Study of Blasting Parameters Optimization of Underground Powerhouse of Pumped Storage Project with Flac3D Numerical Simulation Method

Sheng Wan¹,²,*, Yuhong Zhu³, Hui Li³

¹Hubei Key Laboratory of Road-bridge and Structure Engineering, Wuhan University of Technology, Hubei, Wuhan, China
²Qingyuan Pumped Storage Power Generation Co., ltd, Guangdong, Qingyuan, China
³SINOHYDRO BUREAU 14 CO., LTD. Guangdong, Guangzhou, China

*Corresponding first author e-mail: 37364674@qq.com

Abstract. Based on optimization from Mohr-Coulomb constitutive model, FLAC³D procedure is used to simulate the excavation of Qingyuan pumped storage power station. By adding the monitoring simulation, the consequence reveals that the minimum main stress is mainly distributed in the center place of top and base of goaf. At the beginning of excavation, the rock stratum in the center of exposed surface of top of goaf is mostly tensed which causes tensile stress failure characteristics easily, and meanwhile, the skewback of top arch and other corners are easily occur shear failure, following with the excavation proceeding, the main failure form of rock stratum is changing to shear failure on partial corners. This paper mainly discusses on the blasting parameters optimization by adapting the kerve step blasting from "−−" type to “V” type. Our practice might as well serve as a reference for similar projects to come.

1. Introduction

Pumped storage power station, as an important adjusted effect on safety and stabilization of power grid, has the advantages of clear, environmental protection, high efficiency and stabilization, it is predicted that the scale of installed capacity will reach 1070MW by 2020.

In the aspect of effect research of blasting vibration, Li Xingping and his team adopt site blasting vibration test and digital simulation for researching the blasting damage range and criterion of conventional power station, which draws a conclusion of particle velocity induced by blasting. Luo Yi and his team adopt damage criterion and damage variable, by considering the degradation parameter of stone mass on different degree of damage parts in calculation, taking the degraded parameter into account of related damage parts to carry out numerical simulation.
calculation of following excavation and blasting for simulating the accumulation damage effect of that.

In the aspect of numerical simulation, Li Xingping and his team adopt FLAC3D and introduce damage variable D to study the blasting damage range and criterion, as a result therefore come up with the conclusion of damage depth and horizontal radius are increasing following with the explosive increasing of each section, the damage range is reducing following with the blast-hole depth increasing, the maximum horizontal radius of blasting damage is on the top surface of blast-hole.

Hereby the thesis adopts FLAC3D to simulate the number of excavation of underground powerhouse of pumped storage power station for optimizing the blasting parameter, controlling the interfering of surrounding rock and finally increasing the blasting quality.

2. Project Profile

2.1. Engineering Characteristic

The underground powerhouse of Qingyuan pumped storage power station is comprised of main engine room, auxiliary powerhouse and installation place with the excavation size of 169.5m×25.5m×55.7m。Ledge beams of underground powerhouse are installed on the upstream and downstream side-walls of second storey, the total length of each sidewall is 143.5m with 0.5m of horizontal width of excavation rock bench, it’s W*H=1.6m*2.9m after casting。

2.2. Engineering Geology

The underground powerhouse mainly spread over medium-macro biotite granite of Yanshan third period (γ52(3)) which is mainly comprised of plutonic intrusions and medium-plutonic intrusions in good integrity with exposure of batholith, stock and dyke. There are small amount of kaolinite mineralization alteration and chlorite mineralization alteration on parts of granitic pluton with irregular regiment massive and partial developing along with both sides of fault structure and fissure zone.

3. Mechanical Model

3.1. Mechanical Model

Hereby the thesis adopts Mohr-Coulomb model to conclude the mechanic constitutive model of rock mass. The failure envelope of Mohr-Coulomb model is determined by Mohr-Coulomb criterion. The incremental theory of Plasticity assumes the strain increment of stone could be separated into elastic strain increment $e_i^e$ and plastic strain increment $e_i^p$, e.g.:

$$\Delta e_i = \Delta e_i^e + \Delta e_i^p (i = 1, 2, 3)$$

1) Elastic strain increment

The equation of elastic strain increment as per Hooke rule is:

$$\Delta \sigma_1 = E\Delta e_1^e + \gamma(\Delta e_2^e + \Delta e_3^e)$$

$$\Delta \sigma_2 = E\Delta e_2^e + \gamma(\Delta e_1^e + \Delta e_3^e)$$

$$\Delta \sigma_3 = E\Delta e_3^e + \gamma(\Delta e_1^e + \Delta e_2^e)$$

2) Plastic strain increment

Mohr-Coulomb condition is:
\[
\frac{\sigma_i - \sigma_3}{2} = c \cos \phi + \frac{\sigma_1 + \sigma_3}{2} \sin \phi \tag{5}
\]

\[
\tau = c \sigma_n \tan \phi \tag{6}
\]

In the equation: \( \sigma \) — cohesive force; \( \phi \) — internal friction angle; \( \sigma_n \) — normal stress on shearing surface.

on \( \sigma_1 - \sigma_3 \) plane, \( AB \) is failure envelope, Mohr-Coulomb yield equation is:

\[
f = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi} \tag{7}
\]

In the equation:

\[
N_\phi = \frac{1 + \sin \phi}{1 - \sin \phi} \tag{8}
\]

as per related flow rule:

\[
g = \sigma_1 - \sigma_3 \frac{1 + \sin \phi}{1 - \sin \phi} \tag{9}
\]

In the equation: \( g \) — plastic potential surface; \( \phi \) — expansion angle.

Plastic strain increment:

\[
\Delta e^p_i = \lambda' \frac{\partial g}{\partial \sigma_i} \tag{10}
\]

In the equation: \( \lambda' \) is the function to determine the Plastic strain, it is non-negative plastic factor.

\[
\Delta \sigma_i = \Delta \sigma_i^N - \Delta \sigma_i^O \tag{11}
\]

In the equation, \( N, O \) are new and original stress state respectively.

let:

\[
\sigma_1' = \sigma_1^O + E\Delta e_1 + \gamma(\Delta e_2 + \Delta e_3) \tag{12}
\]

\[
\sigma_2' = \sigma_2^O + E\Delta e_2 + \gamma(\Delta e_1 + \Delta e_3) \tag{13}
\]

\[
\sigma_3' = \sigma_3^O + E\Delta e_3 + \gamma(\Delta e_1 + \Delta e_2) \tag{14}
\]

\[
\lambda' = \frac{f(\sigma_1', \sigma_2')}{(E - \gamma N_\phi) - (\gamma - EN_\phi)N_\phi} \tag{15}
\]

so:

\[
N_\phi = \frac{1 + \sin \phi}{1 - \sin \phi}; \phi \text{ is expansion angle.}
\]

3.2. Mechanical Parameter

As per the deformation behaviour and strength behaviour of rock mechanics, the thesis adopts density, bulk modulus, shear modulus, cohesion, internal friction angle as main mechanical parameter, in which the bulk modulus and shear modulus are concluded by the following equation:
In the equation, $K$ is bulk modulus, $G$ is shear modulus, $E$, $\mu$ are elasticity modulus and Poisson's ratio of rock.

4. Numerical Simulation

4.1. Excavation Model

The excavation model is built as per the construction statement. The monitoring points are set in excavation model. In consideration of symmetry, aside from the monitoring points to be set to top arch of main powerhouse, the rest points of monitoring are set on the upstream head-wall.

4.2. Model scale

The study scale is mainly within the area of underground powerhouse, $X$ direction:300m, $Y$ direction:500m, $Z$ direction:300m. $X$ axis of three-dimensional computing coordinate coincides with longitudinal axis of powerhouse which the direction to downstream is positive; $Z$ axis coincide with longitudinal axis of powerhouse which the direction to earth’s surface is positive; $Y$ axis is following with the direction of powerhouse, origin of coordinates is the intersection point of base and longitudinal axis.

4.3. Three-dimensional initial stress field simulation

As per the achievement studied by Yi Jianming\textsuperscript{xii}, Li Yongsong\textsuperscript{xiii}, Guo Xifeng\textsuperscript{xiv} for Qinyuan pumped storage power station, it is concluded that the powerhouse area is intermediate stress area. It is concluded that the powerhouse area is intermediate stress area. The proposed crustal stress survey value as shown in form 1. In accordance with the feasibility study, the coefficient of horizontal pressure normally is $0.94 \sim 1.5$, mechanical parameter as shown in form 2.

\begin{table}[h]
\centering
\caption{Proposed geostress value of underground powerhouse}
\begin{tabular}{llll}
\hline
Proposed value & Stress/Mpa & dip Angle/Deg & Azimuth angle \\
\hline
$\sigma_1$ & 14.0±0.5 & 40 & close to SN \\
$\sigma_2$ & 11.0±0.5 & 40 & NW/NE \\
$\sigma_3$ & 8.5±0.5 & 15 & close to EW \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{model mechanics parameter list}
\begin{tabular}{llllllll}
\hline
lithology & unit weight/KN/m$^3$ & elasticity modulus/GPa & bulk modulu s/GPa & shear modulu s/GPa & Tensile Streng t/MPa & Poisson' s ratio/\(\mu\) & cohesion/MPa & Internal friction angle/° \\
\hline
granite & 27.00 & 51.72 & 28.7 & 21.6 & 2.54 & 0.2 & 2.5 & 51 \\
\hline
\end{tabular}
\end{table}

4.4. Excavation Simulation

As per FLAC\textsuperscript{3D} to calculate the excavation of underground powerhouse after modeling, maximum and minimum main stress nephogram of excavation surface as shown in diagram1. Maximum main stress in goaf is mainly distributed on the angle place and lateral wall of
excavation area, minimum main stress is mainly distributed on the center of top and base of goaf and center of upstream and downstream side wall. The main stress curves of feature monitoring points(partial) as shown in diagram 2.

![Diagram 1 Maximum-minimum main stress nephogram on all excavation surface after overall excavation](image1)

![Diagram 2 Maximum-minimum main stress change curve of 1-10 monitoring points on top arch of main powerhouse](image2)

5. **Value analysis**

5.1. **Overall stress status**

As per simulation conclusion, upon the underground caverns excavation, the original balance status of rock mass has been broken, the interfering of excavation causes the relocation of stress with same feature, stress field has been changed a lot, the minimum main stress is mainly distributed in the center place of top and base of goaf. At the beginning of excavation, the rock stratum in the center of exposed surface of top of goaf is mostly tensed which causes tensile stress failure characteristics easily, and meanwhile, the skewback of top arch and other corners are easily occur shear failure, following with the excavation proceeding, the main failure form of rock stratum is changing to shear failure on partial corners.

5.2. **Stress Change Rule**

(1) The minimum main stress of side wall of main powerhouse reliefs a lot after underground cavern excavation, the minimum main stresses of side wall are less; the maximum main stress of side wall is increasing while excavating, and it decreases in later period without so uniform distribution. After excavation completion, the minimum main stress of side wall of main powerhouse is -1.5~1.6MPa; the maximum stress of upstream side wall is -12-10Mpa; the stress of downstream side wall is -15~10MPa; the stress concentration occurs at the skewback of top arch and both endings of underground cavern, the stress partially reaches to -32MPa.  

(2) Judging from the distribution regularities of stress vector surround the cavern after excavating, the obvious stress concentration has been found at the place of skewback and corner of top arch of main powerhouse. The surrounding rock stress could recover to original stress gradually following with distance increasing from cavern wall.
6. Workmanship Optimization

As per the simulation result of surrounding rock of underground powerhouse, the original blasting work parameter could be optimized. The top arch and side wall could be done in accordance with original scheme that changes the profile filling of rock wall from “concentration” to “dispersion”, that is, separating the 150g/strip φ25 smooth blasting roll to 10 strips(15g/strip) and 12 strips(12.5g/strip) uniformly, it is called “Uniform micro-filling” which is good for making blasting surface, and meanwhile, it adjusts the kerve step blasting from “—” type to “V” type, that is, changing from 10 holes/section to 6 holes/section and 3 holes/section to ensure the integrity of bed rock of excavation surface. The blasting parameter of ledge beam and protection layer as shown in form 3 after optimizing.

Form 3 Blasting parameter of ledge beam and protection layer

| Type | Diameter (mm) | Depth (m) | Distance (cm) | Resistance line (cm) | linear charge density range | single-hole charge range |
|------|--------------|-----------|---------------|----------------------|---------------------------|------------------------|
| 1    | 4            | 2         | 400           | 600                  | 100~120                   | 600                    |
| 2    | 4            | 2         | 4, 2          | 600                  | 180~200                   | 600                    |
| 3    | 4            | 2         | 4, 2          | 1000                 | 80~100                    | 3                      |

Notes: 1. Type 1 means smooth blasting hole, type 2 means cushion blasting hole, type 3 means stepped hole
2. unit of items as following: diameter mm, depth m, distance cm, resistance line cm, linear charge density g/m, single-hole charge kg.

7. Achievement

7.1. Blasting effect

Incomplete rate of top arch smooth blasting hole: surrounding rock type I 100%, surrounding rock type II 98.5%, no insufficient excavation on rock wall, over-excavation 0-12cm, unevenness 0~8.6cm, banquette is not over 15cm, distance deviation of smooth blasting holes 0-5cm.

7.2. Ledge beam smooth blasting effect

Incomplete rate of rock bench of ledge beam: surrounding rock type I 100%, surrounding rock type II 98.3%, no insufficient excavation on rock wall, average over-excavation 6.6cm, unevenness 0~6cm, banquette is generally not over 5cm, distance deviation of smooth blasting holes 0-4cm.

7.3. Side Wall Presplitting Effect

Incomplete rate of side wall presplitting: surrounding rock type I~II 97.2%, no insufficient excavation on rock wall, over-excavation 0~15cm, unevenness 0~8.3cm, banquette is generally not over 12cm, distance deviation of smooth blasting holes 0-5cm.

8. Conclusion

The blasting technique used for Qinyuan pumped storage power station has been awarded as first prize of CSEB technology advancement, the blasting parameter and construction workmanship has been proved well by practice. The determination of blasting parameter and workmanship execution adopt the method of FLAC3D FEM calculation, that is useful for reference to the blasting design of related project.
References

[1] Cui Jichun. Pumped storage power station plan and sustainable development study[J]. Water Resources and Power, 2008, 26 (3): 80-82.

[2] National Energy Administration. The points plan achievement of national pumped storage power station[M]. Beijing: China Electric Power Press, 2014:4.

[3] Zhang Chunsheng, Jiang Zhongjian. Pumped storage power station design[M]. Beijing: China Electric Power Press, 2012:471-474.

[4] Zhang Wenxuan, Study on vibration failure characteristics of excavation and blasting of large-scale underground plant[D]. Beijing, department of engineering mechanics, USTC, 2008: 2-3.

[5] Li Xingping and his team. Study on blasting vibration effect of underground caverns Xiluodu power station[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 30 (3): 493-501.

[6] Li Xingping and his team. Vibration test and study on rock anchor beam blasting of certain underground plant[J]. Journal of Wuhan University of Technology, 2009, 31 (16): 66-71.

[7] Luo Yi and his team. Study on surrounding rock deformation characteristic considering accumulation damage effect[J]. Rock and Soil Mechanics, 2014 (11): 3041-3048.

[8] Jiang Jian, Zhou Yu and Sun Wen, Excavation and blasting technique of large-scale caverns[J]. Engineering blasting, 2003, 9 (1): 38-42.

[9] Jiang Jian, Gao Bihua. Summary of excavation and blasting of underground caverns[J]. Journal of the Yangtze academy of sciences, 2003, 20, sp1.: 32-35.

[10] CSEB, GB6722—2014 Safety regulation for blasting [S], Beijing: China Standards Press, 2014.

[11] Li Xingping, Chen Junyi and their team. Study on damage range and judgement of underground powerhouse blasting of Xiluodu power station[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29 (10): 2042-2049.

[12] Yi Jianming, Guo Xifeng and their team, crustal stress test analysis and high pressure tunnel design verification of Qin Yuan pumped storage power station [J]. Journal of the Yangtze academy of sciences, 2008, 25 (5): 43-45.

[13] Li Yongsong, Chen Jianping and their team, Crustal stress field analysis of Qinyuan pumped storage power station[J]. Hydraulic Electrogenerating, 2011, 37 (9): 29-31.

[14] Guo Xifeng, Yi Jianming and their team, FE regression analysis of crustal stress field of pumped storage power station[J]. Journal of the Yangtze academy of sciences, 2008, 25 (5): 55-58.