Deformation and Reinforcement Monitoring Analysis of Tail Water Outlet Slope in a Hydropower Station

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Abstract. The slope stability situation surrounding the dam site area is very important to each correlative department during constructing hydroelectric power station. So it is important to enforce the high slope rock deformation monitoring, and to process and analyze the measuring data timely. Surface displacement of different height of slope were tracked and monitored based on the field investigation of a hydroelectric power station in Jinsha river. Deformation and the static stability of high slope were analyzed by utilizing rock deformation monitoring data. Taking the left-bank tailrace outlet slope of underground power station for example, we analyzed the slope stability by numerical simulation to obtain the characteristics of deformation and failure of slope. The time and space deformation distribution regularity of rock mass were summarized, the deformation, stress and failure of the studied slope were simulated. The results intuitively show the displacement distribution characteristics and slope plastic failure.

1. Introduction
The hydropower stations such as Li Jiaxia (165 m), Lashiwa (250 m), Ertan (245 m), Xiaowan (292 m), Xiluodu (278 m), Jingping first stage (305 m) and so on [1] have built a large number of super-high arch dams in the western part of China where is rich in hydropower resources. Valley deformation is a common problem faced by high arch dams. For one thing, due to the complex topography and geological conditions in the dam site area, both the magnitude and gradient of mountain crustal stress value are large [2]. For another thing, the engineering scale is large, the waterhead is big, the water filling process disturbance is intense. The disturbance of natural slope body, such as slope excavation [3,4] and reservoir water level change [5], will accelerate the deformation of the slope, and various preliminary unconsidered or potential defects will gradually appear [6,7]. This article embarks from the surface displacement monitoring of high slope, the deformation characteristics and laws of arch dam valley bank slope are analyzed as well as the stress state of anchor cable reinforcement after excavation, which lay a foundation for the study of valley deformation.
2. Deformation monitor
The location of the tailrace outlet slope of the underground power station on the right bank is shown in Figure 1, which is located at the right side of the dam foundation downstream. Three diversion tunnels are laid out the slope, which are collected at the outlet, of which one is higher. Multiple monitoring points are arranged on the slope body, the effective displacement monitoring points TP01 to TP06 are selected, and the elevation is successively 962 m, 895 m, 866 m, 956 m, 926 m and 867 m respectively.

![Figure 1. Geographic location of tailwater outlet slope.](image)

![Figure 2. Total horizontal displacement.](image)
The accumulated horizontal displacement values of the six surface displacement monitoring points are shown in Figure 2 (the horizontal displacement is towards the space). In the past five years, the horizontal displacement of each position has not changed much, and the maximum is no more than 9 mm, and the general trend of change law has similar consistency. The maximum horizontal displacement is the measuring point TP06 at the elevation of 867 m, but the measuring point TP03 at the same elevation has a relatively small displacement. The displacement values of the three measurement points above the height of 900 m were all small, and the change laws are similar, with the maximum value not exceeding 5 mm. It can be seen that the change of horizontal displacement is not necessarily related to the elevation, and the deformation of higher elevation is relatively small.

The accumulated vertical displacement value of the six surface displacement monitoring points is shown in Figure 3. In the past five years, the vertical displacement change of each position is generally stable, and gradually increases in stability, and the variation law trend is similar and consistent. The maximum vertical displacement is measuring point TP03 at the elevation of 866 m, and value reached 15 mm. The settlement of TP06, a measuring point at almost the same elevation, is also higher than that at other elevation. The vertical displacement values of the three measuring points above 900 m elevation are all small. It can be seen that the subsidence of low elevation is generally greater than that of high elevation.

The monthly dynamic change of the horizontal displacement of the six surface displacement monitoring points is shown in Figure 4. In the past five years, the horizontal displacement of each position is in dynamic change, varying around value 0, basically fluctuating between -4 and 4 mm. The point TP06 with low elevation has the largest change, but the monthly change is no more than 5 mm.
3. Stress monitor
According to the conditions of this project, and analogy with other engineering experience, the single-stage slope ratio of the right bank tail water outlet is 1: 0.3. The cave face slope below elevation 850.5 m is a vertical slope, and setting 3 m wide horse road every 15 m high. The maximum excavation height of the tail water outlet slope is 168.0 m. The slope excavated at the tail water outlet is reinforced by comprehensive measures, such as shotcrete, system anchor, anchor cable, drainage (slope drainage and water interception outside the slope.), etc. The thickness of the concrete on the slope is 10 cm. The upright slopes below elevation 850.5 m are supported by system anchor with φ28 mm, length 9.0 m and spacing 1.5 m× 1.5 m. The tail water outlet are provided with 2 rows of locking anchor with φ32 mm, length 12.0 m and spacing 1.2 m×1.2 m. Each grade of slope above elevation 850.5 m are supported by 2 rows of system locking anchor with φ28 mm, length 9.0 m and spacing 2.0×2.0 m. The system anchor of other parts are φ25 mm, length 6.0 m and spacing 2.0 m× 2.0 m. Each level of the slope lay out of two rows of the prestressed anchor cable with 2000 kN, the length 30 m and spacing 6 m×6 m, but for slopes with poor local geological conditions, the distance between the anchor cable is encrypted to 4.5 m×4.5 m, and the anchor piles are randomly set according to the need. The slope is systematically with φ56 drainage holes with spacing of 4.0 m×4.0 m (or 4.5 m×4.5 m) and depth of 3.0 m. Gutters are layout on all levels of the horse road, the two sections of which are connected to the water intercepting ditch, which is set outside of the slope opening line.

In order to understand the changes of anchoring effect and support stress of tailrace tunnel, we set up a fixed number of anchor cable dynamometers and anchor stress meters in 4# and 6# tailrace tunnel. Taking 2017.12 for example, we analyse the bolt stress and anchor force measurement.

Anchor barstress measurements is between at -1.93 MPa~349.97 MPa (R02WSSD12 bolt stress, in sidewalls left bank of second 12# tailrace tunnel, K0+088.40 EL786.38), the monthly change of stress is between at -1.71 MPa~1.19 MPa (R02WSSD07 bolt stress, in sidewalls left bank of second 7# tailrace tunnel, K0+93.34 EL786.26), as shown in Fig.5 and Fig.6.

![Figure 5. Stress and T of 12# tailwater tunnel](image)

![Figure 6. Stress and T of 7# tailwater tunnel](image)

Anchorage capability (design value is 1500 kN) is between at 1415.3 kN ~ 2162.9 kN (MS01WSSD12 dynamometer, in sidewalls left bank of second 12# tailrace tunnel, K0+071.90 EL788.04), the monthly change of anchorage capability is between at -30.2 kN ~ 9.8 kN (MS03WSSD07 dynamometer, in sidewalls left bank of second 7# tailrace tunnel, K0+71.84 EL787.60), as shown in Fig.7 and Fig.8.
Anchorage capability (design value is 2000 kN) is between at 1264.7 kN ~ 2040.4 kN (MS34YCKT dynamometer, in crown left bank of second 6# tailrace tunnel, K0+137.50 EL809.22), the monthly change of anchorage capability is between at -7.4 kN ~ -3.5 kN (MS48YCKT07 dynamometer, in the 4WB8 block of 4# tailrace tunnel, K0+186 EL807.32), as shown in Chart 7 and 8.

The monitoring results of anchor cable dynamometer whose design value is 2000 kN, the details are in Table 1.
Table 1. Anchor cable dynamometer monitoring results of tailwater tunnel of the right bank underground power station (2000 kN).

| Instrument codes | Stake number (m) | Position | Memc lock value memc (kN) | Loss rate after locked (%) | Measurement range (kN) | Anchorage force (kN) | Monthly variation (kN) |
|------------------|-----------------|----------|--------------------------|----------------------------|------------------------|---------------------|----------------------|
| MS45YCKT         | 0+205 EL811.52  | 4#main hole of tail water, block 4WB9 | 1396.6                   | 9.4                        | 2000                   | 1271.5              | 1264.7               | -6.8                 |
| MS48YCKT         | 0+186 EL807.32  | 4#main hole of tail water, block 4WB8 | 1786.9                   | 9.3                        | 2000                   | 1628.3              | 1620.9               | -7.4                 |
| MS46YCKT         | 0+169 EL806.4   | 5#main hole of tail water, block 5WB4 | 1903.1                   | 9.4                        | 2000                   | 1730                | 1723.4               | -6.6                 |
| MS49YCKT         | 0+221.5 EL813.78 | 5#main hole of tail water, center line of block | 1901.0                   | 9.2                        | 2000                   | 1732.8              | 1726.7               | -6.1                 |
| MS34YCKT         | 0+137.59 EL809.22 | 6#hole of tail water, left side of the arch | 2035.3                   | -0.3                       | 2000                   | 2047.1              | 2040.4               | -6.7                 |
| MS38YCKT         | 0+126.00 EL808.06 | 6#hole of tail water, left side of the arch | 1957.7                   | 3.1                        | 2000                   | 1903.3              | 1896.7               | -6.6                 |
| MS39YCKT         | 0+123.00 EL808.10 | 6#hole of tail water, left side of the arch | 2132.9                   | 5.6                        | 2000                   | 2017.2              | 2013.7               | -3.5                 |
| MS40YCKT         | 0+129.00 EL808.54 | 5#main hole of tail water, left side of the arch | 2002.5                   | 6.1                        | 2000                   | 1887.4              | 1880.7               | -6.7                 |
| MS43YCKT         | 0+43.0 EL808.57  | 5#main hole of tail water | 1987.5                   | 1.5                        | 2000                   | 1963.9              | 1957.9               | -6                   |

4. Conclusions
(1) Based on the data of displacement monitoring and anchor cable stress of tailrace tunnel outlet slope which is on the right bank of the underground power station, the distortion rule, developing trend and present situation of slope loads cables are analyzed. The horizontal displacement of the rock mass of the left bank slope increased slowly and stable with no sign of sudden change; the vertical settlement is small and increase slowly, which is overall normal; the anchor cable strengthened in the diversion tunnel withstand the normal stress, and the anchorage effect is better within the controllable range.

(2) The precision of the observation result is high by means of displacement and deformation observation of slope surface and stress monitoring of anchor cable in rock mass. The method is simple and reliable, and the deformation of slope and unfavorable geological structure can be quickly monitored.

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