Deformation response and anchorage control of excavation unloading of high and steep rock slope

Zhihong Dong*, Xiuli Ding, Shuling Huang, Yongjin Wu, Aiqing Wu
(Yangtze River Scientific Research Institute, Key Laboratory of Geotechnical Mechanics and Engineering of the Ministry of Water Resources, Huangpu Road, Wuhan, 430010, China)
* Corresponding author , E-mail address: 14968857@qq.com.cn (Zhihong Dong).

Abstract: The stability and anchorage control of high and steep slopes in Southwest China are challenging problems in engineering construction. Considering the unloading stability of high and steep rock slopes, field monitoring and numerical analysis methods are used for feedback analysis to study the deformation, stress response, anchorage support scheme, and anchorage stress characteristics during the unloading process of slope excavation. The research shows that the displacement of rock mass of the high slope gradually increases and the local deformation exceeds 200 mm. The unloading relaxation area resulting from slope excavation is 25 m deep. The safety of the slope can be guaranteed after the joint reinforcement of deep anchor cable.

Keywords: high rock slope; excavation unloading; field monitoring; dynamic feedback analysis; anchorage support

1. Introduction
In the hydropower development in Western China, the scale of the project is increasing and the terrain conditions are becoming increasingly complex. The height and scale of rock-slope engineering undertakings are growing, and the stability analysis and engineering design challenges are escalating. The instability of rock slopes often plagues engineering construction and leads to significant loss of life and property, as well as delay of construction schedules and increase in treatment costs. The design for stability and excavation support of rock slopes needs to consider the safety and economic benefits of engineering construction and operation period. Comprehensive research on slope stability and excavation support is vital for engineering practice and economic value. Based on the practice of high rock slopes of hydropower engineering in China, many scholars summarized and analyzed the main technical characteristics and key technical problems of slope engineering, presented research results, and proposed solutions for slope engineering [1-11]. However, due to the complexity of geological conditions in Western China, many problems still persist in the construction of high slopes, e.g., in the Wudongde Hydropower Station because of its complex geological conditions and prominent high slope. The stability of the left side slope at the outlet of the Wudongde spillway tunnel (referred to as “the left side slope”), which belongs to the class A slope, affects the operation safety of the plunge pool and tailrace. The unloading relaxation of slope rock mass is very pronounced, and wave velocity of rock mass is certainly reduced. The unloading relaxation depth of the slope
is large, 25 m on average, but reaches down to 29.2 m. During the excavation process, the internal and external monitoring results showed that the unloading deformation of rock mass was significant, with the internal maximum deformation of 92.47 mm and external deformation of 212.05 mm. In addition to the deformation being large, the duration was also long, and the unloading relaxation range and depth are clearly beyond what would be expected of an ordinary rock. Compared to the locking value, the anchorage force increased by 71.4%, maximum increase was 53%, and maximum anchoring force was 2873.8 kN. These adverse factors make the safety concerns of the slope construction very prominent. In the present work, the deformation mechanisms and stability of the slope are studied. Based on the results of a geological exploration undertaken during the construction period, the acquired safety monitoring data and results of geophysical prospecting combined with the deformation and failure analysis during the construction process, a numerical simulation method is used for slope investigations, and the slope excavation stability is evaluated. The research results will provide a reference for similar projects.

2. Project overview

The Wudongde Hydropower Station is located in the lower reaches of the Jinsha River in China, and, with an installed capacity of 10200 MW, is the second largest hydropower station under construction in the world. The project comprises the dam, spillway tunnel energy dissipation, water diversion, and a power generation system. The dam is a concrete double-curvature arch dam with the maximum dam height of 270 m. The flood discharge and energy dissipation structure comprise five surface outlets, six middle outlets, and a plunge pool behind the dam, as well as three spillway tunnels and an outlet plunge pool arranged on the left bank. The outlet slope of spillway tunnel is divided into the front side slope and left side slope. The intersection of the front side slope and left side slope is the mouth of the Huashan debris flow gully.

The natural height of the left side slope is 970 m, maximum height of the excavated slope is 183.5 m, excavation slope ratio is 1:0.2-1:0.3, and average slope angle is 64°. The rock mass of the left side slope comprises Pt2l10 gray interbedded with thin limestone, Pt2l gray thin-layer dolomite and limestone, Z2g silty mudstone shale, and Z2d dolomite.
3. Slope excavation and support scheme

(1) Excavation parameters of the slope are as follows: a 3 m wide berm is set every 15 m, and the single-stage excavation slope ratio above the 850 m elevation is 1:0.2; the slope ratio below the 850 m elevation is 1:0.3.

(2) Support parameters: the elevation of the slope opening line is 950–910 m, and two rows of 3 φ 28 L = 12 m @ 2 m × 2 m anchor pile locks are used. Two rows of 2000 kN prestressed anchor cables are arranged for each slope with a spacing of 4 m.

(3) Above the slope elevation of 806 m, systematic anchor bolts are arranged at intervals of φ 25, L = 6 m and 3 m, and 3 φ 28, L = 12 m, 3 m, and 3 m; below the slope elevation of 806 m, the spacing of system anchor bolts with length of φ 25 and 9 m is 3 m, and the spacing between anchor piles with L = 12 m is 3 m.

(4) Reinforcement mesh of slope surface 6: 5 mm @ 20 cm × 20 cm and the thickness of C25 concrete spraying is 12 cm.

(5) The drainage holes with diameter of 76 mm and length of 4 m are arranged with spacing of 3 m.
4. Unloading response and anchorage control of high steep anti-dip layered slope

(1) Slope surface displacement pattern were as follows: after the excavation of spillway tunnel slope, the upstream side slope of hanging-wall rock mass of fault F6 deformed slightly to the outside of the slope, and sank vertically, whereas the downstream side of the hanging-wall rock mass of fault F6 deformed slightly to the upstream side of the slope and sank vertically. Specifically, the three appearance points on the 1-1 monitoring section of the slope were sinking outward with an inclination of 18°–25° and those of the 4-4 monitoring profile and the surrounding appearance points were essentially settling outward, with a larger dip angle of 27°–44°. The vertical slope outward deformation was −2.7–212 mm in terms of displacement value, −0.9–45.4 mm in the parallel slope direction, and −0.4–192.3 mm in the vertical direction. The vertical slope outward and sinking deformations were large, mainly concentrated in the F6 hanging-wall IV2 rock mass at elevations above EL925 m and near the opening line and below.

(2) Deep deformation characteristics of slope were as follows: The hole deformations were generally −0.92–40 mm, and there were three measurement points where they were greater than 50 mm (m10xhds displacement of 71.6 mm, M11xhds displacement of 89.4 mm, and M12xhds displacement of 66.6 mm). These three measurement points were all located in the overburden clear slope area near EL925–EL970 m of the excavation slope and opening line of fault F6. The overall slope deformation monitoring statistics show that there were three measurement points with displacements larger than 50 mm, accounting for 17.6% of the total, two measurement points with displacements of 20–50 mm, accounting for 11.8% of the total, three measurement points with displacements of 10–20 mm, accounting for 17.6% of the total, and nine measurement points with displacements less than 10 mm, accounting for 52.9% of the total. Figure 6 shows the layout of the multi-point displacement meters adopted for monitoring deformations. It can be seen from the figure that #1 geological section is the part with large deformation in the hanging wall of fault F6 (corresponding to 4-4 monitoring section), m11xhds and M12xhds are located in Z2d of the Dengying formation, and M10xhds is located in Z2g of the Guanyinyan formation. The deformation range along the depth direction was mostly between 10–20 m and 30–40 m, whereas the deformation values of m13xhds, M14xhds, and M15xhds in the lower part were 5−21 mm, and the deformation range was mostly between 0–10 m and 10–20 m. 3# The geological conditions of the section were slightly better, belonging in classes Ⅲ2–Ⅳ1. Except for a few measurement points M03, the deformations of other parts were 4–17 mm.

From the observed largest deformation depth, the main deformation section was located in the 0–10 m, 10–20 m, and 30–40 m sections inside the slope. Combined with the acoustic detection results, the relaxation zone of the slope rock mass was observed to be 25 m deep on average, reaching down to 29.2 m, whereas the shallowest part was 11.8 m. The wave velocity in the relaxation area was 2500–3100 m/s. It can be seen that the deep relaxation deformation characteristics of the overall slope deformation are certain. The left side slope at the outlet of the spillway tunnel was sensitive to neither the instantaneous blasting vibration, which is mainly affected by the adverse geological structural planes, such as medium thick to thin-layer strata and faults, nor to excavation unloading and blasting vibration. The insensitivity to the instantaneous blasting vibration shows that the stress unloading, and rock-mass relaxation deformation caused by large-scale excavation of the slope with poor rock-mass quality during excavation, the deformations of slope rock mass clearly increased, whereas the deformation rate was aligned with the stress. Due to the poor quality of rock mass, especially in the vicinity of faults and in the process of slope deformation, the rock-mass quality and mechanical strength decreased continuously, the relaxation range deepened, but the deformation gradually slowed down over a long time after excavation.
5. Analysis of high and steep anti-dip layered slope

5.1 Numerical simulation model

Based on the engineering geological conditions exposed by the excavation of the left side slope and topographic data, the overall three-dimensional geological generalization numerical simulation model of the slope was established. Based on the results of slope safety monitoring and geophysical detection, the mechanical parameters of slope rock mass were inversely analyzed using a FLAC$^3$D three-dimensional numerical model. Utilizing the model, the mechanical responses, deformations, failure mechanisms, potential instability modes, and reinforcement measures for the left side slope at the outlet of spillway tunnel under excavation and unloading conditions were studied. The overall stability of the slope under the action of earthquake and other factors was checked.
Fig. 8 Numerical simulation model

Fig. 9 Displacement isochromatic zone after slope excavation

Fig. 10 Displacement cloud area after excavation (Section 1)
5.2 Results
The overall displacement characteristics of the slope were as follows: With the downward excavation of the slope, the rock mass outside the slope was gradually removed, and the height of the artificial slope increased. Especially, with the excavation of the middle and lower rock mass, the unloading relaxation of the middle and lower slope weakened the support function of the upper rock mass, and the displacements of the slope body gradually increased. The deformation vectors of the slope rock mass were facing outward. In addition, due to the relaxation caused by excavation unloading of the shallow surface of the slope, the rock-mass displacement in this area was greater than that in the deep part, which showed a trend of gradual decrease toward the inside of the slope. The deformation of the slope was generally controlled by poor lithology, the upper hard and lower soft rock structure, fault F₆ cutting, excavation slope and frontal slope restraint, and external factors such as slope blasting excavation, and seasonal floods. The large deformation part of the slope was located in grade IV₂ rock mass of poor quality at the upper and lower wall of the Huashangou fault, and grade IV₂ rock mass at an elevation below EL830 m. Fault F₆ is steeply inclined to the mountain, and the hanging-wall deformation was greater than that of the footwall, extrusion fault, and footwall rock mass, whereas the footwall slope played the role of the reverse impedance body. However, when the slope foot in the middle and lower part of the slope is weakened, poor rock mass excavated, and slope is unloaded and relaxed, the rock-mass quality will be improved. When the mechanical parameters are reduced, the lower part of the slope pulls the upper part, and the upper part sinks outwards.

5.3 Overall stability evaluation results
The failure mode and failure area of the slope on the left side of the spillway tunnel outlet under the limit state are shown in Fig. 12. The deformation and instability were concentrated in the upper and lower walls of fault F₆ at the upstream side of the slope, especially near the unloading relaxation zone. When the strength reduction coefficient exceeded 1.22, an inflection point appeared in the displacement curve of the characteristic point above the shear outlet of the slope, and the upper rock mass of the slope tended to lose stability as a whole.
6. Conclusions
The stability of slope rock mass was analyzed and evaluated by integrating the geological conditions of slope rock, monitoring, geophysical testing results, and three-dimensional numerical simulations. Considering the mechanism of slope deformation and cracking, the poor lateral rock-mass structure of the left side slope at the outlet of the spillway tunnel was the internal geological reason for the larger deformations of the slope. The large-scale, poorly performing fault F6 boosted the slope deformations and formed the lateral boundary between the upper and lower walls of the deforming mass. The large-scale excavation and unloading of the middle and lower part of the slope as well as the significant lag of the slope support below the EL850 m elevation caused the rock mass and structural plane in the slope to exhibit strong stress relaxation and long-term deformation adjustment. The excavation of the IV2 rock mass below EL830 m of the slope weakened the supporting function of the slope base, and the excavation disturbance further aggravated the damage and deterioration of the rock mass and structural plane. In the slope body, especially in the unloading relaxation zone, the rock mass and structural plane fracture, opening and dislocation, fracture concentration, and the initiation and gradual development of the deep sliding surface, are the deep large deformation of the slope on the left side of the outlet of the spillway tunnel, and the continuous change is longer the root cause of time.

Using the dynamic feedback analysis and dynamic design of the high and steep slope, a multi-level support system was adopted, including grading slope ratio, deep-anchor cables, shallow anchor piles, partition supports, grouting reinforcement rock mass, strict sequence excavation, and controlled blasting. Through the dynamic design and strict construction management, the slope excavation effects were accounted for and stability control were realized.

Acknowledgments
This study was supported by the National Key R&D Program of China (2017YFC1501303), the National Natural Science Foundation of China (51779018,51539002), and the Fundamental Research Funds for the Central Public Welfare Research Institutes (CKSF2017054-YT). These supports are gratefully acknowledged and appreciated.

References
[1] Zuyu Chen, Zhen Wang, Hao Xi. Recent advances in high slope reinforcement in China: Case studies[J]. Journal of Rock Mechanics and Geotechnical Engineering, 2016(8): 775-788
[2] İbrahim Ferid Öge. Investigation of design parameters of a failed soil slope by back analysis[J]. Engineering Failure Analysis, 2017(82): 266-279
[3] Song Shengwu, Feng Xuemin, Xiang Boyu, Xing Wanbo, Zeng Yong. Research on key technology of high and steep rock slope engineering of Southwest hydropower [J].
Journal of rock mechanics and engineering, 2011, 30 (1): 1-22 (in Chinese)

[4] Chen ShengHong, Chen Shangfa, Yang Qigui. Feedback analysis of ship lock slope of Three Gorges Project [J]. Journal of rock mechanics and engineering, 2001 (5): 619-626 (in Chinese)

[5] Gao Dashui, Zeng Yong. Monitoring and analysis of prestress state of anchor cable in high slope of Three Gorges Permanent Shiplock [J]. Journal of rock mechanics and engineering, 2001 (5): 653-656 (in Chinese)

[6] Huang Runqiu, Xu Qiang. Geological disaster process simulation and process control [J], progress in natural science, 1999, 9 (12): 1273-1279 (in Chinese)

[7] Huang Runqiu. Geodynamical process and stability control of high rock slope development [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(8): 1525-1544 (in Chinese)

[8] Lionel Causse, Roger Cojean, Jean-Alain Fleurisson. Interaction between tunnel and unstable slope-Influence of timedependent behavior of a tunnel excavation in a deep-seated gravitational slope deformation [J]. Tunnelling and Underground Space Technology, 2015(50): 270-281

[9] Chuangbing Zhou, Yifeng Chen, Qinghui Jiang. A generalized multi-field coupling approach and its application to stability and deformation control of a high slope [J]. Journal of Rock Mechanics and Geotechnical Engineering, 2011, 3 (3): 193-206

[10] Yang Sun, Qinghui Jiang, Tao Yin. A back-analysis method using an intelligent multi-objective optimization for predicting slope deformation induced by excavation [J]. Engineering Geology, 2018(239): 214-228

[11] Yang Sun, Qinghui Jiang, Tao Yin. A back-analysis method using an intelligent multi-objective optimization for predicting slope deformation induced by excavation [J]. Engineering Geology 2018(239):214–228