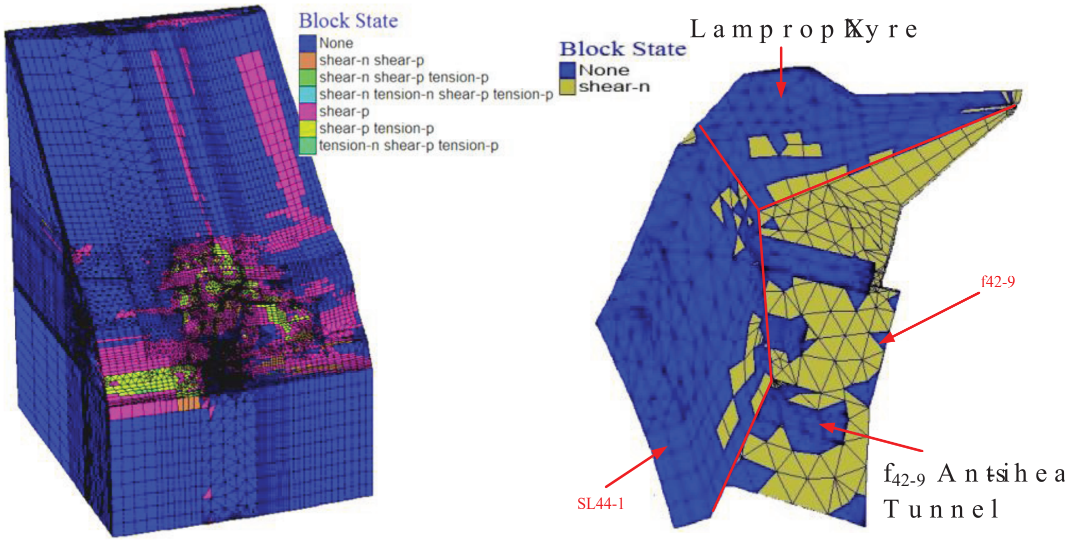


Figure 6 : Deformation increment of left abutment slope bellow El.1885.0m

4.3 Long-term slope stability analysis

As FEM analysis predicted, after going through 300 months of rheological deformation since the slope excavation completion in August 2009, most of the slope will be in compressive state, only in some small surface areas are small tensile stress, and will be further successfully alleviated by the anchor reinforcement. Although there is also a small tensile stress zone near the fault f42-9 and the deep-buried fissures, where the stress will also be improved by the anti-shear concrete replacement tunnels.

As FEM analysis shown, there are some plastic yielding zones below El.1880m, and got larger after reservoir impoundment, due to the boundaries of "large block", namely, joint layer SL44-1, lamprophyre X and fault f42-9 are mostly higher above the normal water level El.1880m, they have not the overall yield as shown in Figure 7. So the 'large block' as a whole is stable.



a. The yield zone of slope   b. The yield zone of 'large block'

Figure 7 : The yield zone of left abutment slopet by 3D FEM

5. ANALYSIS ON THE INFLUENCE OF SLOPE LONG-TERM DEFORMATION ON ARCH DAM

5.1 Study on the load applying method of the slope long-term deformation

As for arch dam structure, Long-term deformation of the left bank slope could be regarded as an additional external displacement load, therefore, the load applying method of slope long-term deformation is a key research topic.

By use of 3D elasto-plastic and Visco-elasto-plastic FEM by TFine program and Flac3D program, combined with the inversion analysis of monitoring data for mechanical parameters of dam foundation, several loads applying approaches of slope long-term deformation had been put forward.

Taking the slope deformation of several profiles as objective function, by using of multiple linear fitting method, and increasing the weight of the displacement target near the abutment slope, the least squares optimization based on the elasto-plastic calculation were carried out, and the optimal load applying method of slope long-term deformation is obtained.

Taking into account the effects of different displacement distribution scope, magnitude and patterns, e.g. triangles, trapezoids, as well as other factors, the optimization for load applying had been implemented, and the inverted triangular Polyline distribution pattern was proved to be reasonable, as shown in Figure 8.

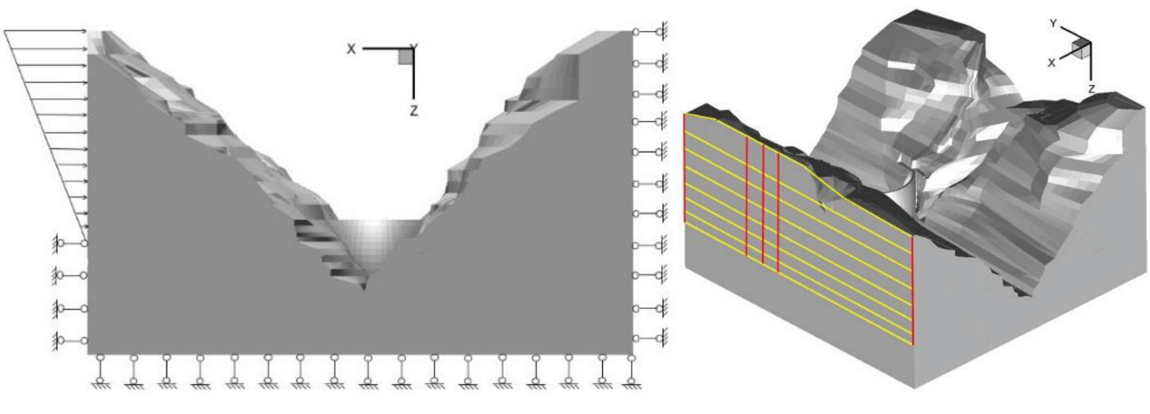


Figure 8 : Dragram of load applying method of long-term deformation of left abutment slope

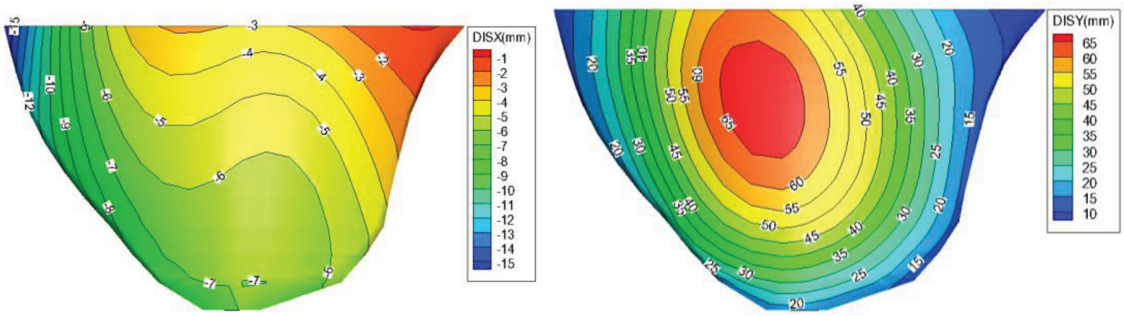
5.2 Dam deformation and stress analysis

(1) *Deformation*

Under normal water level of El.1880m, and the long-term deformation of the slope, the maximum increment of the displacement across river is 16.6mm at the left arch dam crest toward the river bed, while that along river is 9.6mm near the crest of crown cantilever toward upstream, accounting 13.8% to the maximum displacement by water load alone.

Similarly, under dead water level of El.1800m, and the long-term deformation of the slope, the maximum increment of the displacement across river reached 16.1mm at the left arch dam crest toward the river bed; while that along river

9.6mm near the crest of crown cantilever toward upstream, accounting to 29% of the maximum displacement of water load alone. The maximum incremental displacement along river in Left arch end at crest elevation is 2.5mm toward downstream.



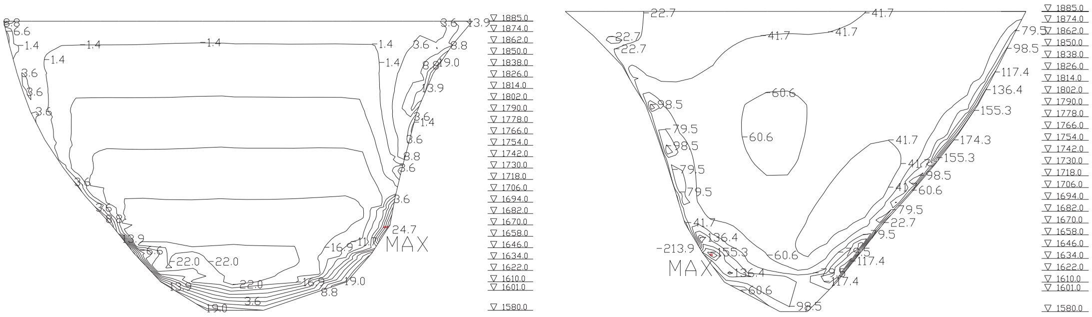
a. Displacement across river; b. Displacement along river

Figure 9 : the upstream dam displacement

(2) *Stress*

Under the normal water level, the long-term deformation of the slope make the maximum value of the main tensile stress decreased from 2.93MPa to 2.47MPa, and the maximum value of the downstream main compressive stress decreased from -21.88MPa to -21.39MPa, but the upstream tensile stress of the arch is about 0.70MPa and 1.25 MPa increased to 0.88 MPa and 1.39 MPa.

Similarly, under the dead water level, the main compressive stress and the main compressive stress are decreased, but the upstream tensile stress region is extended from the abutment to crown cantilever, and the downstream compressive stress is concentrated in the left of crest arch.



a. Tensile stress of upstream dam surface; b. Compressive stress of downstream dam surface

Figure 10 : Principal stress on the dam face under the normal water level and long-term deformation of slope (0.1Mpa)

(3) *Summary of the influence of left abutment slope deformation on dam structure*

(1) The dam stress was mainly sensitive to the deformation of the abutment slope below dam crest, and less sensitive to that above. Given that slope deformation mainly took place in the slope above the crest, it has no significant effect on dam structure.

(2) The high stress area of the dam caused by the deformation of the slope was not coincident with that under the normal load combination. The long-term deformation of the slope has little effects on the dam maximum principal tensile stress and compressive stress.

(3) The long-term deformation of the left bank slope were assumed to provide a thrust to the arch dam which is equivalent to a slight increase in the stiffness of the middle and upper dam foundation, inhibited the asymmetry of foundation in two banks. Therefore, the dam safety has not been undermined.

6. SAFETY EVALUATION OF ARCH DAM UNDER SLOPE LONG-TERM DEFORMATION

6.1 Slope deformation overload analysis

Considering the complexity of the deformation mechanism of the left bank slope and the reliability of the long-term deformation prediction, in order to further analyze the safety of the arch dam under the deformation of the left bank slope, the deformation overloading analysis was carried out.

Taking the predicted long-term deformation of the slope during May, 2014 to Septem-ber,2034, as the base load, then, by magnifying the base load in FEM analysis, the overloading capacity of the left bank slope could be studied by the following three indexes:

(1) The crack-initiation displacement load α1: cracks occurred in dam (normally, in dam heel or the left dam abutment, or other parts prone to cracking);

(2) The nonlinear deformation displacement load α2, indicates the load make the dam start large nonlinear deformation. It could be mainly observed by the turning point of dam displacement, yield area expanding, or plastic energy increment;

(3) The ultimate bearing capacity displacement load α3, indicates the bearing capacity of the dam, and could be found by the connecting of all the yield areas of the dam in FEM analysis.

As the overloading analysis shown, the crack-initiation displacement load α1 = 3, corre-sponding to under normal water level and the dead water level are 60.21mm and 59.28 mm respectively; The nonlinear deformation displacement load α2 = 8; The ultimate bearing capacity displacement load α3 = 12. It shows that Jinping I Arch Dam has high safety for long-term deformation of left bank slope. Under the long-term deformation predicted according to the monitoring data, Jinping I arch dam is safe.

6.2 Summary of the deep deformation of the left abutment slope

As the monitoring data shown, the deep deformation of left abutment slope is small, see in Figure 4. The process of deep deformation also shown that, deformation at EL.1885m has been stable; while at EL.1829m and EL.1785m were affected by the water level changes, that is, abutment slope at these elevations has a trend of move outside during the water level drop, while inside during water level increases. It suggests that the deep deformation of the abutment slope of the left bank is basically stable and its influence on the arch dam is small. The predicted long-term deformation mainly take place in the upstream abutment slope, the deep deformation of the dam foundation slope is small, it will have little effect on the safety of arch dam.

6.3 Analysis of arch chord length change

As monitoring data shown in Figure 11, the length decrease amount of dam chord totally reached 4.15mm ~ 15.36mm by March 21, 2016, while the largest chord shortening was at El.1730m. In general, in the early stages of reservoir impoundment, due to the effects by the excavation unloading, effective stress adjustment in slope and the softening of rock mass immersed in water, dam chord length had a small contraction. Hereafter, the chord length was elongated and compressed with the water level up and down, respectively, exhibiting a good correlation with the water level.

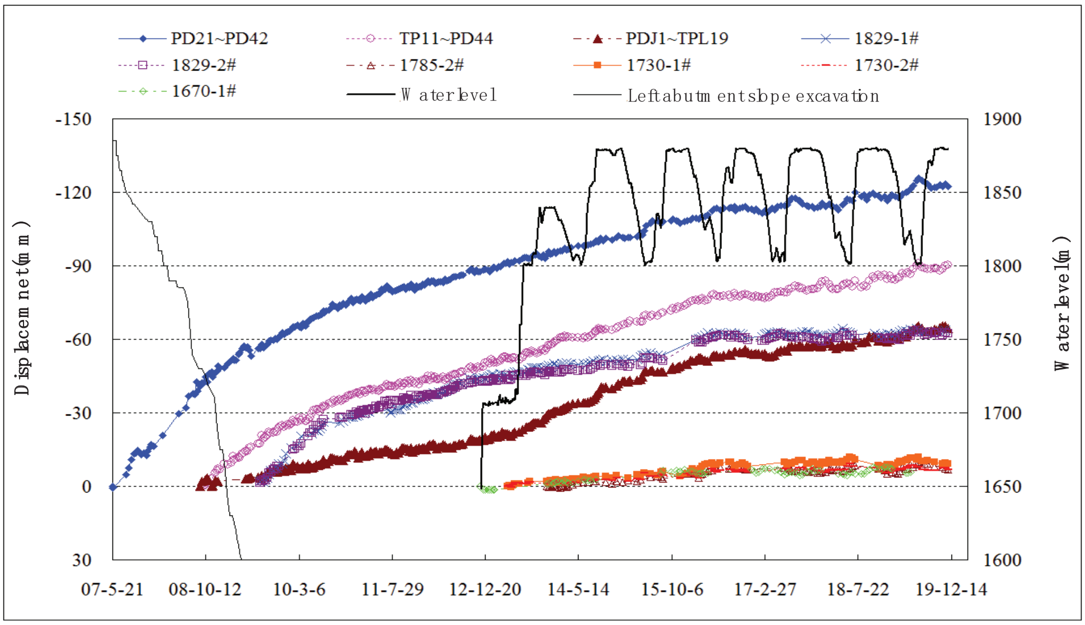


Figure 11 : Pass line of arch chord length Jinping I Dam

7. CONCLUSIONS

(1) The deformation of the left bank slope will have 3 deformation stages, namely, the deformation stage of slope excavation and unloading, the deformation adjustment stage when the effective stress adjustment and softening of rock mass immersed under water take place, and the stage of long-term deformation convergence. Until now, the slope is in the second stage, and “large block” is in a steady state.

(2) As the long-term deformation prediction and safety analysis suggested, the converge of left bank slope deformation will last for a long time till 2034; the long-term deformation will have little effect on the arch dam, and the slope is stable.

(3) As the over-load analysis of long-term deformation shown, the arch dam has strong overload capacity to slope deformation. Equally important, deformation of the dam foundation is small, thus the slope is stable, and the length change of dam chord is consistent with water level in like manner. In a word, the arch dam is proved to be safe under the long-term deformation of the slope.

(4) The effect of long-term deformation of the slope of the arch dam is complex, still requires comprehensive studies in a complex model, taking into account the concrete creep, dam temperature rise, slope and foundation Visco deformation and other factors, and even multi-field coupling effects, to further evaluate the effect of the long-term deformation on arch dam safety.

REFERENCES

China Renewable Energy Engineering Institute, 2007. DL/T 5346–2006 Design specification for concrete arch dams. Beijing: China Electric Power Press. Chinese.

Powerchina Chengdu Engineering Co., Ltd., 2015. Yalong River Jinping a hydropower station project special acceptance report.

Yang Qiang, Liu Yaoru, Cheng Li,Zhou Zhong,Xue lijun. 2015.Safety Study on Long-term Deformation of Left Bank Slope and the Mutual Influence of Arch Dam of Jinping I Hydropower Station, Tsinghua University Research Report.

Zhou Chuangbing, Jiang Qinghui, Wei Wei, 2015. Left bank slope long-term stability analysis and pre-diction', Wuhan University Research Report.

Zhou Zhong, Zhang Jing, Xue Lijun, 2017.The Left Abutment Slope Deformation and its effect on the safety of Jinping I Arch Dam, Yangtze River, No. 2, Vol.603.