Valley Deformation and Slope Seismic Analysis near Tail Water Outlet of a Hydropower Station

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Abstract. The safety and stability problems of high rock slope, such as weaken massif, fully developed geological conformations, widely unloaded or flabby rock layer, and squirming or sliding rock, are often encountered in engineering practice. So it is important to enforce the high slope rock deformation monitoring, and to process and analyze the measuring data timely. The high slope of the left-bank tailrace outlet of Wudongde hydropower station in Jinsha river is given as an example to analyze valley deformation, and to evaluate the seismic stability of high slope by utilizing rock deformation monitoring data. The field data of rock deformation of the left-bank tailrace outlet slope were collected by monitoring system, along with the field data of valley deformation. Based on monitoring data of the left-bank tailrace outlet slope deformation and valley width reduction of Wudongde hydropower station, the time and space deformation distribution regularity of rock mass were summarized. Analysis results and monitoring records reveal the general law of valley deformation, and demonstrate that excavating and other perturbations can quicken the creep deformation of rock mass, and the damage will not happen under action of earthquake.

1. Engineering background
Wudongde Hydropower Station is the most upstream step in the lower reaches of Jinsha river (from Panzhihua city to Yibin city) - Wudongde, Baihetan, Xiluodu and Xiangjiaba. The right bank of the dam site is subordinate to Luquan county, Kunming city, Yunnan province, and the left bank belongs to Huidong county, Sichuan province. The power station is 213.9 km away from Panzhihua city, and 182.5 km distant from Baihetan hydropower station. The linear distances from Kunming, Chengdu, Wuhan, and Shanghai are respectively 125 km, 470 km, 1250 km, and 1950 km. The watershed area and the interannual average discharge of Wudongde water control project are 46,1000 km² and 3830 m³/s , and the annual average runoff is 1207 billion m³. The project is mainly composed of concrete hyperbolic arch dam, subsidiary dam, plunge pool, flood discharge tunnel, pilot generating system and other buildings. The maximum height of arch dam is 270 m. The main task of Wudongde hydropower
station is to generate electricity, and the installed capacity is 10,200 MW, and the average annual power generation is 38.93 billion KW. Besides that, it takes into account the comprehensive utilization of flood control shipping and sediment storage.

In the process of hydropower station development, the stability issue of bank slope is more and more prominent. The analysis methods of slope stability mainly includes the limit equilibrium method and numerical method\[1, 2\]. Field monitoring data analysis, physical model test and numerical simulation methods\[3~5\] are the major methods adopted by the research on landslide deformation and instability mechanism. In recent years, numerical simulation technology has made great progress in slope stability analysis\[6~8\].

2. Geological conditions

The layers of tailwater outlet slope on the right bank of Wudongde underground power station are mainly composed of Pt\(_{21}^{9}\) grey thin-layer limestone and Pt\(_{21}^{10}\) grey medium thick limestone. The slope structure is steep and transverse, the strong unloading zone is generally 10 m wide, and the weak unloading zone is generally 16 m ~ 25 m wide. The middle gentle slope of elevation 950 m ~ 1060 m is buffered for its upper topmost collapse stone, and the developmental block of slope may affect the safe of construction and engineering operating. The lithology of tailwater outlet slope on the right bank is complex, and the rock mass within the effected scope is mainly composed of group 8, 9, 10 segments of Pt\(_{80}\). Overall surrounding rock is given priority to class II and III, and mechanics parameters of rock mass is good. The shallow strong and weak unloading zones are on slope surface, the material parameters of rock mass are relatively poor.

3. Valley monitoring

The side slope of the plunge pool of the spillway tunnel on the left bank is opposite to the side slope of the tailrace exit on the right bank. The horizontal displacement at the same elevation to the direction of overhead is equivalent to the grain width. Valley height survey lines 3~7 are selected by the horizontal displacements of 955 m, 955 m, 925 m, 895 m and 865 m height, as shown in Figure 1.

![Figure 1. Layout of measuring valley line.](image-url)

The displacements of the five valley lines arranged are shown in Figure 2. The valley has increased significantly from dozens to hundreds of millimeters for the past five years. The No.3 at the elevation
of 955 m is maximum, while No.6 at the elevation of 895 m is minimum. Most of the deformation of high elevation is greater than that of low elevation, but there is no correlation.

At present, the amplitude of valley deformation is increasing in no impoundment period. The value occupies a large volume especially in past two years. The main reason is the side slope of the plunge pool of the spillway tunnel on the left bank has large deformation, while the side slope of the tailrace exit on the right bank has small deformation with only a few millimeters, which show that its static stability is better. Here is the method for employing the finite element to analysis the stability of seismic conditions of the slope.

4. Earthquake analysis

4.1. Calculation model
The 3-D numerical calculation model of excavation slope is shown in Figure 2. The calculation model mainly includes the tailrace exit slope on the right bank, tailrace tunnel, high diversion tunnel, etc. The origin of coordinates is located at the center point of the high diversion tunnel exit. The $X$ axis coincides with axis of tailrace tunnel, the direction pointing to the tailrace tunnel exit is positive, and the $Y$ axis points from 6# tailrace tunnel to 4# tailrace tunnel is positive. The $Z$ axis coincides with the geodetic coordinate system and the upward direction is positive.

![Figure 2. Valley deformation.](image)

![Figure 3. Design sketch and numerical model.](image)
Tailwater outlet slope on the right bank is chosen as the research object, using the finite element of three dimensional elastoplastic method to calculate the whole stability of tailwater outlet slope. Slope calculation range is 268.18 m×230.90 m×339.00 m (x×y×z). A total of 47665 units and 51202 nodes are divided. Numerical calculation consists of 11 stages of excavation, the first two excavation stages are excavation for high diversion tunnel and tailrace tunnel at intervals, and the 3 to 11 stages are excavation for outlet slope.

The lithology of slope is complex, Rock mass within the affected scope is mainly composed of group 8, 9, 10 segments of Ptknl. Overall surrounding rock is given priority to class II and III, and mechanics parameters of rock mass is good. The shallow strong and weak unloading zones are on slope surface, the material parameters of rock mass are relatively poor.

The initial geo-stress field is used as gravity stress field, and the lateral pressure coefficient is selected as 0.8 according to the measured results of both the in-situ stress measurement points nearby and the comprehensive comparison.

4.2. Calculation conditions

The disturbed ground stress field running period of rock mass is using to analysis ground stress field. Bedrock ground motion parameter in site is 50 years exceeding probability 5%. The peak ground acceleration (PGA) is 0.17g, the magnification coefficient is 2.25, and the characteristic period is 0.2 s. The ground motion input time-history is provided by earthquake engineering research institute of Yunnan, as shown in Figure 4(a) and 4(b). In the calculation only vertical and horizontal earthquake ground motion has been considered, and the PGA of vertical horizontal earthquake ground motion is 2/3 of horizontal. According to similar engineering experience, the damping ratio is 5%.

4.3. Displacement distribution of slope

The displacement time history and acceleration are shown in Figure 5. From the results of computation, the waves of displacement time history agree with certain earthquake waves. The plastic displacement has little change during the earthquake, mostly in wave motion and elastic displacement. Most of the deformation can be restored after the earthquake. The calculated values of monitoring points in surface of each slope are similar to design values from acceleration response spectrum, and the maximum value of magnification coefficient is 1.3. Relative displacement of slope is gradually accelerated from bottom to top which is based on the bottom of 5#tailrace tunnel after the earthquake. The maximum value of relative displacement is 7.3 mm and located at the top, which is smaller than that of surrounding rock deformation in the soil excavation stage. On the whole, the slope deformation is primarily elastic deformation under earthquake, the amplification effect of free surface is not obvious, and the overall thickness deformation is relatively small.
4.4. Failure distribution of slope
The distribution condition of failure area is shown in Figure 6. The regularity of distribution condition of failure area of the overall under seismic loading and under normal operating conditions are basically the same. Destruction scope has been concentrated tunnel-face side slope of 5# and 6# tailrace tunnel, and the damage is relatively serious at slope toe. The range of original failure zones are further developed under seismic loading, but limited. Overall, the range of failure zones is currently quite limited, and the failure depth is in bolt support control.

4.5. Stress distribution of slope
The distributing disciplinarian of slope stress under seismic loading and at runtime is basically the same. The first principal stress are -0.22 MPa~3.53 MPa. The tunnel-face side slope of 5# and 6# tailrace tunnel have been a modest stress concentration. The third main stress are -0.15 MPa~1.43 MPa, the tensile stress areas are distributed mainly at middle part of 5# and 6# slopes. On the whole, after earthquake, the slope stress under seismic wave additional stress field have a certain range of concussion, but peak stress is in the allowable range of carrying capacity of rock mass, and the whole stresses distribution is regulated.

To summarize, the seismic stability of side slope of the tailrace exit of Wudongde hydropower station is good. So there will be no instability failure under earthquake.

5. Conclusions
This paper studies on valley deformation of the side slope of the tailrace exit and the seismic stability of side slope on the right bank with simulation through analysis on observed deformation data of dam area of Wudongde hydropower station. It shows that the slope has better seismic stability, and there will be no instability failure under earthquake.
After post-impoundment, rock mass of slope will be softened under the action of seepage. So it is necessary to be constantly monitored, and to strengthen monitoring force and widen deformation monitor scope of the reservoir area.

Analysis of valley deformation regularity, safety behavior and the rock deformation of high slope based on safety monitoring data are the rational supplement for current numerical simulation. The effective combination between safety monitoring data and numerical simulation will be helpful to reveal the properties of rock deformation of high slope, and will be important to the timely discovery and early eliminate for safety risk.

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