Stability of Large-scale Slope Excavated in Weak Rocks with faults: a case study

HUANG Shuling¹, QIN Yang¹, DING Xiuli¹, HU Zhongping², WANG Hui², YIN Xiansong², DU Zekuai², WU Yongjin¹,³,*

1. Key Laboratory of Geotechnical Mechanics and Engineering of Ministry of Water Resources, Changjiang River Scientific Research Institute, Wuhan 430010, China

2. Changjiang Institute of Survey Planning Design and Research, Wuhan 430010, China

3. College of Mechanics and Materials, Hohai University, Nanjing 210098, China

* wuyjj@foxmail.com

Abstract. The slope stability of HUANGJINXIA water control project is very prominent during the construction period. Focusing on the main features of the right bank slope of the dam during the construction period, the geological, physical, and monitoring data were integrated to analyse the influence of the fault f_{17}, which runs horizontally across the entire shoulder slope and tilts out of the slope at a slow dip angle. Analysis of the effect of fault f_{17} on the flow field and deformation stability of the slope, the potential deformation damage mechanisms of slopes to propose targeted reinforcement solutions. On this basis, the numerical analysis method were used to review the slope stability respectively. The results show that after adopting large tonnage anchor cable support and deep drainage measures, the slope deformation has basically converged and no new signs of deformation have been found on the slope surface; the calculation results also show that the incremental deformation of subsequent excavation of the slope is not significant and the safety factor values during the construction and operation periods meet the requirements of the design specifications; the targeted reinforcement measures have effectively ensured the stability of the slope.

Key words: HANJIANG-TO-WEIHE River Valley Water Diversion Project, rock slope; structural plane; deformation mutation; numerical calculation

1. Introduction

The stability of rock slope is a common problem in water conservancy and hydropower projects, which affects and restricts each other. Different from soil slope, rock slope has the characteristics of complex rock mass structure, intersecting and cutting structural surfaces such as faults and fissures, and discontinuity. In previous engineering cases, the structural plane in rock mass, especially the weak structural plane, is often the controlling factor of slope deformation and instability. In the process of water conservancy and hydropower project construction, special attention should be paid to the distribution and mechanical properties of structural plane of rock mass. If the geological exploration is
not detailed in the early stage and the excavation treatment is improper, it will have a significant adverse impact on the construction and operation of the project\textsuperscript{[1-4]}. HUANGJINXIA water control project, as one of the main water sources, is key to the construction of the whole HANJIANG-TO-WEIHE River Valley Water Diversion Project. Slope, as the foundation of HUANGJINXIA project, its stability and safety are related to the construction and operation of the whole project. In the process of the right bank slope construction, several large-scale faults and fissured structural planes were exposed, especially fault f\textsubscript{17} (The fault zone runs through the whole dam abutment slope transversely, with large thickness and gentle inclination outside the slope). Focusing on the main features of the right bank abutment slope during the construction period, the geological, physical, and monitoring data were integrated to analyse the potential deformation damage mechanisms of slopes to propose targeted reinforcement solutions. On this basis, the numerical analysis method was used to review the stability of the slope. The research results enrich the case study of structural plane-controlled slope and provide important technical support for the project.

2. An outline of the studied project

2.1. Overview of the slope

HUANGJINXIA water control project is composed of water retaining structure, discharge structure, pumping station, power station and navigation structure (Figure 1). The dam adopts RCC gravity dam with crest elevation of 455m, maximum dam height of 63m and dam axis length of 349m. The natural slope inclination of the right bank abutment is 30-40°. The top elevation of riverside slope is 770m. The terrain is gentle and steep, and large-scale gullies are developed on both sides of the slope. The top elevation of excavation slope is 510m, the bottom elevation is 392m, and the maximum slope height is 118m. The slope is excavated by grading from top to bottom, and a 3 m wide berm is set every 15 m, the excavation slope ratio is 1:0.4-1:0.85(Figure 2)\textsuperscript{[5]}.

2.2. Identification of adverse geological condition of the Right bank abutment slope

2.2.1. Lithology. Proterozoic Qingbaikou Period diorite is exposed on the right bank slope, followed by intrusions of felsic dikes and monzonite dikes. Diorite is gray-white, fine-medium grain structure, massive structure. The main mineral components are plagioclase (60-75%), amphibole (11-20%), quartz (5-10%), biotite (4-15%), etc.

2.2.2. Rock mass structure. The statistical results show that the faults predominantly strike the NW group, followed by the NEE and NNE groups, and there are few developments in the NNW group. Except for the relatively large scale of the f\textsubscript{17} fault, other faults are mainly fractured faults. Among the faults revealed, the main faults are medium and steep dip angle faults, accounting for about 95%.

2.2.3. Fault f\textsubscript{17}. The strike of the fault f\textsubscript{17} is basically consistent with the slope, and the fault dip is 28-56°, dip angle is generally 6-13°. It is a gentle dip fault out of the slope. The fault basically extends through the whole right abutment slope, with an exposed length of about 150m and an elevation of 461-464m (Figure 3). The width of f\textsubscript{17} fault zone exposed on the slope is 0.5-1.3m, which can be roughly divided into three layers from top to bottom (Figure 4): fault gouge, cataclastic rock and gravelly soil, fault gouge. The structure is loose, easy to disintegrate when meeting water, with poor properties, and obvious flowing water along the fault.

2.2.4. Weathering of rock mass. Taking the fault f\textsubscript{17} as the boundary, the hanging wall rock mass of the fault is strongly weathered with a horizontal thickness of 22-38m, and the unloading phenomenon is serious; The rock mass in the footwall of the fault is basically a weakly weathered upper zone.

2.2.5. Hydrogeology. The groundwater in this area is mainly bedrock fissure water. The groundwater activity along f\textsubscript{17} fault zone is strong, with water seepage or flowing. There is obvious water flow at the 0+12 seepage point under the dam at the initial stage of excavation, and the water volume is about
1.0L/min; Obvious water flow occurred at 0+35 seepage point under the dam after rainfall, and the water volume reached 0.8-1.0L/min. According to the analysis of hydrogeological phenomena revealed by excavation, the $f_{17}$ fault zone has certain water resistance and is the main area of groundwater enrichment. According to the previous drilling and inclinometer hole, the groundwater level in this area is generally 2-3m above $f_{17}$.

Figure 1. Schematic diagram of HUANGJINXIA water control project.

Figure 2. This Slope engineering geological section (Dam axis section). 1. Quaternary deposit; 2. Proterozoic Qingbaikou period; 3. Diorite; 4. Boundary between bedrock and overburden; 5. Lower limit of strong weathering; 6. Boundary between upper and lower weakly weathered zones; 7. Lower limit of weak weathering; 8. Fault, fracture; 9. Dike.

Figure 3. Geological sketch of excavation slope.
2.3. Construction process of the Right bank abutment slope
The slope has been excavated since the end of 2015, and the fault is found when the slope elevation reaches 488m. To ensure the stress effect of anchor pile and anchor cable, the support scheme for the strongly weathered slope above 470m elevation is strengthened to "anchor pile + anchor cable + concrete lattice beam". After the left bank abutment slope collapsed on July 19, 2016, for safety reasons, the slope anchor cables with an elevation of more than 470m were densified and some anchor cables were lengthened. In December 2017, the slope was excavated to an elevation of 465m, and large unloading cracks were found on the slope downstream of the dam axis. At the same time, the deformation of the multi-point displacement meter with elevation of 489m on the downstream side of the dam axis increases in the deep part. In April 2018, the slope was excavated to an elevation of 461m, exposing a large-scale fault f_{317}. Therefore, the slope support scheme from the elevation of 470m to the highway subgrade is adjusted. The concrete lattice beam is modified to the reinforced concrete slab, the deep drainage hole is arranged, and the bedrock drainage hole is arranged at the elevation of 455m.

3. Behavior of rock mass in the excavation slope
The main deformation sign of slope surface is cracks in shotcrete, and there are many near vertical cracks on the raceway. From the slope opening line to the elevation of 560m, cracks along the slope direction appear in the natural slope accumulation layer. Four monitoring sections are arranged on the slope above 455m elevation of the right bank abutment, and the layout of monitoring facilities is shown in figure 5.

3.1. Multipoint displacement meter
As of August 31, 2019, the maximum cumulative displacement measured by multi-point displacement meter is 8.3mm (M03YBP). However, from May 2017 to June 2018, there was a phenomenon of short-term increase in displacement rate (Figure 6). With the completion of slope support measures with elevation of 455-470m, the displacement has tended to converge.

3.2. Inclinometer
After August 2017, the inclinometer slowly slips at 24.5m hole depth (elevation is about 463.5m), and the deformation continues to develop until mid-June 2018, and the cumulative sliding deformation at the sliding surface is about 20mm (Figure 7 and Figure 8). Later, with the deep support measures, the deformation development has gradually stabilized.

3.3. Anchor cable dynamometer
In the initial stage, due to clip retraction and formation compression, the anchoring force has a short time rapid relaxation, and then it is gradually stable or slow relaxation. As of August 31, 2019, the loss rate is within 9.0%. The measured value of anchor stress is generally between - 80MPa and 40MPa, which is far less than the allowable stress.
3.4. Deformation mechanism of the excavated slope
The deformation is mainly caused by the unloading adjustment of the strongly weathered rock mass. The cracks in the upper part of the opening line do not extend down to the deep, which are the Shallow Shrinkage Cracks of the soil after rain. The deformation position shown by inclinometer is consistent with the f_y17 fault. The analysis shows that f_y17 fault is the controlling structural plane affecting the stability of the slope. After taking anchor cable support and deep drainage measures, the slope deformation has converged, and no new deformation sign has been found.
4. Numerical analysis of the slope stability

4.1. Numerical analysis model
The numerical analysis of rock mass stability is widely recognized as an important approach for assessing slope stability and design feasibility. The numerical analysis results were referenced as bases for support design. According to the geological conditions revealed by the slope during the construction period, a numerical simulation model of the slope is established, which comprehensively considers the formation lithology, rock unloading, main geological structure, and excavation reinforcement scheme, as shown in Figure 9. The geological structures in the model mainly include faults f_{y17}, f_{HPD2-5}, f_{HPD2-1}, f_{HPD2-4}, and some large fissures.

4.2. Mechanical properties of rock masses
In the numerical analysis, the ideal elastic-plastic model with Mohr Coulomb criterion with tensile cut-off limit as yield function is adopted. The mechanical indexes of slope rock mass and main structural plane are shown in Table 1.

**Table 1. Physical and mechanical parameters of slope rock mass.**

| Lithology                        | $\gamma$ (kN/m$^3$) | $E$ (GPa) | $\mu$ | $f$  | $C$ (MPa) |
|----------------------------------|----------------------|------------|-------|------|----------|
| Strong weathering zone           | 26.5                 | 0.5        | 0.32  | 0.45 | 0.15     |
| Weakly weathered upper zone      | 28.2                 | 4.5        | 0.27  | 0.85 | 0.8      |
| Weakly weathered lower zone      | 28.4                 | 6.5        | 0.26  | 1.0  | 0.9      |
| Fresh rock mass                  | 28.5                 | 18.0       | 0.25  | 1.2  | 1.1      |
| Fault f_{y17}                    |                      |            |       | 0.45 | 0.07     |
| Fault f_{HPD2-5}                 |                      |            |       | 0.58 | 0.12     |
| Fault f_{HPD2-1}/f_{HPD2-4}      |                      |            |       | 0.45 | 0.06     |

4.3. Numerical analysis results

4.3.1. Deformation. When the right abutment slope is excavated to an elevation of 455.0m (current situation), the distribution of faults has a significant impact on the deformation of the excavated slope. The larger deformation area of the slope is mainly concentrated in the strongly weathered rock above the fault, and the deformation trend is downward along the slope. The incremental displacement value is generally between 5.0mm and 25.0mm, and the maximum is about 30.4mm (Figure 10). The excavation of the slope below the elevation of 455m has little influence on the deformation of the slope above the elevation of 455m (Figure 11).

4.3.2. Plastic zone. There is local stress concentration near the excavation line, and the excavation slope is generally in the state of compressive stress. The tensile stress area is mainly concentrated in the free face of the excavation slope and the area near the fault. From the inside of the slope to the surface of the excavation slope, the stress vector deflects, the maximum principal stress of the slope surface is parallel to the excavation line, and the minimum principal stress tends to zero. The plastic zone of the excavated slope is mainly distributed in the rock body of the upper strongly weathered zone of the slope and near the fault (Figure 12). The maximum depth is close to 16m.

4.3.3. Safety factor. The essence of sliding failure of slope is the strength failure phenomenon caused by insufficient shear strength of rock, soil, or structural plane. Therefore, the strength reduction method is used to review the safety factor of slope stability. In the numerical calculation, the instability criterion uses the calculation non convergence, the inflection points of the relationship curve between the displacement of the key point and the strength reduction factor of the slope, and the breakthrough of the shear strain rate concentration zone to judge whether the slope enters the critical state [6-7]. The results show that: the most dangerous sliding path of the slope is along the fault f_{y17} in
the front, $f_{HPD2.5}$ in the middle, and strongly weathered bottom boundary in the back (Figure 13). Its shear exit is located at the exposed part of the excavation free face of fault $f_{y17}$, and the instability area is mainly concentrated in the strongly weathered rock mass and colluvial deposits on the upper part of the fault. Under various conditions, the stability safety factor of the right bank abutment slope is between 1.24 and 1.36, which meets the requirements of the design code (Figure 14) \[10\].

5. Conclusions
Based on the behavior of the slope during the construction period, comprehensive geological, geophysical, and monitoring data are used to analyze the influence of the fault $f_{y17}$ on the stability of the right bank abutment slope. In the follow-up construction process of the slope, it is suggested to strengthen the drainage of $f_{y17}$ fault and hanging wall slope rock, reduce the groundwater level of the slope, and reduce the impact of groundwater on the stability of the slope. And the excavation control should be done to avoid the disturbance to the upper broken rock mass, and the support should be strengthened in time. Improve slope monitoring facilities and strengthen safety monitoring.

6. References
[1] G.P.Giani. Rock Slope Stability Analysis[M]. Rotterdam, Netherlands, A.A. Balkema, 1992.
[2] Cho SE, LeeSR. Instability of unsaturated soil slopes due to infiltration[J]. Computers and Geotechnics, 2001, 28(3): 185-208.
[3] HUANG Runqiu, ZHAO Jianjun, JU Nengpan, et al. Study on deformation mechanism and control method of bedding rock slope along Tangtun expressway[J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(2): 240 – 246.(In Chinese)
[4] Wu Aiqing, Yang Qigui, Chen Shenghong, Ding Xiuli. Research and Practice on Key Technologies of landslide disaster evaluation, prediction, and prevention in hydropower projects [R]. Wuhan: Yangtze River Science Institute, Yangtze River Water Conservancy Commission, 2007. (In Chinese)

[5] Wu Yongjin, Ding Xiuli, Huang Shuling. Stability analysis and evaluation of left bank slope in zone I of huangjinxia dam during construction [R]. Wuhan: Yangtze River Science Institute, Yangtze River Water Conservancy Commission, 2019. (In Chinese)

[6] Baili. Z, Zhuijiang. S. Computational soil mechanics [M]. Shanghai Science and Technology Literature Publishing House, Inc, Shanghai. 1990. (In Chinese)

[7] Itasca Consulting Group, Inc. 3DEC version5.00, users manuals[M]. [S.1] Itasca Consulting Group, Inc, 2015.

Acknowledgments
The work was supported by the National key research and development project of China (Nos. 2017YFC1501305).