Optimization Analysis of Suki Kinari Underground Powerhouse Caverns Based on an Efficient CATIA-Abaqus Model

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Abstract. Underground powerhouse caverns, which are large-scale, complex-type, and intersecting circuits, are considered as a complicated, constrained, and irreversible nonlinear system. They are divided into several layers for excavation. Various stress states occur whenever they are subjected to excavation; therefore, deformation and failure arise because of stress redistribution and concentration. Based on the determinate excavation scheme, the sectional shape of underground powerhouse caverns, especially the aspect ratio of the main powerhouse, is the key factor that affects the stability of the surrounding rock masses. Furthermore, during the excavation process, the integrity and stability of rock pillar, whose thickness is determined by the interval of caverns, are considered as crucial issues, because damage occurs in the thinner rock pillar. Consequently, the interval of caverns is the important parameter that needs to be investigated. In this study, we combine building information modeling with numerical analysis to investigate the effect of the aspect ratio of the main powerhouse and the interval between the main powerhouse and the main transform chamber. For the Suki Kinari (SK) underground powerhouse caverns, the 3D terrain and geological model was created in accordance with the detailed geological information. The parameterized underground powerhouse model and the supporting system were designed by CATIA, and the numerical model that involves the excavation scheme was generated by ABAQUS. The results show the following: (1) As the aspect ratio increases, the deformation of the main powerhouse exhibits various features, indicating that the arch crown settlement reduces while the deformation of the sidewalls increases. (2) As the aspect ratio increases, the overall deformation of the particular parts exhibits the characteristic of rapidly decreasing and then gradually forming a convergent trend. (3) Intense disturbance occurs on the rock pillar because of bidirectional unloading during the excavation process, and the rock pillar weakens rapidly and then gradually stabilizes as the thickness increases, suggesting the property of exponential function of the total deformation. Finally, the conclusions are applied on the SK underground powerhouse caverns to reveal the optimal aspect ratio and interval.
1. Introduction
Underground powerhouse caverns, which are large-scale, complex-type, and intersecting circuits, are considered as a complicated, constrained, and irreversible nonlinear system. Intense stress field disturbances occur within the surrounding rock masses and vary with the distance from the free face [1]. The stress state of the surrounding rock mass tends to redistribute to a new balance with the following disturbing phenomena: bulking and cracking of the shotcrete layers, stress-induced fracturing, and heavy damage to the zone near the surrounding rock mass [2,3,4]. This threatens the stability of the underground caverns. Researches indicate that the stability of the underground caverns is affected by the design and excavation parameters, including the aspect ratio, interval between the main powerhouse and the main transformer, and excavation schemes [5,6,7,8]. On the basis of a large number of numerical simulations, Weishen (2010) formulated an equation considering four basic factors to predict displacement at the key point on the high sidewalls of the powerhouse. Furthermore, the optimization of the aspect ratio and interval needs to be under the conditions of safety, space saving, stability of surrounding rock masses, and construction consuming to improve the economic benefits and meet the functional requirements [10]. Researchers have conducted many studies on the optimal aspect ratio of tunnels. The design and excavation method of large-span soft rock urban tunnel is studied by numerical analysis [11]. Weizhong (2011) combined Abaqus with Python to optimize the aspect ratio of large-span tunnel in a shallow broken rock mass. The optimal support parameters and construction scheme are selected based on the Longtoushan tunnel using the finite element numerical method [12]. The research on aspect ratio primarily focuses on the numerical method or the combination of the numerical method and mathematical theory on tunnels. Studies focusing on the optimization of the aspect ratio of underground powerhouse caverns are limited. Xinhong (2017) stated that thinner rock pillars have the potential to develop large deformation and a wide relaxation zone, which can affect the integrity and self-supporting capacity of the surrounding rock. Therefore, the interval is considered as a key factor that needs to be studied. Moreover, there are very few studies on optimal interval. In this study, based on the Suki Kinari underground caverns, we combine building information modeling with numerical analysis to create an efficient CATIA–Abaqus model [13]. The effect of the aspect ratio and the interval between the main powerhouse and the transformer chamber have been discussed using the combination of numerical analysis and statistical method to obtain appropriate value of the aspect ratio and interval (thickness of rock pillar).

2. Project background

2.1. Introduction of the SK hydropower station
The SK hydropower project site, which is located in the Kunhar River, Khyber Pashtun, is currently under construction. Figure 1(a) shows the layout of the geographical location of the SK hydropower station.

The underground powerhouse caverns at the SK hydropower station primarily comprises the main powerhouse, the main transformer chamber, the bus-bar tunnels (tunnels connect the main powerhouse to the main transformer chamber), the access tunnels, the tailrace surge chamber, and tailrace tunnels. The main powerhouse caverns, including the main powerhouse, the main transformer chamber, and the tailrace surge chamber, are arranged in parallel, as shown in Figure 1(b).
Figure 1. The layout of the underground diversion system of the SK hydropower station. (a) The geographical location of the SK hydropower station. (b) Arrangement of the underground powerhouse caverns.

The main powerhouse is located downstream of the dam site, 20 km far away. It is buried underground, with a crest elevation of 1352 m and a bottom elevation of 1306 m, as well as depths of 450 m vertically and 250 m horizontally. Figure 2 shows the buried conditions of the underground powerhouse of the SK hydropower station in the cross-section profile. The excavation dimension is 24 m in width, 53 m in height, and 134.6 m in length, with a sectional shape of straight wall and arch roof. Moreover, the main transformer chamber, which has the same form as the main powerhouse, is designed to be 7.8 m in width, 33.35 m in height, and 126.85 m in length. The distance between the centerlines of the main transformer chamber and the main powerhouse is 45 m, and the tailrace surge chamber is 5 m in width, 5.5 m in height, and 1568 m in length.
2.2. Geological conditions

The powerhouse is located in the typically mountainous region, with a steep slope (which has a dip angle of >40°), and the elevation varies from 1350 to 3600 m. A ravine, which is called Mangial, with a cross-sectional shape of “V” and a strike of SN, exists at the centerline of the underground powerhouse within which caverns are constructed in parallel with each other. The surrounding rock masses of the underground powerhouse are relatively intact and generally have intermediate quality with a dry uniaxial compressive strength of 32–96 MPa.

As shown by the typical geological map in Figure 3, regional faults and secondary and third small faults can be seen in the underground powerhouse station. Moreover, the other structural planes with dozens of compression-crushed zones, small anticlines, and several joints and fissures affect the stability of the rock mass of the powerhouse caverns. This leads to construction delay, substantial economic losses, and personal safety threats. There are two main regional fault zones, the Panjal fault zone and Bunja fault zone, both of which are regional thrust fault zones.

Figure 3. The typical geological map around the underground powerhouse.

The in situ stress of the underground powerhouse area was tested using the hydraulic fracturing method on April and December 2018. A total of four geological exploration holes (Table 1) were drilled. The test results of the four boreholes are presented in Tables 2 and 3, which show that the maximum horizontal principal stress is 11.1–14.3 MPa, and the vertical principal stress varies from 8.4 to 12.4 MPa in the underground powerhouse area. This indicates that the lateral pressure coefficient of the maximum horizontal geostress is between 0.9 and 1.2 with the average value of 1.1. The high lateral pressure stress indicates that the
horizontal geostress controls the state of the in situ stress field. We can learn from it that the maximum principal stress (σ₁) is 14.9 MPa, which intersects with the main powerhouse axes at an angle of ~ 56°; the third principal stress (σ₃) is 8.4 MPa, which is at the intersection angle with the main powerhouse axes at an angle of 74°; and the vertical stress has a magnitude of 12.7 MPa, which is equal to the geostatic stress of the overlying rock mass. The ratio of rock mass strength/stress Rc/Rm (where Rₖ denotes the saturated uniaxial compressive strength of the rock mass in the underground powerhouse area, which is taken as 60 MPa, and Rₘ denotes the maximum value of stress in the surrounding rock mass of the underground powerhouse during excavation) is ~4.2. This indicates that the underground powerhouse is located in a high geostress area.

Table 1. The detailed information of the exploration boreholes

| No. | Orifice elevation/m | Orifice direction/° | Depth/m | Comments               |
|-----|---------------------|---------------------|---------|------------------------|
| ZKC18 | 1754.59             | Vertical            | 475     | From the surface       |
| ZKC19 |                    |                     | 294     |                        |
| ZKC20 | 1343.83             |                     | 243     | Intersectional boreholes |
| ZKC21 |                    |                     |         |                        |

Table 2. The test results of the in situ stress for the vertical borehole ZKC18

| No. | Elevation/m | Hole depth/m | σH/MPa | σh/MPa | σv/MPa | λ = σH/σv | The strike of the maximum stress |
|-----|-------------|--------------|--------|--------|--------|------------|----------------------------------|
| 1   | 1441.5      | 313.1        | 9.1    | 6.2    | 8.4    | 1.1        | N66°W                            |
| 2   | 1423.5      | 331.1        | 9.9    | 5.8    | 8.8    | 1.1        |                                  |
| 3   | 1415.8      | 338.8        | 9.9    | 6.3    | 9.0    | 1.1        |                                  |
| 4   | 1406.4      | 348.2        | 11.5   | 7.0    | 9.3    | 1.2        |                                  |
| 5   | 1395.7      | 358.9        | 11.6   | 6.8    | 9.6    | 1.2        |                                  |
| 6   | 1373.8      | 380.8        | 9.1    | 6.4    | 10.2   | 0.9        |                                  |
| 7   | 1366.0      | 388.6        | 10.4   | 6.9    | 10.4   | 1.0        | N51°W                            |
| 8   | 1337.7      | 416.9        | 11.1   | 7.5    | 11.1   | 1.0        |                                  |
| 9   | 1328.8      | 425.8        | 13.4   | 8.2    | 11.4   | 1.2        |                                  |
| 10  | 1319.2      | 435.4        | 12.2   | 8.3    | 11.6   | 1.0        | N62°W                            |
| 11  | 1314.9      | 439.7        | 14.3   | 9.5    | 11.7   | 1.2        |                                  |
| 12  | 1308.4      | 446.2        | 12.3   | 8.6    | 11.9   | 1.0        | N38°W                            |
| 13  | 1291.3      | 463.3        | 13.3   | 8.2    | 12.4   | 1.1        |                                  |

σH, The maximum of the horizontal principal stress; σh, the minimum of the horizontal principal stress; σv, the gravity stress of the rock mass overlying the test point; and λ, the lateral pressure coefficient of the maximum horizontal principal stress.

Table 3. The test results of the in situ stress for the three intersectional boreholes

| σX  | σY  | σZ  | τXY | τYZ | τZX | σH  | σh  | σV  | Strike of σH | σ₁  | σ₂  | σ₃  | Value α/° | β/° | Value α/° | β/° | Value α/° | β/° |
|-----|-----|-----|------|------|------|-----|-----|-----|---------------|-----|-----|-----|----------|-----|----------|-----|----------|-----|
| 11.2| 10.7| 12.7| 1.5  | 2.7  | 0.2  | 12.4| 9.5 | 9.5 | N40°W         | 14.9| 49  | 295 | 113       | 26  | 170       | 8.4 | 29        | 65  |

The unit of all stresses is MPa.
XYZ denotes the geodetic coordinates; X axis denotes the due north; Y axis denotes the due west; Z axis denotes the straight up; α denotes the dip angle of the principal stress; and β denotes the dip direction of the principal stress.
σH, The first principal stress; σ₂, the second principal stress; σ₃, the third principal stress.
σH, The maximum of the horizontal principal stress; σh, the minimum of the horizontal principal stress.

2.3. The excavation steps and methods

In large-scale powerhouse caverns, layered excavation method is used during the construction process. The main powerhouse, which is 53 m in height, is separated into ten levels. Similarly, the main transformer chamber, which is 33.35 m in height, is divided into four layers. Excavation on underground powerhouse systems is conducted using the conventional drill and blast method in 16 and 7 steps, respectively. Figure 4 shows the specific stratified excavation scheme of the underground powerhouse caverns.
Figure 4. The specific stratified excavation scheme of the underground powerhouse caverns.

3. Model building and case study

3.1. Model building

For the specific geo-technological conditions and the underground powerhouse layout, we set the simulation model as five times the size of underground powerhouse (1000 m × 600 m × 300 m), so as to eliminate the effect of the boundary conditions during numerical analysis. Figure 5 shows the geological map of the research area. From the figure, the research area has simple lithology and few faults. Thus, for the sake of simplification, we used it as a homogeneous 3D terrain and geological model.

The 3D numerical model is shown in Figure 6, and the modeling process is demonstrated in Figure 7. Topographic geological model and underground powerhouse model are required to conduct numerical analysis. The topographic geological model was created using CATIA for the region of interest, which has simple lithology and intact rock mass. Therefore, we considered the rock mass of the research area to be single metamorphic basalt. The physical and mechanical parameters of it are obtained using back analysis, which is presented in Table 4. The supporting system was installed as per the design resources provided by the design units, including bar anchors and rock bolts. The detailed arrangement of the supporting system is presented in Figure 6(c). The ideal elastic–plastic model and the Mohr–Coulomb failure criterion were used for the rock masses, which was meshed by 1,708,497 tetrahedral elements with 374,501 nodes. The supporting system was used as an elastic model.
Figure 5. The geological map of the research area.

Figure 6. The detailed 3D numerical models. (a) The topographic geological model. (b) The underground powerhouse system. (c) The supporting system.

Figure 7. The detailed modeling process for the 3D simulation model.
Table 4. The property parameters of the rock mass and the supporting system

| Parameter          | Young’s modulus $E$ (MPa) | Poisson’s ratio $\nu$ | Cohesion ratio $c$ (MPa) | Friction angle $\phi$ (°) | Density $\rho$ (g/cm$^3$) |
|--------------------|---------------------------|-----------------------|--------------------------|---------------------------|---------------------------|
| Supporting system  | $2 \times 10^5$           | 0.3                   |                          |                           | 7.85                      |
| Rock mass          | $9 \times 10^3$           | 0.3                   | 1.6                      | 45                        | 2.75                      |

The boundary conditions are as follows: four sides of the model were constrained in the normal direction, and a fixed constraint was imposed at the bottom side. The geostress parameters, presented in Table 4, were determined using back analysis [14]. Therefore, a finite numerical model with the practical geological and terrain conditions was set up, and the initial geostress field was calculated and is presented in Figure 8.

![Figure 8](image-url) (a) The contoured diagrams of initial stress. (b) The equilibrium of *in situ* stresses.

3.2. Case study

The aspect ratio (height/width) has an impact on the stability of the surrounding rock masses, and this affects the rate of space utilization. Moreover, the stress field of the main powerhouse and the main transformer cavern affects each other during the construction, and intense disturbance occurs on the rock pillar, which is caused by bidirectional unloading. The proper interval can both meet the functional requirements and improve the stability of the surrounding rock masses, so as to achieve the maximum economic benefit ratio. Thus, the interval is considered to be an important index that needs to be studied. Accordingly, for the 3D layout of the underground caverns, the following schemes are considered in the numerical analysis:

1. The design and excavation parameters provided by the design institute.
2. The excavation parameters consistent with (1) (the aspect ratio of the main powerhouse: 0.1, 0.239, 0.3, and 0.5).
3. The excavation parameters and the aspect ratio of the main powerhouse similar to (1) (the interval of the main powerhouse and the main transformer chamber: 87.65, 70, 46.65, 30, and 15.65 m).

4. Numerical analysis and results

For the purpose of deliberating the displacement features of various design parameters, we take one typical cross sections which is shown in Figure 9 to illustrate.
Figure 9. The layout of the research section. (a) The position of the study longitudinal section; (b) The sectional layout of the profile.

4.1. The influence of the aspect ratio

4.1.1. Deformation features. The numerical results indicate that the stress field and deformation characteristics of the surrounding rock masses are similar for the four aspect ratios. Figure 10 shows the calculated results of the vertical and horizontal deformation distribution for the aspect ratio of 0.239 [15]. From the contoured diagrams, we can see that:

1. The deformation of the arch crown is primarily subsidence, and the bottom rebound and sidewalls deform towards the interior.
2. The rock pillar is intensely disturbed because of bidirectional unloading.
3. The asymmetric horizontal deformation concentrates on the area where the bus bar and the main powerhouse meet and on the middle of the sidewalls.

Figure 10. The deformation contoured diagrams for the aspect ratio of 0.239. (a) Horizontal deformation. (b) Vertical settlement.

4.1.2. Determination of the aspect ratio. To examine the optimal aspect ratio for the main powerhouse of the SK hydropower station, we analyze the deformation of the three key points, which are located in the arch crown and in the middle of the sidewalls (Figure 11). Figure 12 shows the deformation at the arch crown and the maximum horizontal deformation at the sidewalls of the main powerhouse for various aspect ratios. From the figure, it can be seen that:

1. The settlement of the arch crown reduces as the aspect ratio of the main powerhouse increases. It reaches the maximum value of 21 mm at the aspect ratio of 0.1 and the minimum value of 18 mm at 0.5.
2. The deformation of the middle of the sidewalls increases from 29 mm at the aspect ratio of 0.1 to 35 mm at 0.5.
Figure 11. The arrangement of key points.

Figure 12. (a) The vertical deformation at various aspect ratios. (b) The horizontal deformation at the left sidewall of the main powerhouse for various aspect ratios.

Consider the arch of the main powerhouse as a three-hinged arch structure (Figure 13). As the arch rise increases, the horizontal pressure stress at the arch foot decreases, which results from the radial pressure of the arch structure and leads to generally increasing horizontal deformation. Otherwise, the increasing horizontal stress prevents arch crown deformation.

Figure 13. The schematic of the arch of the main powerhouse.

Considering the integrated effects of the aspect ratio, the total deformation of the three key points has been studied using the statistical method. The expression of the aspect ratio and the total displacement for the three key points are presented in Eq. (1), thus indicating the polynomial relationship. In this equation, the $R^2$ is 0.99, which means that the statistics fit well. As presented in Figure 14, by solving the minimum of the function, the optimal aspect ratio is ~0.2, which is close to the parameter provided by the design institute (0.239).
4.2. The influence of interval

4.2.1. Deformation features. Because of space limitations, Figures 15 and 16 show the displacement distribution for the intervals 15.65 m and 46.65 m between the main powerhouse and the main transformer chamber. The magnitude of the vertical settlement at the arch crown and the rock pillar increases and the horizontal displacement at the right sidewall decreases but increases at the left sidewall with the decrease in the interval. Hence, the rock masses at the rock pillar and arch crown are more easily damaged. From the contoured diagrams, it can be seen that:

1. The rock masses settle at the arch crown of the main powerhouse and the main transformer chamber and then rebound at the bottom.
2. Large deformation occurs upstream of the sidewalls and at the intersection of the main powerhouse and bus bar.
3. The heavily influenced area offsets to the right above the arch crown with increasing interval, indicating that the disturbance caused by bidirectional unloading during the excavation process weakens.
4. The rock pillar is intensely disturbed and is easily damaged. Thus, to prevent large deformation, thru-anchor cables are required.

\[ y = 93.3x^2 - 37.3x + 85.7 \]  

(1)
4.2.2. Determination of interval. Seven key points, the layout of which are shown in Figure 17, were selected for studying the effect of the interval between the main powerhouse and the main transformer chamber. Figure 17(b) shows the deformation at the seven key points for various intervals. From the figure, the deformation decreases at the arch crown of the main powerhouse, the main transformer chamber, and the bus bar. Moreover, less convergence occurs downstream of the sidewalls, whereas more convergence occurs upstream of the sidewalls because of the construction scheme.

![Figure 17.](image)

(a) The layout of key points. (b) Deformation features for different intervals at various parts.

To eliminate the local error, consider the total deformation of the seven key points using the summation method. The characteristics of the total deformation versus the interval are shown in Figure 18. Similarly, we investigated it using the statistical method, and the result is concluded with Eq. (2), in which the $R^2$ is 0.95, suggesting that the statistics fit well.

$$y = 1846 \times x^{1.727} + 144.9 \quad (2)$$

Evidently, an exponential relationship exists between the interval and total deformation. This indicates that as the interval increases, the total deformation significantly decreases at first and then later flattens. For example, the total deformation decreases by 10 mm for the interval that increases from 16.65 to 30 m, whereas it decreases by only 0.4 mm for the interval that increases from 70 to 87.65 m. Therefore, the parameter (46.65 m) provided by the design institute is in the flat section, where the total deformation tends to be stable, suggesting the optimal interval for the SK hydropower station.

![Figure 18.](image)

The deformation characteristics of the key points for various intervals.

5. Conclusions

In this study, we combine building information modeling with numerical analysis to create an efficient CATIA–Abaqus model. Then, the effect of the aspect ratio and the interval between the main powerhouse and the transformer chamber have been discussed. Consequently, the conclusions are applied on the SK underground powerhouse caverns to reveal the optimal aspect ratio and interval. The primary conclusions are summarized as follows:

(1) The settlement of the arch crown reduces while the deformation of the sidewalls increases with the increase in the aspect ratio.
(2) The total deformation of the main powerhouse has a polynomial relationship with the aspect ratio.

(3) The overall deformation of the underground caverns exhibits the characteristic of decreasing significantly and forming a convergent trend as the interval increases, suggesting an exponential relationship.

(4) The integrity and stability of the rock pillar weaken because of bidirectional unloading during the excavation process. To prevent large deformation of the rock pillar, thru-anchor cables are required to ensure the stability of the powerhouse.

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