Safety monitoring and stability analysis of left abutment slope of Jinping I hydropower station

Shengwu Song*, Dewen Cai, Xuemin Feng, Xiaopeng Chen, Dikai Wang

Chengdu Hydroelectric Investigation and Design Institute, China Hydropower Engineering Consulting Group Corporation, Chengdu, 610072, China

Received 19 November 2010; received in revised form 6 May 2011; accepted 15 May 2011

Abstract: Safety monitoring and stability analysis of high slopes are important for high dam construction in high mountainous regions or precipitous gorges. In this paper, deformation characteristics of toppling block at upper abutment, deforming tensile rip wedge in the middle part and deep fractures are comprehensively analyzed based on the geological conditions, construction methods and monitoring results of left abutment slope in Jinping I hydropower station. Safety analyses of surface and shallow-buried rock masses and the corresponding anchorage system are presented. The monitoring results indicate that the global stability of the large wedge block in the left abutment is effectively under control, and the abutment slope is stable in a global sense. After the completion of excavation, the deformations of toppling block at the top of the slope and deep fracture zone continue at a very low rate, which can be explained as “rock mass creep”. Further monitoring and analysis are needed.

Key words: Jinping I hydropower station; left abutment slope; safety monitoring; analysis and evaluation; stability analysis

1 Introduction

Jinping I hydropower station is located at the border of Yanyuan and Muli counties in Sichuan Province, China. It is built on the Yalong River as a controlling cascade hydropower station in the middle and downstream of the main stem. The project consists of concrete double-curvature arch dam, diversion tunnels on the right bank, flood discharge and energy dissipation structures. The arch dam is 305 m in height, the highest one under construction in the world. The total reservoir capacity is 7.76 × 10^9 m^3 at a normal water level of 1 880 m, and the annual regulating reservoir capacity is 4.91 × 10^9 m^3.

The dam site is located in the region composed of precipitous gorges and sharply incised valley. Relative height difference of slopes can reach up to 1 000–1 700 m, with a declination of 30°–90°. The entire right bank and two thirds of the downstream left bank are hosted on rock group T^2_{2-3zT}, which predominantly consists of marble with schist interbeds. Above the elevations of 1 820–1 900 m, the rocks in the left bank mainly consist of metasandstone and slate of group T^3_{2-3zT}. Complex geological structure, together with variable strata and stress-relief disturbance, has affected the stability of rock masses on both sides of the river. The left bank slope, with ridges and gutters around, is cut by bedding planes that have a stride towards the hillside, with inclinations of 55°–70°.

The total height of excavated slope on the left abutment is approximately 530 m (at the elevation of 1 580–2 110 m), and the maximum horizontal excavation depth is 130 m (at the elevation of 1 730 m). The maximum excavation width is 350 m, and the total excavation volume reaches 5.50 × 10^6 m^3. As far as concerned, the left abutment slope is one of the hydropower projects with the largest excavation scale in rock engineering. What is worse, the geological condition is considerably complex and the stability situation is not encouraging. Excavation of the left abutment slope started in September 2005, and the dam crest (at the elevation of 1 885 m) excavation was completed in June 2007. The excavation continued and advanced to the concrete cushion foundation platform (at the elevation of 1 730 m) when the dam foundation in the riverbed (at the elevation of 1 580 m)
was excavated in August 2009 (Fig.1). During construction, systematic studies and analyses of slope stability and corresponding reinforcement measures had been reported [1–14]. Based on the fruitful works, some ideas and issues of high slope engineering are presented from the perspectives of safety monitoring and stability analysis in this paper.

The rocks in the left abutment have an attitude of N0°–30°E and a strike of NW ∠ 25°–45°. NE–NNE fractures in the slope are largely scaled and they are most developed among the faults, such as faults f5, f6, f2, and lamprophyre dyke (X), with attitudes of N30°– 50°E/SE60°–80°, and fractured zones of 1–3 m in width. The secondarily developed fractures have a strike of NEE–EW, represented by fault f2, with an attitude of EW/S40°–60°. There are mainly 3 sets of joints and fissures developed in rock masses: (1) N15°– 35°E, NW ∠ 30°–45°, bedding fissures; (2) SN–N30°E, SE ∠ 60°–80°; and (3) N50°–70°E, SE ∠ 50°–80°.

Generally, the left abutment slope is characterized by a large unloading depth, wide aperture of unloading fissures and complex unloading types, including shallow unloading and deep unloading. Before excavation, the horizontal depth of strong unloading zone in the slope is 70–100 m, with those of shallow and deep unloading zones more than 200 and 250–300 m, respectively.

Deep fractures above the elevation of 1 900 m are strongly developed in the slope of dam left abutment. 25 deep fractures with considerably large scale have been recorded according to the in-situ investigations in 3 adits. These deep fractures are mainly developed inside the fault f5. The maximum horizontal depth is greater than 330 m, and the width of relaxed rock zone of single fracture is 10–20 m. The fractures are mainly of extension type, and an average dislocation of 5–10 cm (the maximum is 30 cm) can be found in some hanging walls of fractures. Fractures are not filled or just filled with a few rock blocks or breccia, and they are generally developed from existing small faults.

Deep fractures below the elevation of 1 900 m in the dam left abutment slope are slightly developed. Only 27 deep fractures are found according to the investigations in 17 adits. These deep fractures are usually small-scale and scattered. They are mainly developed between the horizontal depth of 80–140 m, and the average width of relaxed rock zone of single fracture is 2–6 m (the maximum is 12 m). The inner surfaces of the fractures are fresh and mostly not filled. The fractures are also of extension type, and the dislocation movement is rarely found.

The attitudes of deep fractures can be classified into two sets predominately: N30°–70°E/SE 50°–75° and N0°–30°E/SE 50°–65°. The preferential attitude of deep fractures is commonly the same as the direction of faults in the dam site.

According to the classification methods of slope structures [12–14], the left abutment slope can mainly
be categorized in three types: consequent toppling block, wedge with two sliding surfaces (Fig.2) and massive slope structure.

2.2 Slope treatment

The strike of crane-rail platform slope above the elevation of 1 960 m on the left bank is predominantly N28°E. The top elevation of this slope is 2 050–2 100 m, with a maximum height of 90–140 m. 2–4 berms are arranged on the surface of the slope with a ratio of 1:0.50.

Two berms with a slope ratio of 1:0.50, at the elevations of 1 945 and 1 915 m, respectively, are designed in the slope between the elevations of 1 885–1 960 m. The strikes of its northern section, middle section and southern section are N54°E, N22°–38°E and nearly SN, respectively.

A huge bell-mouth-shaped topography is formed after the slope excavation below the elevation of 1 885 m on the left abutment. A berm, 15 m in height, is set on the slope surface. The strike of upstream slope is nearly SN, with a slope ratio of 1:0.45. The strike of spandrel slope is NE–NEE, and that of downstream slope is NW–NWW, with a slope ratio of 1:0.50.

According to the design, the reinforcement of surface slope and shallow-buried rock masses is considered. The materials used are listed as follows: (1) shotcrete with a total volume of 24 009 m$^3$; (2) 54 140 rock bolts (6 or 9 m in length); (3) 3 558 anchors (12 m in length and a spacing of 2.5 m × 2.5 m); and (4) 4 068 prestressed anchor cables (grades of 2 000 and 3 000 kN). The shotcrete is 20 cm in width. The bars employed in the shotcrete have a diameter of 10 mm and a spacing of 15 cm × 15 cm. Long bolts are installed in the berms of slope. The spacing of concrete grid beams is 4 m × 4 m with a cross-section of 60 cm × 80 cm. The lengths of the prestressed anchors are 40, 60 and 80 m, respectively. They can penetrate through the controlling discontinuities in rock masses to ensure the global stability of the slope.

In addition, reinforcement of deep-seated slope is also conducted by using concrete shear galleries, which are implemented along the fault $f_{42-9}$, and concrete replacement of lamprophyre dyke (X) inside the slope is also considered. Three key concrete shear galleries are located at elevations of 1 883, 1 860 and 1 834 m, respectively, with a cross-section of 9 m × 10 m.

2.3 Monitoring schemes

2.3.1 Issues of slope stability and monitoring

After excavation, the overall stability of the left abutment slope is approximately controlled by the large wedge block (Fig.2). Boundary surfaces of fault $f_{42-9}$, lamprophyre dyke (X) and tensile fracture zones SL$^{441}$ should all be monitored systematically. The rock masses outside the fault $f_5$ and the shallow-buried (or surface) rock masses (0–80 m in depth) are loose and broken. Thus, local instability of rock masses may be encountered. The issues of toppling and raveling of shallow-buried blocks have attracted great attentions, and the loose and broken rock masses should be reinforced comprehensively and systematically. The construction process and effect of safety controlling should be verified by monitoring. The problem whether the deep fractures continue to deform (Fig.3) during construction needs to be solved. Furthermore, the long-term stability of the slope induced by the deep fractures and the unfavorable effects on the resistant block of left abutment and arch dam should be concerned, and field monitoring and analysis are needed.
In this paper, emphasis is put on the monitoring of the left abutment slope, i.e. the large wedge block and the deep fractures, followed by shallow-buried or/and localized blocks in slope surface.

2.3.2 Monitoring layout

Monitoring is implemented for four types of facilities in the left abutment, i.e. slope surfaces, shallow-buried rock masses, deep rock masses and special structures. Monitoring items are primarily focused on slope deformation, followed by anchor loads and mechanical behaviors of structures. The most commonly used monitoring instruments include ground observation platform, graphite pole convergence meter, anchor cable dynamometer and multi-point extensometer. Comparative monitoring at both sides of faults, dykes and deep fractures is taken into account when the overall performance of the slope is monitored (Table 1).

### Table 1 Distribution of monitoring instruments on the left abutment slope.

<table>
<thead>
<tr>
<th>Position</th>
<th>Monitoring item</th>
<th>Monitoring object</th>
<th>Monitoring location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope surface</td>
<td>Deformation</td>
<td>Surface rock mass</td>
<td>Toppling blocks of slope surface and slope above the elevation of 2 000 m</td>
</tr>
<tr>
<td>Shallow-buried slope</td>
<td>Rock mass</td>
<td>Consequent toppling blocks</td>
<td>Small localized blocks and shallow-buried rock mass outside large wedge</td>
</tr>
<tr>
<td>Large wedge block</td>
<td>Displacement of</td>
<td>Large wedge block</td>
<td>Large deformation and shear key galleries along the fault f_{12-9}, two replacement galleries in the fault f_{s6}, and three replacement galleries in lamprophyre dyke (X)</td>
</tr>
<tr>
<td>Large wedge block</td>
<td>Mechanical</td>
<td>Shear key and replacement galleries</td>
<td>Three curtain grouting galleries at the depth of 0–330 m</td>
</tr>
<tr>
<td>Deep rock mass</td>
<td>Deep fractures</td>
<td>Resistance block</td>
<td>Four consolidation</td>
</tr>
<tr>
<td></td>
<td>Displacement</td>
<td>Dam foundation</td>
<td>Grooving galleries at the depth of 0–330 m</td>
</tr>
</tbody>
</table>

Anchorage system is adopted mainly for the reinforcement of slope at a depth of 0–80 m, as well as the local stability of blocks. Observation platforms are arranged on the slope surface. There are 3 and 8 monitoring sections above and below the elevation of 1 960 m, respectively. They are distributed with a uniform spacing along the strike of slope. Anchor load tensiometers are installed on 5% of total anchors randomly. Bolt are arranged with multi-point extensometers to mutually verify the monitoring results.

Monitoring of deep rock mass is to understand the overall and long-term stability of slope. Two or three monitoring sections perpendicular to the slope surface are arranged, with the main cross-section at 0+26. Monitoring instruments are installed at 5 layers of galleries (i.e. adits PD44 and PD42 at the elevation of 1 930 m, two drainage galleries at the elevation of 1 915 m, and three curtain grouting galleries at the elevations of 1 885, 1 829 and 1 785 m, respectively). Elevation difference between galleries is 30–60 m. The depth of monitored rock mass is usually more than 100 m, and the maximum is 330 m. The monitoring locations cover deep fractures, dykes and faults in rock masses. The instruments for the monitoring of deep rock masses include graphite pole convergence meter, displacement across valley (DAV) measuring line, leveling point and sliding micrometer.

Instruments are installed in the resistant rock block of the foundation treatment galleries to monitor the mechanical behavior of local structures. Two or three monitoring sections are adopted: three key concrete shear galleries along the fault f_{12-9}, two concrete replacement galleries of the fault f_{s6}, and three of the lamprophyre dyke (X). The monitoring instruments for those positions include stress and strain meters for reinforced concrete structure and deformation meters for surrounding rock.

### 3 Monitoring results of slope surface deformation and analysis

Five rows of observation platforms are arranged along berms above the elevation of 1 885 m (height of dam crest), with an elevation difference of around 30 m between adjacent rows and a horizontal spacing of 30–50 m. Geodetic method is adopted and the controlling points on the right bank are used as base points during construction. Horizontal displacement is observed by angular intersection method, with an accuracy of ±2 mm. Elevation difference is observed and modified by triangle elevation network. The controlling network is checked every six months, and the observation is carried out twice per month at each
monitoring point. Observation began in December 2005, and monitoring points were rearranged successively according to their elevations, generally 60 m above the excavation face of slope. The excavation and support of left abutment slope were completed in mid May 2009. Then, the left abutment slope was put into operation.

3.1 Slope above the elevation of 1 960 m

The deformation characteristics of monitoring points on the left abutment are shown in Table 2, and the time-history curves of the horizontal deformation of monitoring points above the elevation of 1 960 m are shown in Fig.4.

<table>
<thead>
<tr>
<th>Position</th>
<th>Excavation period (month)</th>
<th>Number of monitoring points</th>
<th>Horizontal displacement (mm)</th>
<th>Increasing rate (mm/month)</th>
<th>Excavation period</th>
<th>Operation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope surface</td>
<td>40.8</td>
<td>7</td>
<td>95.4</td>
<td>113.58</td>
<td>1.76</td>
<td>1.09</td>
</tr>
<tr>
<td>Elevation of 2 020 m</td>
<td>23.7</td>
<td>9</td>
<td>55.6</td>
<td>93.30</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Elevation of 1 990 m</td>
<td>15.8</td>
<td>7</td>
<td>35.6</td>
<td>41.52</td>
<td>1.16</td>
<td>0.94</td>
</tr>
<tr>
<td>Elevation of 1 960 m</td>
<td>14.7</td>
<td>5</td>
<td>32.4</td>
<td>44.61</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Elevation of 1 915 m</td>
<td>15.8</td>
<td>5</td>
<td>29.0</td>
<td>36.67</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Elevation of 1 885 m</td>
<td>16.6</td>
<td>4</td>
<td>45.4</td>
<td>61.89</td>
<td>1.72</td>
<td>1.29</td>
</tr>
<tr>
<td>Below the elevation of 1 885 m</td>
<td>6</td>
<td>15.2</td>
<td>19.64</td>
<td>1.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Operation period is 20 months.

From Table 2, it can be observed as follows:

(1) Deformation of measuring points at the same elevation is almost simultaneous, and the deformation rate at different elevations during operation period keeps constant, implying that the deformation of the slope surface is uniform generally. Thus, the deformation mechanism of the slope is the same.

(2) The slope above the elevation of 2 000 m is characterized by toppling blocks. During slope excavation, the deformation rate of shallow-buried rock masses in the slope is slightly larger than that of deep rock masses, with the features of toppling and raveling.

(3) In excavation period, the deformation rate is closely related to the excavation process. After excavation, the displacement rate is decreased by 30%–40%. It shows that the excavation of slope is the main reason that causes the surface deformation.

(4) The orientation of the horizontal resultant displacement is ES40°–77°, with an average angle of 57°. And its inclination approaches the upstream free surface. The direction of slope deformation is consistent with the dip of fault f42-9, lamprophyre dyke (X) and sandstone slate layer, with a tendency along the structural planes.

From the above analyses, the deformation rate in the slope decreases greatly after excavation, and excavation unloading is one of the main reasons...
causing deformation of slope. However, the deformation of the toppling blocks above the elevation of 2000 m is still increasing slowly so far, which should be concerned.

3.2 Slope below the elevation of 1960 m

Few measuring points below the elevation of 1960 m were considered during excavation. The displacement time-histories of these points are shown in Fig.5. It can be observed that the deformation of these measuring points in operation period is almost simultaneous, and the horizontal resultant displacement is towards the upstream free face with an average angle of ES44°.

3.3 Brief summary

The monitoring results show that deformation of slope is mainly characterized by the integrity and synchronicity of rock mass deformation. Direction of slope deformation is consistent with the dip of structural planes and rock layers, towards the upstream free face. Deflection angle of deformation at the elevation of 1960 m is slightly small because of the strike of spandrel slope.

During construction period, the deformation is mainly controlled by excavation of slope. There is a significant continuous deformation in operation period, which can be explained by rock mass creep (different from rock creep), and it is closely related to slope structure and geological conditions. Further studies on the deformation mechanism of rock mass creep are needed.

4 Deformation analysis of shallow-buried rock mass

Shallow-buried and surface rock masses, including toppling rock mass, unloaded ripping rock mass with a strike towards the river and other locally unstable blocks, are needed to be reinforced by anchorage system. Monitoring instruments mainly include multi-point extensometer and cable load cells.

4.1 Deformation of local blocks during construction

The monitoring depth of multi-point borehole extensometer (MPBX) is considered to be 50–85 m, 5 m deeper than the fixed end of anchors. Results of these MPBXs mainly reflect the deformation of local blocks during construction.

Figure 6 shows the layout of monitoring platform and MPBXs for shallow-buried and surface rock masses, where 47 sets of MPBXs are arranged in total. The statistics of orifice displacement is shown in Table 3. It indicates that the orifice displacement varies from −2.5 to 21.1 mm, 80% of which is less than 5 mm, and no continuous deformation is observed in rock masses.

4.1.1 Block deformation at the elevation of 1960 m

12 sets of MPBXs were arranged in the slope above the crane-rail platform. The orifice displacement varies from −3.0 to 21.0 mm, but those of MD3 and MD11 are relatively large.

The MD3 is located at the elevation of 1990 m inside the berm, with a monitoring depth of 48.7 m (Fig.7(a)). In the early period of excavation, deformation of upper segment (0–18 m deep) increases rapidly to about 10.4 mm, accounting for 50% of total displacement. It is an evidence of blocks toppling and deforming along the fissure flLI4 perpendicular to the slope free face. As excavation continues, deformation gradually develops, shifting from surface to deep rock masses. The deformation of lower segment (18–31.2 m deep) begins to increase, but tends to converge soon after timely support of slope.
Table 3 Statistics of orifice displacement obtained by MPBXs.

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1 960</td>
<td>3.3</td>
<td>21.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>1 960–1 885</td>
<td>5.2</td>
<td>15.8</td>
<td>-1.2</td>
</tr>
<tr>
<td>&lt;1 885</td>
<td>4.2</td>
<td>17.2</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Fig. 6 Layout of monitoring platform and MPBX for shallow-buried and surface rock masses (unit: m).

Fig. 7 Displacement distribution of MPBXs MD3 and MD11.
The MD11 is also located at the elevation of 1 990 m inside the berm, with a depth of 48.7 m (Fig.7(b)). It was arranged for small-scale wedge blocks incised by the fissures gLLII4 and fLLIII5 and excavation free face. The orifice displacement is 8.5 mm, and the depth of deformed rock mass is less than 20 m. After support of slope, the deformation begins to converge.

4.1.2 Connection block deformation of slope at the elevation of 1 885–1 960 m

15 sets of MPBXs were installed in the connection slope at the elevation of 1 885–1 960 m, with a depth of 68.7–89.5 m, 5 m deeper than the fixed end of anchors. MPBXs M5 and M7 can reflect typical blocks deformation, which are briefly described as follows.

The M5 is located at the elevation of 1 945 m inside the berm, with a depth of 89.5 m (Fig.8(a)). There are small-scale blocks incised by the lamprophyre dyke (X), consequent fissure XLB5 and excavation free face, with a depth of about 30 m. Deformation of monitoring points varies significantly, most of which occurs in the depth of 0–52.0 m where the lamprophyre dyke (X) and fissure XLB5 go through. The deformation is commonly 5.2 mm, accounting for 71% of the total. Deformation of this segment has a close relation with excavation process, but these small blocks tend to be stable after excavation.

The M7 is located at the elevation of 1 885 m (dam crest) inside the berm, with a depth of 68.7 m (Fig.8(b)). There are small-scale blocks incised by the lamprophyre dyke (X) and small fault fLB11, with a depth of around 30 m. Deformation mainly occurs in the depth of 0–31.2 m outside the lamprophyre dyke (X), with a value of 12.8 mm, accounting for 81% of the total. Deformation of this segment comes to converge gradually after excavation.

4.1.3 Deformation of spandrel groove slope below the elevation of 1 885 m

For monitoring purpose, 30 sets of MPBXs were installed in spandrel groove slope on the left abutment. Monitoring results show that bigger orifice displacements occur at the points M4C3L, M5C3L, M6C3L, M7C3L and M8C3L, with values of 13.8, 10.3, 17.12, 15.4 and 16.3 mm, respectively. Monthly variation of displacement in this area is mostly less than 1.00 mm, with a slightly increasing trend.

4.2 Anchor load monitoring of shallow-buried rock mass

As shown in Table 4, 210 load dynamometers in total were installed in the left abutment slope. Of these dynamometers, 178 worked normally. The measuring results (see Table 4) indicate that prestress loss happens in most anchors (151 dynamometers). It should be noted that there are prestress increases in 27 anchors, most of which are located around the hanging wall of the lamprophyre dyke (X) and fault f42-9. The load increasing percentage is less than 10%, within a normal range.

4.3 Deformation of large wedge blocks

4.3.1 MPBXs

There are 16 sets of MPBXs going through the lamprophyre dyke (X), 3 of which reflect the relative displacement more than 5 mm at the two sides of the lamprophyre dyke (X) (Table 5). 4 sets of MPBXs go through the fault f42-9, and only 2 of them reflect the
Table 5 Relative displacements of MPBXs through structural planes in large wedge blocks.

<table>
<thead>
<tr>
<th>MPBX</th>
<th>Elevation (m)</th>
<th>Monitoring segment (m)</th>
<th>Relative displacement (mm)</th>
<th>Structural plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>1 886.2</td>
<td>0–52.0</td>
<td>8.3</td>
<td>X and f42-9</td>
</tr>
<tr>
<td>M5</td>
<td>1 946.2</td>
<td>0–52.0</td>
<td>4.7</td>
<td>X</td>
</tr>
<tr>
<td>M7</td>
<td>1 886.2</td>
<td>0–31.2</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>M7C3L</td>
<td>1 823.0</td>
<td>21–39</td>
<td>7.3</td>
<td>f42-9</td>
</tr>
</tbody>
</table>

Relative displacement more than 5 mm at the both sides of the fault f42-9. The maximum relative displacement of the two sides of the two weak structural planes is 12.7 mm.

4.3.2 Anchor loads

19 sets of anchor dynamometers with increasing prestress were distributed around the exposure position of the lamprophyre dyke (X) and fault f42-9. 6 of which were within 20 m of outcrop of the lamprophyre dyke (X) and 6 were within 20 m of outcrop of the fault f42-9. The monitoring results show that after slope excavation, certain deformation of rock masses occurs along the lamprophyre dyke (X) and the fault f42-9.

4.3.3 Working performance of concrete shear galleries and replacement structures

The deformation and joint aperture between concrete and rock mass in concrete shear galleries and replacement galleries along the lamprophyre dyke (X) and the fault f42-9 are all small. Only few parts of concrete structure bear a large stress, and the average stress in reinforced steel bar is about 20 MPa.

4.4 Brief summary

During construction of slope, deformation of some shallow-buried block structures (20–30 m underground) has been observed, which reflects the deformation characteristics of corresponding slope structures. Slope support has been implemented timely, thus, no large systemic deformation is reported and no block has the risk of instability so far.

The sliding surfaces and the exposed boundary of the large wedge block have no significant deformation, which implies that the slope is generally stable at present.

5 Deformation analyses of deep rock masses

5.1 Graphite pole convergence meter

Monitoring instruments in deep fractures in the left abutment slope were installed in adits PD42, PD44, PD54 and drainage gallery at the elevation of 1 915 m, including graphite pole convergence meter and deformation observation platform (Table 6).

Table 6 Arrangement of monitoring instruments in deep fractures.

<table>
<thead>
<tr>
<th>Adit</th>
<th>Instrument</th>
<th>Elevation (m)</th>
<th>Stake number</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD42</td>
<td>ID42S1, ID42S2, L_{PD42}</td>
<td>1 929.32</td>
<td>0–37.00</td>
</tr>
<tr>
<td>PD44</td>
<td>ID44, ID44X, L_{PD44}</td>
<td>1 930.79</td>
<td>0–53.00</td>
</tr>
<tr>
<td>PD54</td>
<td>L_{PD54}</td>
<td>1 824.7</td>
<td>0–53.00</td>
</tr>
<tr>
<td>PDJ1</td>
<td>L_{PDJ1}</td>
<td>1 917</td>
<td>0–289.00</td>
</tr>
</tbody>
</table>

Note: (1) Stake number means distance from dam axis (m), downstream as positive. (2) “ID” represents graphite pole convergence meter, and “L” represents observation line of displacement across valleys.

From in-situ investigations, we know that:

1. The main hole of adit PD42 is 200 m long and its branch hole is 185.25 m long. After slope excavation, 93 m of main hole is remained. Two graphite pole convergence meters, ID42S1 and ID42S2, were set in each hole (Fig.9). The total deformation of two holes is 4.1 and 12.7 mm in 31 months, respectively, most of which occurs in exposed segment of 35.2–64.6 m along the fault f42-9 (Fig.10). Monthly deformations of this segment before and after excavation and during operation period are 1.0, 0.5 and 0.2 mm, respectively. Compared with the monthly deformation before excavation, the decreasing rates after excavation and during operation period are 50% and 80%, respectively, tending to converge.

Fig.9 Arrangement of graphite pole convergence meters in the adits PD42 and PD44.

(2) The main hole of adit PD44 is 202 m long. Two graphite pole convergence meters, ID44 and ID44X, were arranged in parallel (Figs.10(b) and (c)). Observing durations are 37.1 and 26.4 months, respectively, with a total deformation of 44.9 and 18.0 mm, respectively. The deformation in the segment of 76.4–152.0 m in deep fracture zone accounts for 80% of total deformation (Fig.11). The monthly deformations

IV2

IV3

IV4

Unit: m

IV1

IV2

IV3

IV4
Fig. 10 Displacement distribution at various measuring points in the adit PD44 (unit: mm).

of ID44 in this segment before and after excavation and during operation period are 1.9, 0.8 and 0.4 mm, respectively. Compared with the monthly deformation before excavation, the decreasing rates after excavation and during operation are 58% and 79%, respectively, tending to converge (Table 7).

Table 7 Displacements in the segment of 0+76.4–152.0 in adit PD44.

<table>
<thead>
<tr>
<th>Adit</th>
<th>Total displacement (mm)</th>
<th>Excavation to the elevation of 1 730 m</th>
<th>Excavation to the elevation of 1 580 m</th>
<th>Excavation completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID44</td>
<td>30.0</td>
<td>7.9</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>ID44 (76.4–152 m)</td>
<td>25.1</td>
<td>6.7</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>ID44X</td>
<td>3.5</td>
<td>8.4</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>ID44X (76.4–152 m)</td>
<td>3.5</td>
<td>8.4</td>
<td>6.1</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Observation of DAV

By observation of DAV, the distance variation between the two adits at the same elevation in the same section of both valleys can be monitored, and thus, the relative displacement of two valleys can be calculated. Geodetic measurement method is adopted and observation accuracy reaches ±1 mm. By this simple method, total relative displacement of two valleys can be gained before the monitoring and controlling network in dam site is completed. Deformation of each bank can be decomposed by taking advantages of observation points in deeper part of adits, and the distance variation between observation points in adits can be used as comparison and verification of the results obtained by graphite pole convergence meters.

According to exploration conditions of adits, 4 observation lines for DAV, L_{PD42}, L_{PD44}, L_{PD45} and L_{PD41} (Fig. 12), were set. Two types of observation points were set as follows: points across valleys and points in the adits. Total displacement can be observed at points across valleys, and the deformation in deep fractured rock masses can be observed at measuring points in the adits.

5.2.1 Deformation analysis in the left abutment slope

Observation results of DAV show that the total displacement in adits of two valleys is equal to that across the river.

(1) The observation line for DAV in the adit PD42 is at the elevation of 1 930 m. The observed displacement in the depth of 180.0 m in the adit PD21 on the right bank is 1.8 mm, and the contractive displacement
across the river is 73.6 mm. These values indicate that the displacements mainly occur in the adit PD42 on the left bank.

(2) The observation line for DAV in the adit PD44 is at the elevation of 1,930 m. The observed displacement in the depth of 202.1 m in the adit PD44 on the left bank is 23.3 mm, and the contractive displacement across the river is 35.2 mm. The deformation difference of 11.9 mm between them is exactly the value of the corresponding points on the right bank, which is verified by the results of adjacent points in the adit on the right bank.

(3) The observation line for DAV in the adit PD54 is at the elevation of 1,824.7 m. The observed displacement in depth of 238.3 m in the adit PD54 on the left bank is 28.4 mm, and the contractive displacement across the river is 78.7 mm. The deformation difference between them should be the value of the corresponding points on the right bank, which is verified by results of adjacent points in the adit on the right bank.

(4) The observation line for DAV in adit PDJ1 is at the elevation of 1,824.7 m, upstream Pusiluo trench. The observed displacement in the adit PD54 on the right bank is –5.2 mm, implying the slight surface deformation of slope. The deformation across the river (11.3 mm) comes from the surface measuring points on the left bank.

5.2.2 Deep deformation distribution on the left bank

Observed displacement between the observation piles in adits on the left bank reflects the deformation of surrounding rocks.

The monitoring depth of the adit PD42 is 80.3 m, with a total deformation of 23.2 mm. The fault \( f_{42-9} \) and the lamprophyre dyke (X) go through this segment, and the tensile relaxation of these structural planes is the primary reason that causes deformation. The displacement distribution in this deep segment of L-PD42 is shown in Fig.13(a).

The monitoring depth of the adit PD44 is 202.1 m, with a total deformation of 23.0 mm. The displacement distribution in segments of L-PD44 is shown in Fig.13(b). The displacement in the segment of 152.7–97.8 m is 14.1 mm, accounting for 61.3% of total displacement. It is related to deep fractures, SL44-4–SL44-63, developed in this segment. The displacement of TPL3–TPL4 (segment of 97.8–51.2 m) is around 6.0 mm, accounting for 26.0% of total displacement. It is related to deep fracture SL44-3 and small faults such as \( f_{44-5} \) developed in this segment. These two segments are both located in deep fractured zone, and the observed displacement is consistent with the results obtained by the graphite pole convergence meters in the same adits.

5.2.3 Characteristics of time-dependent deformation in the left abutment slope

The monitored and measured displacements across valleys in different periods of time are compared (Fig.14).
(1) Excavation and construction periods
During excavation and construction periods, the displacement rate in adits on the left bank is 1.77 mm per month, but the displacement rate across the river is –4.04 mm per month. The displacement rate in adits on the right bank is actually 0.39 mm per month.

(2) Operation period
After completion of construction, the displacement rate in adits on the left bank is 0.58 mm per month, decreasing by 67.2% against that in the construction period. However, the displacement rate across the river is –1.59 mm per month, decreasing by 60% of that in the construction period. The displacement rate on the right bank is somewhat smaller.

5.3 Brief summary
The monitoring results of DAV and graphite pole convergence meters in deep rock masses of the adits can be verified with each other. It indicates that deformations in deep fractures and surrounding structural planes are slowly increasing, and they are related to and consistent with the deformation of surface rock masses.

6 Evaluation and understanding of slope stability
Based on the monitored data above, evaluation and understanding of slope stability in the left abutment can be achieved and summarized as follows:

(1) The maximum deformation of toppling rock block in the upper slope is 113.58 mm, with an increasing rate of 0.9–1.09 mm per month. The average deformation of surface rock masses in construction period is 28–67 mm, with an increasing rate of 1.0–2.6 mm per month. In operation period, the rate decreases by 0.6–0.9 mm per month, or 30%–40%. During construction period, the deformation of measuring points at the same elevation keeps synchronized, and the deformation of points at different elevations during operation period has the same tread, with an inclination to the upstream free face. It shows the consistent and integrated deformation features in the slope.

(2) The average deformation of shallow-buried and surface rock masses in anchorage zone is less than 4 mm, the maximum is 21 mm, and it tends to converge. Among the total 178 anchor cables, prestress loss is observed in 85 of them, with a loss rate less than 10%, and it also tends to converge. The boundaries of the large wedge, lamprophyre dyke (X) and fault f42-9, demonstrate a fairly small relative deformation (generally 0.3–3.7 mm, few points reaching 12 mm), and the stresses of anchor cables going through these planes increase slightly by 3%–10%. The monitored physical quantities in concrete shear galleries and replacement galleries show a slight variation, and the deformation of rock masses and the stresses of anchor cables around these structures are convergent, which indicate that cables and shear galleries have effective functions on the slope stability.

It can be observed from the above monitoring results that the deformation of the large wedge block has been effectively controlled after support and reinforcement, and the slope keeps stable in a global sense. After excavation, the deformation of toppling rock mass at the top of the slope has a continuous slow increase, but the deformation rate is decreasing, which shows that the slope tends to converge.

(3) There is a relaxation deformation of deep fractured rock masses during excavation period to a certain extent. The monitoring results of graphite pole convergence meters and DAV are consistent with each other, with a monthly deformation of 1.0–2.3 mm during excavation and 0.2–0.5 mm after excavation. The monthly deformation of DAV in the segment across the river is 4.04 mm during excavation period and 1.59 mm after excavation. The monthly deformation of deep fractures in adits PD12, PD22 and PD28 at the ridges IV and VI is 0.1–0.8 mm. The results indicate that, after excavation, the deformation rate is decreasing, but it does not tend to converge entirely.
7 Conclusions and discussion on rock mass creep

Based on monitoring results and stability analyses, the following conclusions for the slope stability of left abutment can be drawn:

1. During slope construction, the short-term deformation occurs in some local surface of shallow blocks and some triangle blocks cut by topography and excavation faces. With monitoring and supporting measures, deformation has tended to be convergent and the blocks keep stable so far. The local instability of the slope is avoided.

2. The global stability of the left abutment slope mainly depends on the stability of the large wedge blocks. The deformation of exposed boundaries of the large wedge block is very small. Variations in deformation and stress in concrete shear galleries and replacement structures in the potential bottom sliding planes, i.e. fault f12.9 and lamprophyre dyke (X), are also small. There is no obvious difference in surface deformations of two sides of the large wedge block. From the monitoring results, judgment can comprehensively be made that the large wedge block is stable, and the left abutment slope keeps stable on the whole.

3. Long-term deformation and stability of slope are mainly presented in the sense of continuous deformation increasing, as the creep of deep rock masses with deep fractures, and consequently the surface deformations of the slope have not been convergent. This issue about the slope stability needs further study.

Tan and Kang [15] brought forward the concept of rock mass creep for the rock mass deformation at dam foundation. They pointed out that rock mass creep mainly included relaxation deformation of structural planes such as faults, dykes and joints, and long-term rock mass deformation might still be the results of unloading excavation. Rock mass deformation of the left abutment slope in Jinping I hydropower station continues to increase with time after excavation. Thus, it is believed that the slope has the characteristics of rock mass creep. Similar behavior of rock mass creep in the Huangtupo slope of the Three Gorges project, Yangtze River, China, has been observed and analyzed by Deng et al. [16], and studies on the rheological properties and long-term stability of rock masses in the high slopes of the shiplock in the Three Gorges project have also been conducted by Xu et al. [17]. These findings suggest that time-dependant deformation and long-term stability of rock masses slopes are closely related to rock mass creep, and the characterization and rheological parameters of rock masses deserve intensive concerns and further studies.

The monitoring results show that deformation of the left abutment slope has characteristic of integrity. During operation period, no obvious deformation of blocks in shallow-buried and surface rock masses has been observed, and the deformation of slope mainly comes from deep rock masses, which refers to the associated developed structural planes, such as faults, dykes and deep fractures. And the deformation is characterized as large scale and long duration.

Unloading excavation may induce the long-term deformation of slope, which can be explained by rock mass creep in hard rock area with high geostresses. The deformation feature indicates that stress redistribution due to unloading excavation needs a long period of time.

Owing to the deformation of abutment slopes, which points to the arch dam and will impose adverse effect on the operation safety of the dam, further study on the interaction between resistant rock block and arch dam should be carried out.

References


