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Stability Analysis of High Abutment Slope at Longjiang Arch Dam Based on Monitoring Data

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Abstract: The abutment slope located at the cable crane platform of left bank in Longjiang hydropower plant is high and steep, its stability directly related to the water intake safety of the hydropower plant. Since the slope appeared partial collapse, rockfall and other abnormal phenomenon during the construction process, anchor-drainage-barrier combined treatments were adopted to guarantee the slope stability, while monitor devices such as multi-point displacement meters and anchor dynamometers were installed to collect necessary information. Under the guidance of the principle of dynamic design, safety monitoring and feedback analysis, information management, the design of the controlling measures is reasonable and the monitoring system layout is appropriate. Therefore, a large number of effective information is obtained and provides the basis for the post-evolution of the control effects. The inner deformation and stress monitoring data of the high rock slope shows that the deformation of the reinforced slope tends to convergence and the slope is general stable, however its stability is still needed to be tracked and monitored considering the complex geological condition and remarkable influences of the rainfall of the slope.

Keywords: *Arch dam; cable crane platform of left bank; high slope; structural control effect*

1. Introduction

High rock slope stability directly influences the overall safety of large-scale water conservancy and hydropower project. In recent years, the reinforcement method of high slope is more targeted with theoretical study improvement and practical experiences accumulation. Taking Xiaowan hydropower station for example, multi-support measurements (such as hanging shotcrete, grid beam, self-drilling anchor, soil anchor) were carried out to deal with 700m-high slope near the drainage ditch in front of the dam[1]. In Longtan hydropower station, the height of rock slope at left abutment is more than 425.0m, integrated reinforcement measurements, including pre-stressed cable, ahead anchorage pile, ahead and systematic bolt, were set up to stable the slope[2]. Additionally, distinctive approaches for reinforcing high rock slope were applied in Hongjiadu, Jinping, Xiluodu, Xiangjiaba and other super large-scale hydropower projects and relatively good results were achieved.

The reinforcement effect of high rock slope has always been paid lots of attentions by researchers. Finite element and other numerical analysis methods based on rock mechanics and kinetic landslide theories are widely used in practice[3-6]. However, due to the limits of geographic theories and geo-survey techniques, the dynamic response of high rock slope is hardly gained during design and construction stages. Therefore, the evolution of high rock slope stability basing on monitoring data is alternative effective method and gains more and more attentions[7,8]. Comprehensive monitoring system is normally set up on high rock slope in large-scale water conservancy and hydropower project. Traditional study methods, such as regression analysis, artificial neural networks, Kalman filtering, fuzzy mathematics, catastrophe theory, are used to predict external deformation of the slope[9], meanwhile, few study is focused on stability evolution by internal monitoring data[10]. The high rock slope deformation and stress of Longjiang hydropower station are analyzed and studied, while reasonability of the comprehensive reinforcement measurements and the slope stability are evaluated.

2. Reinforcement Measurement

Partial collapse, falling rocks, local creep and other anomalies appeared during the construction process of Longjiang hydropower station, and the stability problem become more serious during rainy seasons. Figure 1(a) shows the slope state before reinforcement. The slope stability not only relates to the intake safety of the hydropower station, but also relates to the safety of the whole project. After detailed argumentation, a systematic measurement named ‘anchor – drainage – retention’ method is carried out to insure the slope stability. Figure 1(b) shows the slope state after reinforcement.

(1) Anchorage

The grid beam anchors with design tonnage of 200t were adopted between the elevation of 990.00m and 945.00m. The width and height of the grid are 0.6m and 0.4m separately, and the number and the location of anchors were adjusted by actual geology of the slope. The Φ25 6.3-merter-long mortar anchors with plum-shaped layout were used for rock slope, and were connected to surface steel mesh. The Φ25 1.5-merter-long anchor nails were used for weathered slope, and the same layout as mortar anchors was adopted. For strongly weathered rock slope and the weak weathered slope with elevations between 990.00m and 1020.00m, anchor nails were substituted with mortar anchors. In addition, steel bars were used to reinforce the slope according to the actual excavation situation. For the slope surface, 15.0 cm thick spray of C20 concrete and Φ6.5 @ 200mm steel mesh with 3.5cm protection thick inside were adopted and were connected to anchor bar and anchor nails.

(2)Slope drainage

The shallow-deep drainage mode was used for the slope surface. For the shallow drainage, the 3.0m-deep, 3.0m row spacing and 5°～10° elevation angle drainage holes were drilled, meanwhile, for the deep drainage below the elevation 1020.00m, the two rows of drainage holes were set up on each bridleway and the actual parameters are based on the weathering degree of the rock. The Φ90.0mm drainage holes with 20.0m depth, 5°～10° elevation angle and plum-shaped layout were drilled for the rock slope in good conditions. While for the strongly weathered rock slope, the parameters of the drainage holes are almost the same as which have been mentioned before and moreover, the Φ80.0mm PVC water pipes were installed to enhance the drainage effect.

(3) Concrete retaining wall

The C20 concrete retaining wall was set in elevation between 927.00m and 937.00m to support the potential rock slope sliding body. The original cable machine track foundation concrete was used as the bottom of the retaining wall and was kept the same elevation which is 927.00m. The retaining scale and separating ways are corresponding to the track basis of the original cable machine. In the vertical direction to the slope, 200t anchors and systematic anchors are used. The connecting anchor steels were installed between retaining wall and the cable machine base while anti-crack steel mesh was set on the upper part of the wall.

(a) Before reinforcement

(b) After reinforcement

Figure 1.*Overall perspectives of high slope at cable crane platform of left abutment in Longjiang hydropower plant*

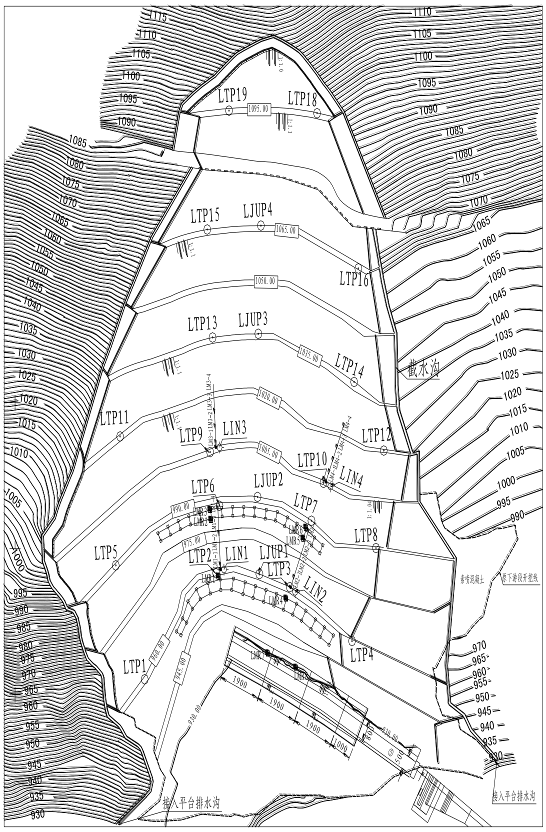
3. Evaluation of slope stability based on monitoring data

3.1. Monitoring layout of the slope

The maximum cross section was selected as the main monitoring section according to the geological condition and the stability analysis of the cable crane platform of left abutment and another observational section was also selected as an auxiliary section. Internal and external deformation observations were carried out in-situ. Main monitoring projects include: (1) 18 external horizontal displacement measuring points were laid in the elevations of 960.00m, 990.00m, 1005.00m and 1095.00m; (2) 2 sets of multi-point displacement meter and 2 sets of inclinometer were arranged in the elevations of 957.00m, 982.00m and 987.00m; (3) 8 sets of three wire anchor dynamometer were furnished in the elevations of 957.00m, 982.00m and 987.00m; (4) 3 sets of anchor stress meter were set in the elevations of 940.00m, 970.00m and 975.00m; (5) 4 holes for monitoring groundwater were drilled in the elevations of 990.00m, 1005.00m, 1035.00m and 1065.00m. Main layout of monitoring sections is shown in Figure 2 and numbers indicate elevation (unit: m).

3.2. Slope stability evaluation

The reinforcement measurements of left bank slope has completed in May 2012. No new rainy season collapse, rockfall phenomena occurred on the slope after reinforcement. The overall perspective of the slope after reinforcement was shown in Figure 1 (b). The analysis of this paper mainly focuses on the data of multi-point displacement meter and monitor internal stresses rock anchor dynamometer, etc. internal monitoring instruments, and finally the stability of the rock slope is evaluated.



LTP-External deformation measuring point; LM- Multi-point displacement meter; LIN- Inclinometer; LJUP- Groundwater; LMR- Anchor dynamometer

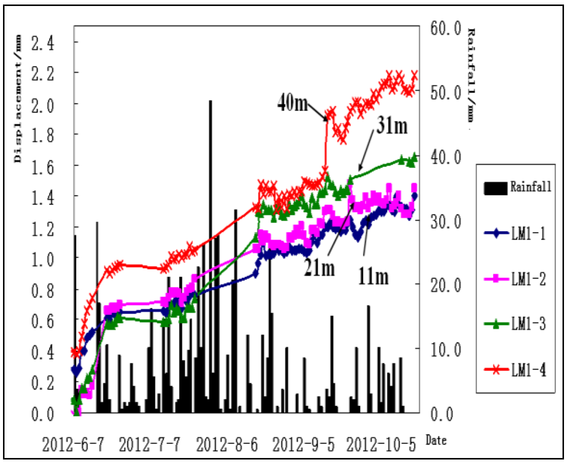
Figure2. *Layout of main monitoring cross-section*

(1) Rock internal deformation

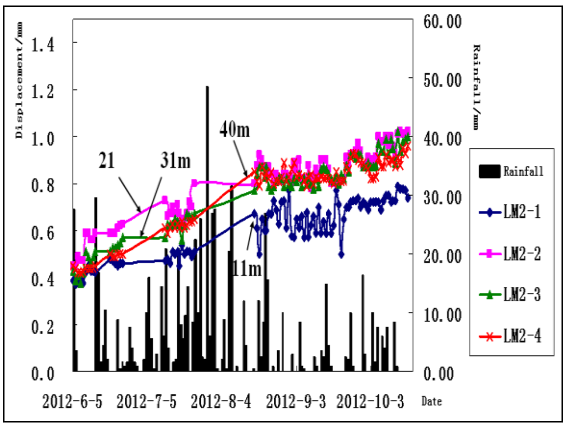
Multiple-point displacement meters LM1, LM2 and LM4 are selected as the study samples. The monitoring displacement time-history curves from June to October in 2012 are shown in Figure 3 and the displacement and its changing rate are shown in Table 1. Judging from the displacement curves, the overall performance of the rock internal deformation is in the creep state and most of the displacement measuring points are still slowly increasing. The spatial distribution of rock displacement is that the higher elevation the larger value of displacement while uniform distribution within the same elevation. The measured maximum displacement value is 4.33mm, appeared in 1006.00m elevation LM4-1 measuring point. Other measuring values of LM1, LM2 are between 0.96mm ~ 2.18mm. During the rainy season of July and August, most displacements value experienced varying amplitude increases and stabilized later. The variation of rock displacement indicates that the slope is significantly affected by rainfall and infiltration.

Except the rainfall effect, the rock displacements are influenced by geological conditions. From the same location at different depths of the rock deformation perspective, different locations showed different rock mass displacement variation. For example multi-point displacement meter LM1 crossing the joints J1 in elevation 960.00m and adjacent to the joints measuring points are LM1-3 and LM1-4, the rock internal deformation of the location increases with depth, shown in Figure 3 (a). The maximum displacement which is 2.18mm occurs in LM1-4(depth 40.0m) while the minimum displacement is only 1.4mm which occurs in LM1-1(depth 11.0m). In the elevation 1006.00m, the displacement curve of LM4 which is set in intact rock is shown in figure 3(c), where the maximum displacement which is 4.33mm occurs in LM4-1(depth 11.0m), while the displacement variations of other three measuring points are consistent.

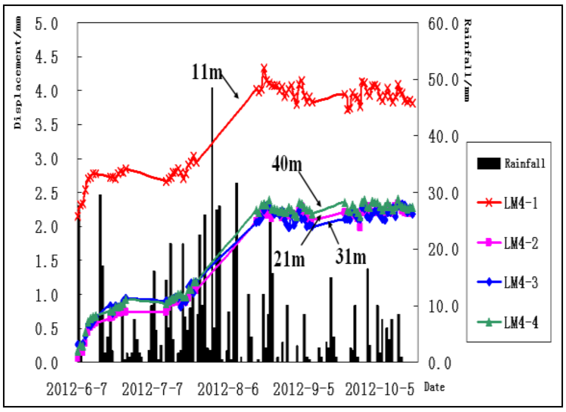
From Table 1 the change rate of displacement, the occurrence of the maximum rate and the larger displacement position are consistent. The maximum change rates of LM1-4 and LM4-1 are 0.36mm•d-1 and 0.37mm•d-1 respectively. From the time-history curve of displacement (Figure 3), larger displacement change rates are not continuous and only occur in the stage when displacement changing steadily. Meanwhile, the average monthly displacement change rates are generally small while the values are between 0.001 and 0.040mm•d-1, which indicates that the deformation of the slope is generally stable.



a) 960.00m-LM1



b) 960.00m-LM2



c) 1006.00m-LM4

Figure 3.*Time-history curves of deformations of multi-displacement meters*

(2) Rock internal stress

The essence of reinforcing rock by pre-stressed anchor is that the anchors and rock together form a work system. The tensile pressure of anchor makes rock in compression and the external loads along the depth direction of the anchor hole extend simultaneously to spread around the anchor tensile force within the affected areas of rock in compression, and thus the shear strength of rock and its own stability can be improved [11]. The deformations of anchor and reinforced rock are consistent and their variations are interconnected and influenced mutually, that is the coupled effect between the rock creep and anchorage force variation of pre-stress anchor. Therefore the losses of anchorage force can objectively reflect the situation of rock creep. Table 2 shows the losses of anchorage force of anchors on the slope and the loss rates are between 0.16% and 2.28%, which indicate that pre-stress anchors play a good role for reinforcement of the slope.

Table 1.*Displacement and its changing rate of multi-displacement meters*

Measuring point	**Maximum displacement (mm)**	**Date (y-m-d)**	**Displacement change rate ($mm \cdot d^{-1}$)**	**Date (y-m-d)**	**Average monthly displacement change rate ($mm \cdot d^{-1}$)**
LM1-1	1.40	2012-10-18	0.11	2012-6-10	0.006-0.019
LM1-2	1.48	2012-9-23	0.24	2012-9-23	0.004-0.033
LM1-3	1.65	2012-10-18	0.17	2012-8-18	0.010-0.040
LM1-4	2.18	2012-10-18	0.36	2012-9-14	0.005-0.029
LM2-1	0.79	2012-10-14	0.16	2012-8-31	0.002-0.007
LM2-2	1.02	2012-10-18	0.12	2012-6-10	0.001-0.009
LM2-3	1.02	2012-10-14	0.13	2012-10-14	0.002-0.008
LM2-4	0.96	2012-10-18	0.08	2012-10-6	0.001-0.005
LM4-1	4.33	2012-8-20	0.37	2012-9-28	0.007-0.037
LM4-2	2.33	2012-10-12	0.24	2012-9-28	0.007-0.036
LM4-3	2.33	2012-10-14	0.22	2012-7-21	0.004-0.036
LM4-4	2.40	2012-10-12	0.21	2012-9-28	0.001-0.040

Table 2.*Pre-stress loss of anchor dynamometers*

	LMR1	**LMR2**	**LMR3**	**LMR4**	**LMR5**	**LMR7**	**LMR8**
Initial anchorage force(kN)	1640	1670	1700	1700	1550	1750	2000
Average loss rate(%)	0.16	0.22	0.19	1.67	2.28	1.12	0.50

4. Conclusion

(1) The high rock slope at the cable machine platform of Longjiang hydropower station is steep and of complex geological condition, whose stability not only affects the intake security of hydropower station, but also directly relates to the dam safety. Under the guidance of the concept ‘Dynamic design, safety monitoring and feedback analysis, information management’, and through the ‘anchor – drainage – retention’ comprehensive reinforcement measures, the overall stability of the slope is ensured.

(2) Dominating concrete retaining wall and pre-stress anchor, supplementing anchor bar, steel hanging nets and other measures, uniting shallow-deep drainage measures, a comprehensive and multi-level slope reinforcement system is formed. From the practical point of view, the system is effective and reliable.

(3) The analysis of the high slope deformation and stress based on measured monitoring data is a reasonable and effective supplement to the numerical method, and is also an important mean to grasp the slope security state and to discover and eliminate the hidden dangers. The monitoring data of Longjiang hydropower station shows that the rock slope deformation become converge after reinforcement and is generally stable. However, in view of the complex geological

conditions and the fact that the slope is significantly affected by rainfall, its stability and monitoring data still need to be continually tracked and analyzed.

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