Study on Excavation of Particular Part of Underground Cavern for Hydropower Station

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Abstract. In the present study, regarding four particular parts of underground cavern for hydropower station, i.e., crown, high sidewall, the intersection between high sidewall and tunnel and tailrace tunnel, by summarizing the previous construction experience, we have proposed the excavation approach based on “middle first and edge later, soft first and hard later”, “layered construction by excavating the thin layer first and supporting as the layer advances”, “tunnel first and wall later, small tunnels into large ones” and “excavating tunnels supported by separation piers”. In addition, the proposed excavation approach has been analyzed and verified with finite element numerical simulation. The result has indicated that the proposed special approach is reasonable and effective to reduce the turbulence on surrounding rocks, lower the influence of unloading during excavating and enhance the local and global stability of caverns and surrounding rocks.

1. Introduction
Particular parts of underground cavern for hydropower station include crown, high sidewall, intersection between high sidewall and tunnel as well as tailrace tunnel and affect greatly on overall stability of cavern group, imposing high requirements on excavation control due to high difficulty in excavating and supporting and complicated force conditions [1], thereby being the key and difficult point for excavating of underground cavern for hydropower station. Complicated environmental conditions further highlight the influences of excavating and unloading on surrounding rocks. During cavern group excavating process, poor control of surrounding rock stability in such particular parts will cause hugely adverse effects on overall stability of underground cavern.

2. Excavation of Crown
Crown generally is the first part to be excavated for an underground cavern and its excavating quality directly affects its surrounding rock stability and greatly relates to overall stability of surrounding rocks of subsequent caverns. According to the experience accumulated in excavating a large number of underground caverns, in this paper, we have concluded the excavating approach of “middle first and edge later, soft first and hard later”. “Middle first and edge later” means it is suggested to excavate middle pilot tunnel if the middle pilot tunnel causes less turbulence on crown whose is supported by strong surrounding rock with good self-stabilizing capacity, which may facilitate increasing working surfaces and delivering rock slags out. “Soft first and hard later” means it is suggested to excavate soft
rock first while retaining strong rocks to support crown when the surrounding rock is not stable enough, then support the excavated surrounding rock, and finally excavate rocks with high strength. Liyang Hydropower Station has poor surrounding rocks around its underground caverns. When excavating the crowns, pilot tunnels through soft surrounding rocks around the two sides were first excavated to ensure such area were supported first, to stabilize spandrel rocks. And next, the middle rock pillars were removed to retain the stability of crown. In the process that two side pilot tunnels were being excavated, the side with the most unfavorable condition was first excavated based on rock direction and dip angle, and then supported by bolts. And then the other side was excavated to ensure the two tunnels were not aligned. When the two tunnels were completely supported, the middle rock pillar was then removed. In this process, the one-time excavating span was reduced to ensure engineering safety.

In this paper, we have analyzed the crown excavating approach of “soft first and hard later” applied in Liyang Hydropower Station by 3D elastoplastic damage finite element simulation [2, 3, 4], and compared its effect with the “hard first and soft later” approach. Surrounding rock damage distributions for crowns excavated with the two approaches are shown in Figure 1. With the “soft first and hard later” approach, the total damage volume of surrounding rock is 20697.1m$^3$ with a total plastic dissipated energy of 1545.6t•m while with the “hard first and soft later” approach, the two figures are 43897.3m$^3$ and 3719.2t•m, respectively. It is therefore known that at unstable surrounding rock condition, the “soft first and hard later” crown excavating approach can effectively lower the turbulence of surrounding rocks to ensure the stable excavating of crown.

3. Excavation of High Sidewall
Underground cavern for hydropower station often encounters problems like high sidewall, large spa, complicated structure and troublesome surrounding rock stability during construction [5]. Against the high sidewall feature, a “layered construction by excavating the thin layer first and supporting as the layer advances” is herein proposed. Layered and phased excavating can gradually release stress and timely support surrounding rocks to effectively limit the adverse effect of high sidewalls on stability of surrounding rocks. Since support is completed as excavating advances, surrounding rocks can be timely supported to shorten the duration that sidewalls are not exposed, thereby effectively taking advantage of the supporting role from rocks, reducing the turbulence of rocks due to load releasing and enhancing the underground cavern stability and construction safety.

Figure 1. Damage zones of crown excavation.

Figure 2. Damage zones of high sidewall excavation.
Take the high sidewall excavating of main plant for Liyang Hydropower Station as an example and numerical simulation has been used to analyze the suitability of layered excavating. In numerical simulation, layered excavating and one-time excavating are considered as the two working conditions. The numerical simulation results are shown in Figure 2 and Table 1. According to the results, total damage volume in layered excavating is about 91,600 m$^3$ less than that in one-time excavating and its total plastic dissipated energy is 5552.1t•m less than that in one-time excavating. One-time excavating causes large turbulence of surrounding rocks while layered excavating causes less thanks to its small excavating volume for each time. As a result, total stability of surrounding rock after layered excavating is higher. Therefore, in high sidewall excavating process, layered and phased excavating is significantly better than one-time excavating.

Table 1. Damage Parameters for Different High Sidewall Excavating Approaches.

| Breaking parameter | Plastic damage volume (m$^3$) | Cracking volume (m$^3$) | Total damage Volume (m$^3$) | Plastic Dissipated Energy (t•m) |
|--------------------|-------------------------------|--------------------------|----------------------------|--------------------------------|
| Layered Excavating | 45298.3                       | 23547.2                  | 68845.8                    | 4794.7                         |
| One-time Excavating| 126830.2                      | 33649.3                  | 160479.4                   | 10346.8                        |

4. Excavation of Intersection between High Sidewall and Tunnel

Many tunnels in underground caverns of hydropower station intersect with high sidewalls of main plant cavern, such as approach tunnel, tailrace tunnel, access tunnel bus tunnel. For these intersections, this paper has proposed the excavating approach of “tunnel first and wall later, small tunnels into large ones”, which means, small caverns are excavated before layered excavating of high sidewalls of large ones. Since this approach gives rise to smaller tunnel sizes which cause less turbulence on rock walls, which are then timely supported before side walls of large tunnels, thereby effectively reducing repeated turbulence on sidewalls of large tunnels and enhancing stability of surrounding rocks around intersections.

Take Liyang Hydropower Station as an example, 3D elastoplastic damage finite element simulation is adopted to analyze applicability of “tunnel first and wall later” to intersection between bus tunnel and main plant. Two approaches are used for numerical simulation, i.e., “tunnel first and wall later” in which bus tunnel is excavated before main plant cavern and “wall first and tunnel later” in which bus tunnel is excavated after main plant cavern.

Rock breaking distributions caused by the two approaches are shown in Figure 3 which indicate that surrounding rocks around the caverns completed by both approaches show similar breaking rules, however, the breaking depth due to “tunnel first and wall later” Approach is less than that due to “wall first and tunnel later” around the intersection between bus tunnel and main plant cavern, particularly the bottom part of this intersection. With the “tunnel first an wall later” approach, total damage volume of rock and total plastic dissipated energy are 19236.7m$^3$ and 1529.1t•m, respectively. With the other approach, the two figures are increased by 39% and 65%, respectively. This is mainly due to less surrounding rock turbulence caused by “tunnel first and wall later” approach. On the other hand, partial stress in surrounding rock is released due to excavating of bus tunnel, then the stress in surrounding rock will be gradually and slowly released in excavating of main plant cavern. As a result, stress distribution in intersection is better and good for stability of surrounding rocks around intersection between bus tunnel and main plant cavern.
Figure 3. Damage zones of excavation of intersection between high sidewall and tunnel.

In a word, “tunnel first and wall later, small tunnels into large ones” approach used in excavating intersection between high sidewall and tunnel can effectively lower turbulence of rock wall and enhance stability of wall rack around the intersection.

5. Excavation of Tailrace Tunnel

High sidewalls of main plant are completed before the tailrace tunnel of underground cavern is excavated. So excavating bottom of high sidewalls may cause sidewall to be unstable. By considering the characteristic of high sidewall due to excavating and loading release, we have made deep research on the force features of surrounding rock around cavern and therefore proposed the tailrace excavating approach based on “excavating tunnels supported by separation piers” which means tailrace tunnels are not excavated completely, with some remaining rock as separation piers for supporting purpose, with these separation piers being reinforced in advance. This approach can reduce large mined-out areas generated by excavating of tailrace tunnel and improve surrounding rock stability.

This approach can avoid intensive release of load in surrounding rocks, and reinforce surrounding rocks step by step to lower its turbulence. Retaining the “separation piers” formed by original rock can lower the large area excavating height for high sidewalls, reduce the sudden energy release from surrounding rock and transfer partial energy to separation piers by taking full advantage of strength and rigidity of separation rocks to reduce small sidewall deformation and improve stress state of supporting structures.

Taking the underground cavern for Xiaowan Hydropower Station as an example, and by using 3D elastoplastic damage finite element simulation, the applicability of “excavating tunnels supported by separation piers” to tailrace tunnel excavating is analyzed. In numerical simulation, two models, i.e., excavating with original rocks as separation piers and excavating without separation piers are constructed as shown in Figure 4. The first model means partial surrounding rocks are retained between the adjacent units at the bottom part of plant as separation piers.

Figure 4. Excavation model of tailrace tunnel.

After the second model, i.e., without original rock as separation piers, is completed, total damage volume of surrounding rock and total plastic dissipated energy are 433232.5m³ and 366862t•m. The first
model, i.e., with original rock as separation piers, is completed, the two figures are reduced by 23.5% and 36.0%, respectively. In terms of damage volume, the approach that retains original rock as separation piers is better. Rock deformations after complete excavating by the two approaches are shown in Figure 5. It is seen from the two Figures that with “original rock as separation piers”, displacements of crown, upstream sidewall and downstream sidewall are smaller than those without “original rock as separation piers”, due to better supports on upstream and downstream sidewalls from retained “original rock as separation piers”, which limits sidewall deformation and enhance overall stability of cavern.

![Deformation of surrounding rocks.](image)

During excavating tailrace tunnel for underground plant for hydropower station, retaining original rock as separation piers can reduce excavating volume at the bottom of tailrace tunnel and lower the excavating height of full section for main plant at separation sites, thereby reducing energy release from surrounding rocks and having separation piers carry partial of released load. Therefore, it is suggested to adopt “original rocks as separation piers” mechanism to fully take advantage of the supporting role from separation piers and to take proper supporting measures timely, in order to ensure the overall excavating stability of underground cavern with large mined-out rate.

6. Conclusion

Based on the review of previous experience in excavating underground cavern for hydropower station, in this paper, we have proposed “middle first and edge later, soft first and hard later” excavating method for crown, “layered construction by excavating the thin layer first and supporting as the layer advances” excavating method for high sidewalls, “tunnel first and wall later, small tunnels into large ones” excavating method for intersection between high sidewalls and tunnel, and “excavating tunnels supported by separation piers” excavating method for tailrace tunnels. The results provide theoretic basis and also of great practical implication in excavating of underground cavern for hydropower station.

References

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