Fluid solid coupling analysis of hard rock wall structure in over kilometer deep shaft

Cheng Li, Liu Xingquan, Zhu Mingde, Hou Kuikui

Laboratory on Deep Mining of Shandong Gold Group Co., Ltd., Yantai 264000, China

Abstract. Taking the auxiliary shaft proposed by Ruihai Mining Co., Ltd. as the research object, in order to study the load law of shaft lining and ingate under high stress fluid solid coupling in deep bedrock and the influence of different permeability coefficient on the stability of shaft lining and ingate surrounding rock, Midas software was used for numerical simulation analysis, and the results show that: (1) After the shaft excavation, the pore water pressure of surrounding rock around the shaft wall and ingate decreases gradually, which is the main permeable area. After the support, the pore water pressure is obviously raised, and the water isolation effect of the supporting layer is obvious. (2) After the shaft excavation, the area near the arc surface of shaft wall tangent to Y direction shows high compressive stress, and the maximum principal stress at -1277.5m depth is more than 150MPa. When the polar angle increases from 0 to 180°, the maximum principal stress increases first and then decreases. (3) After the excavation of ingate, the bottom corner and arch top are stress concentration areas before and after support. (4) Under the action of three different permeability coefficients, the influence of permeability coefficient on pore water pressure and maximum principal stress can be ignored after supporting measures are taken. The research results provide important theoretical basis for auxiliary shaft construction design.

1. Introduction

In recent years, with the continuous reduction of shallow resources, mines are gradually transiting to deep mining, and the design depth of individual mines shaft is more than 1000m. For example, the depth of four single section shafts under construction in Laizhou Huijin Company is more than 1300m[1], and the depth of auxiliary shaft of Sishanling iron mine in Benxi is 1497.7m[2]. As the excavation depth of the shaft increases, the instability of surrounding rock and the cracking and destruction of shaft lining structure are easy to occur[3-8]. At the same time, the rock
burst and high pressure water disaster in deep shaft excavation seriously hinder the construction speed and long-term stability of the shaft [9-10]. Therefore, scholars at home and abroad have carried out a lot of research on the concrete shaft wall structure [11-15]. However, none of the above research results consider the influence of groundwater seepage on the ultimate bearing capacity of the shaft wall. At the same time, the effects of water seepage and water pressure has not been considered in the design theory and relevant formulas of shaft wall structure in the bedrock, the fluid structure coupling mechanical analysis is lacking. Therefore, during the design of deep shaft excavation in hard rock, considering the shaft wall load under the combined action of seepage pressure and surrounding rock stress, it is more practical to design the shaft lining structure based on this.

In this study, taking the auxiliary shaft of Ruihai Gold Mine in Shandong as the engineering background, the vertical shaft structure model was established, and the fluid-solid coupling simulation analysis was carried out, the load law of shaft wall and the influence of different permeability coefficient on the stability of shaft wall and ingate structure were completed under the action of high-stress fluid-solid coupling in deep bedrock, which provides a reasonable scientific basis for the design and construction of shaft wall structure.

2. Project Overview

The proposed auxiliary shaft of Ruihai Mining Co., Ltd. is 26km to the north of Laizhou City, 2km to the north of Xiling village, Sanshandao street. The elevation of the auxiliary shaft is + 5.65m, and the bottom elevation is -1494.1m, the total depth of the shaft is 1330.65m, and the net diameter of the shaft is 6.5m. According to the geological origin, lithological combination, structural position, rock hardness, rock integrity and rock permeability, the survey depth of this hole was divided into the following five engineering rock groups from top to bottom:

1. Loose accumulation rock group, 0.00~38.90m, 38.90m thick;
2. Rock group of bedrock weathering zone, 38.90~65.72m, 26.82m thick;
3. Upper metagabbro formation, 65.72~784.25m, 718.53m thick;
4. Contact alteration zone rock group, 784.25~814.75m, 30.50m thick;
5. The lower monzogranite formation, 814.75~1340.23m, 525.48m thick.

The inferred drawing of the vertical section rock layer is shown in Fig. 1.
3. Establishment of finite element

3.1 Physical and mechanical parameters

According to the preliminary simulation analysis assumption, the model only simulates the deep engineering conditions (buried depth 1000~1500m). According to the engineering geological survey report, the parameters of the shaft passing through each aquifer are shown in table 1. Through the laboratory rock mechanics experiment, the parameters of surrounding rock in deep stratum were obtained: density $\rho = 2.60$ g/cm$^3$, uniaxial compressive strength $\sigma = 56.3$ MPa, rock elastic modulus $E_m = 65.6$ MPa, Poisson's ratio $\nu = 0.18$, cohesion $c = 7.93$ MPa, internal friction angle $\varphi = 53^\circ$.

Table 1 Parameters of shaft passing through each aquifer

| Aquifer group                        | Buried depth of layer bottom (m) | Thickness (m) | Buried depth of static water level (m) | Permeability coefficient (m/d) |
|--------------------------------------|----------------------------------|--------------|----------------------------------------|--------------------------------|
| Loose deposit                        | 58.10                            | 58.10        | 5.15                                   | 1.2571                         |
| Bedrock weathering zone              | 65.60                            | 7.50         | 5.68                                   | 0.6844                         |
| Structural alteration zone (pumping test section 3) | 1185.57                          | 115.27       | 10.50                                  | 0.00661                        |
| Structural alteration zone (pumping test section 4) | 1486.89                          | 22.89        | 7.30                                   | 0.00204                        |
| Structural alteration zone (pumping test section 5) | 1598.40                          | 75.70        | 8.50                                   | 0.01197                        |

For the selection of the original rock stress field, in reference [16], the measurement method of hollow inclusion strain gauge was used to measure the in-situ stress of Sanshandao
gold mine. The regression equation of the principal stress is as follows:

\[
\begin{align*}
\sigma_H &= 0.0449h + 0.81 \\
\sigma_h &= 0.0231h + 0.87 \\
\sigma_v &= 0.0255h + 0.285
\end{align*}
\]  

(1)

Where \(\sigma_H\), \(\sigma_h\), and \(\sigma_v\) are the maximum horizontal principal stress, the minimum horizontal principal stress and the vertical principal stress, MPa.

C30 concrete was used to support the shaft wall and some areas of ingate, specific mechanical parameters can be referred to literature [17]. The Moore-Coulomb failure criterion was used for concrete.

3.2 Geometric model

The inner diameter of the shaft is 6500mm, the thickness of the shaft wall support layer is 400mm, and the bottom thickness is 200mm. Considering the number of overall calculation units of the model and the need for key analysis of deep and high stress areas, the area with shaft elevation of -985m ~ -1419m was selected for analysis. The overall horizontal dimension (surrounding rock area) on both sides of the model is more than 5 times of the wellbore radius which in order to ensure that the mechanical boundary of the model is far away from the stress affected area of the wellbore. The concrete lining with the same specification as the shaft is adopted within 5m of ingate, and the unsupported area of 5m outside the ingate was considered as the free surface of water. The section shape of ingate is a three center arch, with a span size of 4000mm, a size from arch top to bottom plate of 4500mm, an arch height of 1333mm, and a thickness of supporting layer 400mm. Finally, the overall size of the model was determined to be 40m × 40m × 435m. After the initialization of the stress field and seepage field, the excavation, support and the corresponding fluid solid simulation calculation were carried out. The shaft structure and its grid model are shown in Fig. 2 and Fig. 3.
4. Numerical simulation results and analysis

4.1 Calculation and analysis after shaft excavation

4.1.1 Pore water pressure

The cloud chart of pore water pressure from different perspectives is shown in Fig. 4. It can be seen from Fig. 4 (b) and 4 (d) that after the excavation of the shaft, a free seepage surface was formed around the shaft wall and ingate. The pore water pressure gradually decreased from the surrounding rock to the excavation surface. It can be seen from Fig. 4 (c) and 4 (e) that after the support of the shaft, the pore water pressure of the surrounding rock around the shaft wall in X and Y directions and the area near ingate was significantly increased, which was caused by the water separation effect of the shotcrete support layer. As the seepage path points to the direction of water head reduction, it can be seen from Fig. 5 that the surface of shaft wall and ingate portal are the areas with low water head, so these areas are the main permeable area.
Fig. 4 Pore water pressure cloud: (a) Side view after excavation; (b) X-direction profile after excavation; (c) X-direction profile after support; (d) Y-direction profile after excavation; (e) Y-direction profile after support.

Fig. 5 Seepage path: (a) shaft-side view; (b) shaft-top view; (c) ingate-front view

The sample line was arranged along the ingate trend to extract the pore water pressure value of each node before and after the support. The starting point of the sample line is the model boundary and the ending point is the shaft wall boundary. The pore water pressure curve was shown in Fig. 6 at the place 1m away from the surrounding rock above the roof of 2 # and 4 # ingate. It can be seen the curve that after the ingate was supported, the pore water pressure in the supported area was significantly increased, but it has no obvious influence on the area without support, and the water-blocking effect of the support layer was obvious.
4.1.2 Stress analysis

The cloud diagram of the maximum principal stress of the shaft wall before and after support at the buried depth of -1277.5m was shown in Fig. 7. It can be seen from 7(a) that where the arc surface of the shaft wall is tangent to the Y direction, the area near it shows higher compressive stress, and the maximum principal stress exceeds 150 MPa. Where the arc surface of the shaft wall is perpendicular to the Y direction, the compressive stress in the vicinity is relatively small, about 46 MPa. It can also be seen from Fig. 7 (b) that after the shaft wall was supported, the maximum principal stress of the surrounding rock was obviously attenuated, which indicating that the supporting layer plays an important role in the stability of the shaft wall surrounding rock.

![Fig. 6 Variation law curve of pore water pressure along the radial direction of the shaft wall at 1m above the top plate of ingate](image)

![Fig. 7 Cloud chart of maximum principal stress of shaft wall before and after support (buried depth - 1277.5m): (a) before support; (b) after support](image)
maximum principal stress reaches the maximum, and then the maximum principal stress decreases gradually with the increase of the polar angle, and when the pole angle reaches 180 °, the maximum principal stress reaches the minimum again. Under the premise of unsupported, after considering the seepage effect, the increment curve of maximum principal stress around shaft wall at different depths was shown in Fig. 9. It can be seen from the figure that the effective maximum principal stress around the shaft wall was obviously raised, in which, the buried depth of -1085m was raised about 6~6.5Mpa, the buried depth of -1277.5m was raised about 3.5~4.5Mpa, and the buried depth of -1405m was raised about 4.5~5.2Mpa. Therefore, considering the seepage factor, the effective stress acting on the surrounding rock around the shaft wall is higher than the result under the non-seepage calculation condition, which is important engineering significance for the prediction of shaft wall instability and support.

4.2 Calculation analysis after excavation of ingate

Due to space limitation, the article only shows the cloud chart of the maximum principal stress of 1# ingate in Fig. 10. It can be seen from Fig. 10 (a) that the right angle area and large arch area of ingate are the main stress concentration areas, and the maximum principal stress values are about 100MPa and 70MPa respectively. They are all compressive stress states. Therefore, the right angle and roof area are prone to compression shear failure. It can be seen from Figure 10(c) that along the direction of ingate, the closer the vertical wall area on both sides to the shaft wall is, the smaller the maximum principal stress is, and the closer it is to the working face, the higher the stress concentration on both sides is, and the more prone to compression shear failure. It can be seen from Fig. 10 (d) that the maximum principal stress of surrounding rock around the supporting layer decreases obviously which indicates that the support layer has played a certain supporting effect.
In order to explore the variation law of the stress field in the surrounding rock area near the border of ingate, the maximum principal stress value of each calculation unit was extracted within 0.5m away from ingate boundary, and the maximum principal stress-polar angle relationship curve was drawn in Fig. 11. Polar angle is the angle that rotated anticlockwise along the boundary of ingate with the midpoint of top plate as the starting point. It can be seen from the stress curve that the bottom corner area of ingate is an obvious stress concentration area and the maximum value of the maximum principal stress is about 100MPa. Therefore, for the ingate cavern used for repairing the shaft, the right angle area of the bottom plate of ingate cavern is the most prone area to crush damage.
Fig. 11 Relation curve between maximum principal stress and polar angle of ingate roadway boundary

Under the condition of considering seepage factors, the maximum principal stresses in the large arch area and the bottom plate area of ingate cavern are significantly higher than those of the non-seepage calculation results. At the same time, it can also be seen that after supporting, the maximum principal stress of surrounding rock of ingate cavern decreases obviously, in addition, the supporting effect of the roof and bottom of ingate cavern is more obvious than that of two sides.

4.3 Influence analysis of permeability coefficient

In order to explore the variation law of pore water pressure of the shaft wall before and after support under three different rock permeability coefficients, the sample line was set along the radial direction of the shaft wall at the elevation of -1085m and 1m above the roof of 2# ingate to extract the pore water pressure inside the calculation unit. Fig. 12(a)(b) and Fig. 12(c)(d) respectively show the pore water pressure variation in these two areas. It can be seen from the figure that the three permeability coefficients have little influence on the pore water pressure of the surrounding rock of the shaft wall, that is, when the permeability coefficient changes within 0.0061 m/d ~ 0.01197 m/d, the influence on the distribution law of the pore water pressure can be ignored, and the pore water pressure starts to decay from the maximum value of the surrounding rock boundary until the pore water pressure decays to 0 in the area near the shaft wall.
Fig. 12 Variation curve of pore water pressure along radial direction of shaft wall under three different permeability coefficients: (a) before the support, the elevation is -1085m; (b) after the support, the elevation is -1085m; (c) before the support, 1m above the top plate of 2 # ingate; (d) after the support, 1 m above the top plate of 2 # ingate.

In order to explore the influence of three permeability coefficients on the maximum principal stress around the shaft wall, the maximum principal stress value was extracted from the calculation unit at the elevation of -1277.5m, and the curve of the maximum principal stress variation was drawn. It can be seen from the curves of the three maximum principal stresses (Fig.13) that before and after the support, the curves of the maximum principal stresses around the shaft wall corresponding to the three permeability coefficients were basically the same, that is, the three permeability coefficients have no effect on the maximum principal stress. By extracting the value after support, the influence range of permeability coefficient 1 to 3 is 0~0.05MPa, permeability coefficient 1 to 2 is 0~0.02MPa. That is to say this influence can be basically ignored.

Fig.13 Variation curves of the maximum principal stress around the shaft wall under three different permeability coefficients: (a) before support; (b) after support.

5. Conclusion

(1) After the excavation of the shaft, the tangential area between the arc surface of shaft wall and Y direction shows high compressive stress. When the polar angle increases from 0 ° to 180 °, the variation law of the maximum principal stress of the wall rock presents a U-shaped curve. And the maximum principal stress of surrounding rock decreases obviously after the support of shaft lining, which indicates that the supporting layer plays an important role in the stability of surrounding rock.
(2) After the excavation of shaft and ingate, the effective maximum principal stress of surrounding rock is significantly increased compared with that without seepage. However, the influence of permeability coefficient on pore water pressure and maximum principal stress can be ignored after supporting measures are taken. It shows that the effect of C30 concrete support is obvious, which can meet the construction requirements of shaft and ingate under different permeability coefficients.

(3) Whether it is the result of fluid structure coupling or non fluid structure coupling calculation, the right angle of bottom plate and arch top of ingate cavern are the most prone areas of extrusion failure. Therefore, it is necessary to strengthen the support measures in the actual construction process.

6. References

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