Field Monitoring and Numerical Simulation Analysis of Deep Shaft Concrete Wall Support

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Affected by faults, fractures, and high ground stress, the deep shaft wall is prone to deformation and fracture, which affects the safety of mine construction. To investigate the stress and deformation of the shaft wall at the horsehead gate connection, the force-measuring bolt and vibrating string concrete strain gauges were installed for on-site monitoring prior to the shaft wall pouring. It was found that the concrete strains and forces on the shaft wall were divided into four stages during the tedious shaft construction. The measured data showed that the maximum pressure and tension on the shaft wall were 4.5 MPa and 1.3 MPa, respectively, the maximum axial compressive and tensile strains were -500 με and 1700 με, and the maximum circumferential compressive and tensile strains were -1000 με and 400 με. During the shaft excavation construction, there is a tensile state in the shaft wall at the connection of the horsehead gate. In addition, there will be uneven stress in the concrete support structure and a sharp increase in the local stress of the shaft wall. Therefore, the problem of supporting the wall of deep shafts is undoubtedly a significant challenge in the construction of shafts. The numerical simulation results combined with the on-site monitoring of the layers show that stress concentrations occur at the lower end of the shaft wall and the interconnections between the walls during the excavation process. Therefore, it is essential to pay attention to the stress values in the lower part of the wall when constructing deeper sections to avoid stress concentrations and pay attention to the construction quality when constructing the wall joints to meet the wall’s safety needs support.

1. Introduction

With economy and social progress, shallow mineral resources are drying up, and the construction of deep mines is gradually increasing. The deep rock mass environment is characterized by “three highs”: high ground stress, high ground temperature, and high pore water pressure. Under the action of “three highs,” rock shows exceptional mechanical behavior. Gu et al. [1] studied the influence of underground mining on the stability of deep shafts using Dongfeng Iron Mine as the research background with FLAC3D and found that the mining of ore bodies would increase shaft deformation. He [2] found the mechanical characteristics of the interaction between the anisotropy of deep rock mass and the deep environment through research and revealed the mechanical mechanism of deep rock deformation. Xie et al. [3] made a series of studies on sandstone, conglomerate, and andesite at different depths of 1000–6400 m in the Song Liao Basin. It is found that the brittleness of rock is mainly controlled by confining pressure at the same depth. With the increase of depth, the increase of hard minerals will lead to the increase of brittleness of rock. Cai [4] proposed the “equivalent release load” theory, in which each step of underground excavation is an “equivalent release load” loading process, and the excavation process and mining sequence will lead to different “equivalent release load” loading paths. An experimental study on the postpeak characteristics of rock mass deeper than 1000 m was carried out by Shuang et al. [5, 6], and the variation law of permeability from peak to the residual stage under confining pressure was obtained. Hongguang et al. [7] done a series of research on the stability of the supporting
structure in the interlaced zone of the deep roadway and found that the stress of the supporting structure of the horsehead gate is in an unstable state during the grouting period, and the cross-section of the supporting structure is prone to tensile and shear failure. Zhao et al. [8] analyzed the stability of surrounding rock in the ultradeep shaft and proposed that the instability of surrounding rock mainly includes three types: structural plane control type, stress control type, and transformation from structural plane control type to stress control type. Guo and Yang [9] from the causes of broken strata, respectively, given the broken rock, fault, weak interlayer surrounding rock stress model and used to guide the deep shaft in the broken rock support design. Xia et al. [10] sorted out a series of dynamic rock mechanics tests conducted by scholars at home and abroad using confining pressure Hopkinson pressure bar, mainly summarized the results of the correlation of dynamic mechanical strength rate of deep rock, and introduced two test methods of dynamic fracture toughness.

Poojari and Herath et al. [11, 12] made a series of studies on concrete in shaft walls and found that concrete shaft walls are less stressed in the early stage mainly for the following two reasons: (1) in the early stage of construction grouting, the slurry has a small transport and diffusion radius in the fissure, and the transport and diffusion range is limited; (2) the concrete is mixed with fly ash as the mix, and the hydration rate of fly ash is slow, resulting in the early strength of concrete is low. Rupert [13] used the crack-temperature relationship for early age concrete to estimate the cracking trend of concrete structures and gave an approximate formula for the effect of temperature considering concrete mixing, cement, and admixtures. In recent years, with the rapid development of computer technology, the accuracy of simulation analysis in some countries has become more accurate. The simulation of engineering is also more and more consistent with the actual situation, such as Shin and Hak Chul [14] through three-dimensional finite element numerical calculation to study the impact of factors such as surface thermal changes and shrinkage on the early characteristics of concrete, considering the impact of these factors more consistent with the actual engineering simulation procedure. Scholars at home and abroad have done much research on deep surrounding rock and shaft wall concrete materials. During the excavation of deep and ultradeep shafts, the stress and deformation law of shaft wall is of great significance to guide the safe production of mines. Therefore, it is urgent to summarize shaft walls’ stress and deformation law during excavation.

In this paper, the stress and strain of the shaft wall concrete in the 28-day age are measured based on the research background of the -1120 m horsehead gate shaft wall of the air intake shaft in a mine. The stress and strain laws in the process of shaft excavation are summarized, and the numerical simulation of this section of the shaft wall is carried out to explore the weak links of the shaft wall during excavation and position that should be paid special attention to in the construction of the shaft wall, to guide the safe production of mine construction.

### 2. Monitoring Instruments and Monitoring Horizons

The force-measuring bolt device is used for the stress monitoring of shaft wall concrete [15]. The force-measuring bolt comprises the steel bar meter, the force transmission rod, and the diaphragm. The concrete strain monitoring adopts the vibrating wire strain sensor, the sensor’s maximum upper limit is 2000 με, the maximum lower limit is -2000
με, and it has the temperature measurement function and temperature compensation function. The temperature measurement function can monitor the temperature change of the shaft wall at the horsehead gate to study the strain change caused by the temperature change. The calculation formula of the vibrating wire strain sensor is

$$\varepsilon = k (f_i^2 - f_0^2) + k_T (T_i - T_0),$$  \hspace{1cm} (1)$$

where $\varepsilon$ is the current time variable relative to the initial position, με; $k$ is the coefficient of vibrating wire strain gauge, $k = 2.48 \times 10^{-3}$ (με/Hz$^2$); $f_i$ is the output frequency of vibrating wire strain gauge at present time, Hz; $f_0$ is the initial output frequency of vibrating wire strain gauge, Hz; $k_T$ is the temperature correction coefficient, $k_T = 2.2$; $T_i$ is the current temperature, °C; and $T_0$ is the initial temperature, °C.

The shaft wall at the horsehead gate of the -1120 m return air well is measured; when the shaft wall is constructed to the monitoring layer, the vertical hole is drilled at the measuring point 1-3 of the surrounding rock, and the hole depth is about 1 m; the arrangement of the measuring points is shown in Figure 1. The force-measuring bolt was assembled and inserted into the hole, and the steel bar was anchored with the hole wall using epoxy resin. After the force-measuring bolt is installed, three mutually perpendicular holes are punched on one side of the force-
measuring bolt to fix the strain sensor. The vibrating wire strain sensor is fixed on the surrounding rock following the axial and circumferential directions. After the equipment installation was completed, the data of three measuring points were collected for 28 days after the construction team poured the shaft wall. Four groups of data were collected at each measuring point each time.

3. Analysis of Monitoring Results


When the shaft was constructed to the -1120 m horsehead gate, the monitoring equipment was embedded in the corresponding position of the shaft wall. After completing the shaft pouring, the data of each measuring point were continuously collected within the age of 28 days of concrete. The monitoring data of the force-measuring bolt are shown in Figure 2.

From Figure 2, it can be seen that the concrete pouring of measuring point 1 shaft wall is in the state of tension at the early stage, and it is in the state of compression after solidification, and the shaft walls of measuring points 2 and 3 are always in the state of compression. The concrete stress law is as follows.

In the early concrete pouring stage, the stress of measuring point 1 shaft wall is divided into two stages (fluctuation stage and stable stage). From September 20 to September 25, the shaft wall is in the tensile stage, and the tensile force increases gradually. On September 23, the peak tensile force is about 1.4 MPa, and the tensile force of the later shaft wall decreases gradually and changes to the compressive state. After September 25, the measuring point shows a compressive state, and the compressive stress is about 0.2 MPa and remains stable. The shaft wall of measuring point 1 is tensioned in the early concrete pouring stage. During the excavation of deep engineering, the shaft wall is prone to rupture under tension, so the tensioned state of the shaft wall should be avoided during construction. It is recommended to use steel fiber reinforced concrete to increase the tensile strength of the shaft wall to meet the needs of shaft wall design.

The measuring point 2 has always been under pressure from the beginning of monitoring, and the stress on the shaft wall at the early stage of concrete pouring is about 0.2 MPa. At the same time, when the tensile force of measuring point 1 reaches the peak value, the pressure on measuring point 2 gradually decreases to about 0.1 MPa, and the stress on the shaft wall is stable within ten days. The stress of the measuring point had a significant mutation on October 6 and October 12, and the pressure on the shaft wall increased rapidly and then recovered, with a peak pressure of about 2.1 MPa. Combined with the construction conditions, the two sharp increase of shaft wall stress is mainly due to the pregrouting and blasting of the working face in the process of shaft excavation. When the deep shaft adopts

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Depth of burial/m</th>
<th>Bulk modulus/GPa</th>
<th>Shear modulus/GPa</th>
<th>Cohesion/MPa</th>
<th>Friction/°</th>
<th>Tensile strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation stratum 1</td>
<td>1090</td>
<td>2.04</td>
<td>2.62</td>
<td>4.39</td>
<td>53.11</td>
<td>5.350</td>
</tr>
<tr>
<td>Excavation stratum 2</td>
<td>2.74</td>
<td>1.97</td>
<td>7.82</td>
<td>44.21</td>
<td>5.462</td>
<td></td>
</tr>
<tr>
<td>Excavation stratum 3</td>
<td>2.54</td>
<td>1.60</td>
<td>7.89</td>
<td>55.86</td>
<td>6.151</td>
<td></td>
</tr>
<tr>
<td>Rock cap</td>
<td>3.74</td>
<td>2.03</td>
<td>6.00</td>
<td>44.58</td>
<td>5.827</td>
<td></td>
</tr>
<tr>
<td>Fracture zone</td>
<td>1120</td>
<td>0.92</td>
<td>1.06</td>
<td>3.61</td>
<td>36.43</td>
<td>3.351</td>
</tr>
</tbody>
</table>

Table 2: Shaft wall parameters.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus C50</td>
<td>E</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>P</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Thickness</td>
<td>D</td>
<td>mm</td>
</tr>
</tbody>
</table>
the pregrouting at the working face, it is necessary to pay attention to the stress of the shaft wall to avoid the shaft wall rupture caused by the excessive grouting pressure.

The stress on the shaft wall of measuring point 3 is roughly divided into the following stages: the pressure on the shaft wall is relatively stable from September 20 to September 23 in the early stage of concrete pouring, and the pressure value is about 0.2 MPa. After September 25, the stress on the point increases gradually, and the pressure on the shaft wall increases. After September 28, it remains stable, and the pressure on the shaft wall is about 1.5 MPa. After October 6, the force increased rapidly. By October 15, the force on the shaft wall was about 4.5 MPa and then tended to be stable.

The stress of the three monitoring points of the shaft wall has a good consistency; during the shaft excavation construction, the stress of the shaft wall concrete is divided into the following stages: (1) the fluctuation stage of the initial concrete pouring, (2) the stable stage of concrete after condensation, (3) unstable stage affected by construction, and (4) restability stage of shaft wall stress.

When the shaft wall tension of measuring point 1 reaches the maximum, the pressure on the shaft walls of measuring points 2 and 3 decreases and increases. At the

Figure 5: Nephogram of ground stress calculation.
(a) Maximum deformation of surrounding rock depth of process 1

(b) Maximum deformation of surrounding rock depth of process 2

(c) Maximum deformation of surrounding rock depth of process 3

Figure 6: Continued.
same time, under the influence of construction factors, when the shaft wall stress of measuring point 2 mutated, the shaft wall stress of measuring point 3 increased rapidly, and the influence of the shaft wall stress of the three measuring points on the construction showed good consistency.

3.2. Measurement and Analysis of Shaft Wall Strain. As shown in Figure 3(a), it can be seen from the overall trend in the figure that the axial strain of measuring points 1 and 3 of shaft wall concrete always shows a state of compression. The maximum compressive strain occurs at measuring point 1, and the peak value of compressive strain is about 500 $\mu e$. Within three days after concrete pouring, the axial strain of the measuring point increases first and then decreases. At this stage, the maximum compressive strain is about 400 $\mu e$ and then increases slightly after September 25, and finally, the strain is stable at about 500 $\mu e$. The measuring point 3 is relatively stable, and the maximum compressive strain is about 280 $\mu e$. From concrete pouring to late solidification, the axial strain of the measuring point is relatively stable, and there is no noticeable fluctuation.

The axial strain of measuring point 2 is different. In the early three days of pouring, the shaft wall first shows a compressive state, and the axial compressive strain of shaft wall concrete is about -250 $\mu e$. After three days, the measuring point changes from compressive strain to tensile strain rapidly and tends to be relatively stable after reaching the peak value of 1500 $\mu e$. On October 8, the strain decreases rapidly, stabilizes at 1000 $\mu e$, and maintains a tensile state. The axial point is subjected to axial tension, and the concrete shaft wall is relatively dangerous. It is recommended to increase the axial tensile capacity of the shaft wall by adding steel fiber to concrete.

As shown in Figure 3(b), the measuring points 1 and 2 are in the compressive state. In the early stage of concrete pouring, the compressive strains of the two measuring points both are -400 $\mu e$, and then, compressive strain increases rapidly to -800 $\mu e$ around 7-days, then tends to grow slowly. Finally, the maximum compressive strain of measuring point 1 tends to be stable at -900 $\mu e$, and the maximum compressive strain of measuring point 2 tends to be stable at -1000 $\mu e$. The variation law of circumferential strain at both points is consistent. The measuring point 3 shows the process of tension first and then compression, the circumferential strain of the shaft wall in the early ten days of concrete pouring is a tensile state, and the maximum tensile strain is close to 400 $\mu e$. With the solidification of concrete, the circumferential tensile strain of the measuring point gradually decreases and changes from tensile state to

![Figure 6: Maximum deformation of surrounding rock process.](image)

![Figure 7: Maximum principal stress–construction process.](image)
compressive state, but it shows a low compressive strain. The maximum compressive strain is about $-100 \mu e$ and tends to be stable after 28 days of pouring.


We take the intake air shaft as a research object, and the numerical simulation is carried out to analyze the stability of surrounding rock in deep excavation. According to the design needs, the bedrock section from the vertical depth of -1090 m to the vertical depth of -1120 m, there is a horsehead gate at -1120 m, and the working face is pregrouting before the construction of the horsehead gate to strengthen the stratum. According to the elastic theory, the mechanical model of the rock cap is a thick circular plate, and the rock cap bears the grouting pressure. The model is established, as shown in Figure 4.

Simulation methods have discrete element methods and standard software such as UDEC or PFC and the finite element method and standard software such as FLAC and ABAQUS. The finite element method is more suitable for engineering simulation of large deformation of mine, so the FLAC software is selected [16, 17]. The Mohr-Coulomb strength criterion was adopted in the model; the model was considered as an elastoplastic constitutive model.

Figure 8: Maximum principal stress nephogram.
4.1. Analysis of Maximum Deformation of Surrounding Rock in Well Side. To characterize the deformation characteristics of the surrounding rock after the excavation of the full shaft model and determine the large deformation area, in the simulation calculation process, the deformation of the surrounding rock in the X and Y directions is counted. The maximum deformation in each direction is taken as the variation law of the deformation and depth of the surrounding rock of the shaft under the support of the high-performance concrete wall, as shown in Figure 6. The analysis shows that the deformation range of surrounding rock is about 0.4 mm in the process of shaft excavation, and the maximum deformation of surrounding rock occurs in front of the heading face, and the maximum deformation is about 3.5 mm. The deformation of surrounding rock in maximum principal stress direction is more significant than that in minimum principal stress direction. The result shows that the deformation of surrounding rock in the direction of maximum principal stress is significantly greater than that of minimum principal stress. The main reason is that the radial stress distributed on X-axis is more significant than that on Y-axis.

In the construction process, the deformation of the well side will cause the support structure to produce tensile shear failure, thereby reducing the stability of the shaft. Attention should be paid to the dynamic situation before the work is on time. Advanced detection can be carried out if necessary, and corresponding supporting measures can be taken to prevent large deformation of shaft surrounding rock and water inrush disasters.

4.2. Variation Law of Stress Field in Shaft Excavation. To analyze the stress state of surrounding rock and shaft wall after shaft excavation and support, the maximum principal stress—construction process diagram is shown in Figure 7, and the results of the maximum principal stress calculation are shown in Figure 8. With the excavation process, the maximum principal stress of the stratum gradually increases. The calculation result of the initial stress is 29.81 MPa, and the maximum principal stress under the final grouting pressure is 40.99 MPa. The maximum principal stress of the shaft wall gradually increases with the cycle operation, and the peak value of the maximum principal stress of the shaft wall is 32.6 MPa. The 28-day compressive strength of the designed C50 concrete shaft wall is 65 MPa, which meets the design requirements. From the stress nephogram, in the process of shaft excavation, it is easy to produce stress concentration on both sides of the bottom of the shaft wall, and the peak stress can reach 40.99 MPa, and it is easy to produce damage in the place of stress concentration, which harms the construction. Therefore, it is necessary to pay attention to avoid the damage of the shaft wall caused by excessive stress concentration.

The shaft wall is prone to tensile-shear failure in the deep shaft support project. In order to analyze the stress of surrounding rock and shaft wall after shaft excavation, excavation, and support, the maximum shear stress—construction process diagram is made, as shown in Figure 9, and the results of the maximum shear stress calculation are shown in Figure 10. With the excavation process, the maximum shear stress of surrounding rock decreases first and then increases. The maximum shear stress at the end of excavation process 1 is 15.09 MPa. With the excavation construction, the maximum shear stress decreases to 14.15 MPa at the end of excavation process 3, but with the grouting operation, the maximum shear stress gradually increases, and the peak shear stress is 15.42 MPa. The maximum shear stress appears from the cloud image distribution at the top of the shaft wall. The shear stress concentration area appears when connecting the shaft walls with the cycle operation. In support of the deep shaft wall, the connection of the shaft wall is prone to shear failure. In constructing shaft wall connections, attention should be paid to ensure the construction quality to meet the safety needs of shaft wall support.

4.3. Plastic-Zone Analysis. Excavation disturbance causes stress redistribution and local stress concentration. When
the stress exceeds the strength of the surrounding rock, it enters the plastic state. Due to the emergence of the plastic zone, the stress continuously transfers to the deep, and the maximum principal stress from the shaft wall to the deep surrounding rock increases first and then decreases and finally stabilizes in the region. In the plastic zone distribution, Figure 11 shows that when process 1 is completed, the wall rock mainly produces shear failure, a shear failure, and a small range of tensile failure. When process 2 is completed, the plastic zone failure of surrounding rock in the sidewall is still mainly concentrated in the upper shaft wall. Shear failure and tensile failure coexist. Plastic failure also occurs in the heading face, and the failure range is small. With the continuous excavation, the plastic zone is still mainly the shear and tensile failure of the upper surrounding rock caused by the completion of process 2, but a small range of pure shear failure occurs in the heading face. After grouting, the plastic zone is mainly distributed in the surrounding grouting holes and heading face. The grouting holes around the rock cap are mainly a tensile failure, and there is a small range of shear failure. Therefore, in the process of deep engineering construction, with the excavation process, the surrounding rock of the well is mainly a shear failure, and there is a small range of tensile failure, which will produce a small range of tensile failure in front of the work. At the same time, the shaft wall is prone to rupture due to the action of tension and shear. In the construction process, it is necessary to improve the tensile and shear resistance of the shaft wall, which is verified by the measured results.

Figure 10: Maximum shear stress nephogram.
Figure 11: Plastic failure zone nephogram.
5. Conclusions

(1) During the shaft excavation, the maximum pressure on the shaft wall measuring point is 4.5 MPa; the maximum tension is 1.3 MPa. The maximum axial compressive strain of shaft is -500 με; the maximum tensile strain is 1700 με. The maximum circumferential compressive strain of shaft wall is -1000 με; the maximum tensile strain is 400 με.

(2) During the construction of shaft excavation, the strain and stress of shaft wall concrete are divided into the following stages: (1) the fluctuation stage at the initial stage of concrete pouring, (2) the stable stage of concrete after condensation, (3) unstable stage affected by construction, and (4) restability stage of shaft wall stress.

(3) Combined with the construction conditions, the two sharp increase of shaft wall stress is mainly due to blasting construction and pregrouting of the working face. In deep shaft excavation blasting construction and working face pregrouting, it is necessary to pay attention to the wall stress and avoid the rupture caused by excessive grouting pressure.

(4) According to the axial and circumferential strain gauges, the shaft wall appears tensile state. Combined with the measured force anchor, the tensile state exists in some parts of the shaft wall at the early concrete pouring stage. The shaft wall will be pulled during the construction of shaft excavation and grouting. To support the deep shaft wall, it is recommended to use high-performance steel fiber concrete to improve the tensile capacity of the shaft wall.

(5) Through numerical simulation, it is found that stress concentration is prone to occur at the bottom of the shaft wall during excavation, which is a weak zone in support of the deep shaft wall, so it is necessary to avoid the damage caused by excessive stress concentration. At the same time, shear failure is prone to occur at the joint of shaft wall, and construction quality should be ensured to meet the safety requirements of shaft wall support.

Data Availability

All data included in this study are available by contacting the first author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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