Study on Mutual Feedback Mechanism and Stability Control of Toppling Slope and Tunnels with High Excavation Rate

Huifeng Zheng\textsuperscript{1}*\textsuperscript{a}, Shuo Zheng\textsuperscript{1b}, Yi Chen\textsuperscript{2a}, Guanye Wu\textsuperscript{1c}, Yong Zhou\textsuperscript{1d}

\textsuperscript{1}Huadong Engineering Corporation Limited. Hangzhou 311122, China
\textsuperscript{2}Zhejiang Gongshang University, Hangzhou 310018, China
\textsuperscript{1a}zheng_hf@hdec.com, \textsuperscript{2a}chenyiwork@126.com, \textsuperscript{1b}zheng_s@hdec.com, \textsuperscript{1c}wu_gy@hdec.com, \textsuperscript{1d}zhou_y7@hdec.com

Abstract—During the construction of large-scale hydropower projects in deep mountain gorge areas of the Western China, the difficulties, such as uncontrollable large deformation, great deformation caused by small disturbance, are often encountered in the process of implementation. In particular, due to the limitation of topography, geological conditions and the layout of structures, the slope and dense tunnel group with large section need to be excavated simultaneously in the toppling rock mass. The feedback action mechanism between slope and tunnel excavation is complicated and the deformation control of toppling rock is difficult, which leads to great challenges to engineering construction. In MW hydropower project in west of China, the intake slope, the spillway channel slope, four headrace tunnels, and the sand flushing tunnel, as well as the construction traffic tunnel are arranged in Huishi Ridge on the left bank, where two high slopes and six large cross-section tunnels are simultaneously excavated and the excavation rate in the toppling deformation rock mass is over 50%, moreover, the lateral coverage thickness of tunnel body is less than the diameter of the tunnel, which leads to the great difficulty of stability control. The excavation stability and safe of the thin mountain ridge is the vital issue to the success of the whole project. Based on the study of the physical and mechanical parameters of toppling rock mass of MW HPP, the mutual feedback mechanism of toppling slope and tunnel group is revealed, an excavation method involving horizontal partitioning, vertical layering, reserving rock plug and reasonable skipping warehouse is proposed. Monitoring results shows that the slope and surrounding rock of the tunnels are stable during the operation period. The research of this paper based on the MW HPP can provide reference for other similar projects.

1. Introduction

During the construction of large-scale hydropower projects in deep mountain gorge areas of the Western China, the difficulties, such as uncontrollable deformation, large deformation caused by small disturbance, are often encountered in the process of implementation\textsuperscript{[3]}. In particular, due to the limitation of topography, geological conditions and the layout of structures, the slope and dense tunnel group with large section need to be excavated simultaneously in the toppling rock mass. The interaction mechanism of excavation between slope and tunnels is complicated and the deformation control of toppling rock is difficult, which leads to great challenges and has extensively attracted by researchers and engineers, who have studied the deformation mechanism and influencing factors of the toppling slope from the aspects of theory, experiment, and numerical simulation\textsuperscript{[2-7]}. Simultaneous excavation of slopes and large-section dense tunnels has been carried out in the Huishi Ridge, where is the core location of MW Hydropower Station in the west of China. In the process of construction, it was faced with the challenge...
of large deformation and stability control caused by the interaction between the high slope and the large section dense tunnels of toppling rock mass. Through the rock parameters feedback based on real-time monitoring data, the excavation response analysis of the intake slope and the headrace tunnels were carried out, and the construction scheme of Huishi Ridge was studied. Finally, based on the analysis of the monitoring data after completion, the stability and safety of slope and tunnels were evaluated. As a typical case of the interaction of the cave-slope system in the toppling rock mass, the effective stability control to excavation of MW HPP is a useful reference for similar projects.

1.1 Project Overview
MW project consists of gravelly soil core rockfill dam, the left bank spillway, flushing and emptying tunnel, diversion and power generation systems and ground powerhouse. The total installed capacity of the power station is 1400MW. The slope rock mass in the engineering area has developed toppling deformation, with the maximum horizontal depth over 200m. At the same time, faults, intralayer dislocation zones and joints in the dumped rock mass are relatively developed. The depth and range of toppling rock in MW project is rare in domestic and abroad hydropower projects. Fig.1 the engineering geology profile.

1.2 Layout of engineering slope and tunnel group in Huishi Ridge
The MW HPP is arranged around the isolated and thin Huishi Ridge on the left bank. The right side is adjacent to the left dam abutment, the left side is the spillway slope, the front is the intake slope, and 4 headrace tunnels, sand flushing and emptying tunnel, irrigation water intake traffic tunnel are simultaneously arranged in the mountain. Fig.2 is the plane distribution of tunnels in Huishi Ridge.
less than the tunnel diameter. The small spacing and dense arrangement of large cross-section tunnels in the water diversion system lead to the excavation rate in Huishi Ridge exceeds 50%. Fig.3 is the elevation view of intake slope of Huishi Ridge.

![Fig.3 Elevation view of intake slope of Huishi Ridge](image)

### 1.3 Basic geological condition of Huishi Ridge

The rock mass in the Huishi Ridge region is the fourth subrock group (J2h2-4) of the upper member of the Middle Jurassic Huakaizuo Formation, sericite quartz sandstone interposed with metamorphic quartz sandstone, metamorphic calcareous sandstone and sandy sericite slate, with a small amount of chlorite sericite slate It is a thin interlayer structure, and the angle between the slope and the strike of the rock stratum is 41°.

According to the classification standards of toppling deformation, the distribution characteristics of slope rock masses are determined: extremely strong toppling A-type rock masses are distributed above 1420m elevation, strong toppling B1-type rock masses are distributed in elevation between 1410m and 1420m; strong toppling B2-type rock masses are distributed in elevation between 1395m and 1410m; weakly toppling C-type rock masses are distributed between 1390 m and 1395m in elevation, and the following are normal rock masses. The integrity of the slope rock mass is poor and relatively broken because of stratum lithology, structural surface, and development of toppling deformation. According to the CSMR slope rock mass classification, it is determined that the rock mass is mainly type III. The slope has a deep underground water depth, no underground water is exposed on the excavated slope, and the slope rock mass is dry. Fig.4 is the geological section of toppling rock mass and main discontinuities of Huishi Rigde.

![Fig.4 Geological Section of toppling rock mass and main discontinuities of Huishi Rigde](image)
2. Back analysis of toppling deformation rock mass parameters in the Huishi Ridge

2.1 Three-dimensional numerical back analysis model

The 3DEC\(^8\) was employed to establish an integral three-dimensional numerical model of the Huishi Ridge (see Fig.5 and Fig.6). The main discontinuities such as F\(_{44}\), F\(_{121}\), F\(_{122}\), F\(_{109}\) and other major faults, anti-dip planes, and downslope gently-dipping discontinuities are included in the model. The toppling rock in the model includes the extremely toppling A-type, the upper segment B\(_1\)-type and the lower segment B\(_2\)-type of the strong toppling rock mass, and the weakly toppling C-type. The Mohr-coulomb elastoplastic constitutive is adopted for the numerical analysis, and strain softening model is adopted for the area affected by excavation. Fig.5(a) is the simulation of the anti-dip discontinuities of the integral model of the intake slope, and Fig.5(b) is the grading feature of the intake slope rock mass.

![Fig.5 Three-dimensional numerical model of Huishi Ridge](image)

2.2 Safety monitoring instrument layout and result analysis during construction period

During the excavation construction of the intake slope of MW Hydropower Station, various monitoring measures were arranged, including surface observation point (TPjb), anchor cable dynamometer (DjbZ), multi-point displacement meter (Mjb), and reinforcement meter (Rjb). Fig.6 is the monitoring arrangement of the intake slope.

![Fig.6 The monitoring arrangement of the intake slope](image)

Since January 2014, the intake slope has been excavated below the elevation of 1395m, resulting in a significant increase in the deformation rate of slope. Monitoring data shows that the deformation of the multi-point displacement meter on the intake slope is 0.55\(~0.97\)mm/d, and the displacement of the end of MJbZ4-1 reaches 75mm (see Fig.7). The variation tendency of the anchor cable dynamometer is similar to that of the multi-point displacement meter, and the anchor cable load growth has increased...
significantly. Among them, the DJbZ3-2 load increment is 32% of the design tension force, and the increment has reached 257.8KN compared to the locked value (see Fig.8).

![Fig.7 Monitoring time-history of multi-point displacement meter MJBZ4-1 in the intake slope](image1)

![Fig.8 Load time-history of anchor cable dynamometer DJBZ3-2 in the intake slope](image2)

2.3 Back analysis of toppling deformation rock mass parameters
Combining the slope deformation monitoring results and the three-dimensional numerical model for feedback analysis, the actual physical and mechanical parameters resulted from the back analysis are closer to of the rock mass on site. Numerical calculation results show that the displacement values of monitoring are in good agreement with the numerical calculation results of the three-dimensional model, and the maximum deformation error between them is only 10.8%. Table 1 shows the rock mass parameters through feedback analysis of Huishi Ridge, including the excavation unloading area affected by blasting.

![Table 1 Slope rock mass mechanical parameters by feedback analysis](table1)

3. The mutual feedback analysis of “tunnel-slope” system in Huishi Ridge during excavation period
3.1 Excavation response analysis of water intake slope
In May 2014, the intake slope was excavated to elevation of 1370m. Fig.9, Fig.10 and Fig.11 respectively show the deformation contour of the overall, vertical and outward normal direction of the intake slope. Calculations show that the maximum deformation of the slope is about 60mm and occurs at the place above the 1# and 2# headrace tunnels. The faults F_44, F_121, and F_50 form the slope displacement control boundary. The vertical deformation of the slope is about 40mm at an elevation of 1415m. With respect to the deformation of the outward normal of the slope, the deformation at lower
part is obviously larger than the upper part. The normal deformation of the slope at an elevation of 1380m is about 40~60mm. The excavation deformations resulted from numerical analysis are in good agreement with the monitoring results of multi-point displacement meters except MjbZ4-1.

3.2 Excavation response analysis of the upper level section of headrace tunnel group

At the end of June 2014, the upper flat section of the headrace tunnels began to be excavated, with an excavation volume of about 2000m³. Three-dimensional numerical simulation showed that although the amount of excavation at this stage is not too much, it still disturbs the slope to a certain extent, and the excavation displacement increment reached about 10~15mm. The displacement increment of the low-elevation part of the intake slope is larger than that of the high-elevation part, and the deformation trend of the slope is the falling deformation in direction of excavation.
3.3 Excavation response analysis of the rock plugs of headrace tunnel entrances
The excavation of the rock plugs of the headrace tunnels started in September 2015, with an excavation volume of about 4500m³. Three-dimensional numerical simulation showed that the impact of rock plugs excavation is not prominent, and the slope deformation increment is less than 10mm.

3.4 The excavation construction scheme of Huishi Ridge
Aiming at the practical engineering problems encountered during the construction of large-section tunnel group on the slope with strong toppling at the water intake of MW Hydropower Station, targeted dynamic excavation and support design work was carried out. Based on the numerical analysis, and fully considering the influence of the mutual feedback of the excavation of the "tunnels-slope" system, a comprehensive excavation method involving horizontal partitioning, vertical layering, reserving rock plug and reasonable skipping warehouse is put forward for the excavation of a high and steep toppling slope. Through the proposed scheme, the safe and rapid excavation and construction of the water inlet slope and the dense tunnel group is realized.

3.5 The long-term monitoring data analysis after the completion of the water inlet slope
The long-term monitoring data analysis after the completion of the construction of the intake slope and tunnel group of the MW Hydropower Station, which were obtained during the supporting installation and subsequent excavation, shows that the maximum accumulated horizontal displacement at the intake slope surface is 56.4mm at elevation of 1435.00m (see Fig.16), and the maximum accumulated settlement deformation is 108.8mm at elevation of 1436.00m. The apparent and deep monitoring of deformations have stabilized after 2015, which show that the Huishi Ridge is stable on the whole.

4. Conclusion
Due to the limitation of topography, geological conditions, as well as the intensive layout of structures, the excavation and construction conditions of Huishi Ridge of the MW Hydropower Station are very
complicated. The deformation and stability of the toppling slope excavation itself is difficult to control. In addition, the excavation of large-section dense tunnel group in such toppling rock mass further increases the difficulty of rock mass stability control. The simultaneous excavation of slope and tunnels in toppling rock mass mutually influenced, which brought out prominent safety and stability problems. Therefore, the problem of stability control under the mutual feedback action of the "toppling slope + dense tunnel group" system is a huge challenge.

Based on the safety monitoring during the construction period and the three-dimensional numerical model, the feedback analysis of the rock mass parameters is carried out, which provides the basis for the mutual feedback analysis of the Huishi Ridge "toppling slope + dense tunnel group" system.

Based on the three-dimensional numerical feedback analysis and design scheme of excavation, the response analysis of the excavation of the intake slope, the upper flat section of the headrace tunnels, and the rock plugs of the cave entrance section in Huishi Ridge was carried out, which reveals the mutual influence of "toppling slope + dense tunnel group" during the construction period.

Based on the full consideration of the mutual action of the excavation of the "tunnels-slope" system, a comprehensive excavation scheme for the excavation of a high and steep toppling slope involving horizontal partitioning, vertical layering, reserving rock plug and reasonable skipping warehouse is put forward, which ensured the safe and rapid excavation and construction of the water inlet slope and the dense tunnel group. A toppling deformation rock mass excavation method is proposed that fully considers the mutual feedback influence of the excavation of the tunnel-slope system. And an excavation method involving horizontal partitioning, vertical layering, reserving rock plug and reasonable skipping warehouse is proposed to ensure the slope and tunnel group construction safety and excavation stability.

Monitoring data after completion of the project showed that the water intake slope and tunnel group are in a stable and safe state.

Reference
[1] LU Wen-bo, YAN E-chuan, ZOU Hao, ZHANG Shi-shu. Development rules of toppling deformation slopes in China[J]. Journal of Yangtze River Scientific Research Institute, 2017, 34(8): 111~119.
[2] HAN Bei-chuan, WAN G Si-jing. Mechanism for toppling deformation of slope and analysis of influencing factors on it[J]. Journal of Engineering Geology, 1999, 7(3): 213~217.
[3] HUANG Qiuxiang, WANG Jialin. Study of the deformation characteristics of an anti-dip slopewith soft internal layers[J]. China Civil Engineering Journal, 2011, 44(5):109~114.
[4] ZUO Bao-cheng, CHEN Cong-xin, LIU Xiao-wei, SHEN Qiang. Modeling experiment study on failure mechanism of counter-tilt rock slope[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(19): 3505~3511.
[5] LIU Li-juan, YOU Xiang, GU Cheng-zhuang. Numerical simulation of toppling rock mass of Xinlong Hydropower Station[J]. Journal of Yangtze River Scientific Research Institute, 2014, 31(11): 92~96.
[6] Huifeng Zheng, Guanye Wu, Yi Chen, Nengpan Ju. Study on Deformation Failure Mechanism and Control Measure of Toppling Slope. Journal of Physics Conference Series Volume 1624, 2nd International Conference on Computer Modelling, Simulation and Algorithm: 1354~1361.
[7] Wu Guanye, Zheng Quanchun, Zheng Huifeng. Toppling Deformation Mechanism and Reinforce Effectiveness AnalysisIn Slope of Miaowei Hydropower Station. Chinese Journal of Underground Space and Engineering, 2017, 13(2): 538~544.
[8] Itasca Consulting Group Inc. UDEC (universal distinct element code) user's manual version 4.0[M].