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Influence of Eccentric Water Injection on Shaft Wall Stability

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Influence of Eccentric Water Injection on Shaft Wall Stability

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Abstract. The approach of water injection is an effective way to prevent shaft failure. However, due to the building existence or the need for adding a single water injection hole, the symmetric arrangement of the water injection borehole becomes more and more difficult. Therefore, eccentric water injection becomes a water injection method that has to be used. In this paper, the numerical simulation method was used to study the influence of eccentric water injection on the shaft stability by setting the water pressure and injection position distance from the shaft. The results showed that the larger the water injection pressure was, the smaller the vertical compressive stress on the shaft wall was and the larger the strata uplift was. The farther the injection position from the shaft was, the larger the vertical compressive stress on the shaft wall was. It also showed that the farther injection position distance from the shaft was, the weaker the lateral transfer of water pressure was, and the larger the vertical pressure difference between the water injection side and the opposite side was. Combined with the simulation results and the pre-industrial tests, the optimal water injection engineering parameters were determined as injection pressure of 0.3 MPa with injection position 50 m away from the shaft.

1. Introduction

The Huang-huai area is the main coal mining base in eastern China, and most of the vertical shafts in the area pass through alluvial aquifers (>100m thick). Since the 1990s, many mining areas such as Xuhuai, Yanzhou, and Jining have experienced non-mining shaft failure such as wall instability, ring wall cracking, and steel exposure, which poses a serious threat to the normal transportation and safe production of mines[1-3]. After years of research, it is found that the shaft failure in the Huang-huai area is related to the continuous hydrophobicity of bottom of alluvial aquifer layer. The water level, stratum and shaft wall are the three elements of shaft failure[4-8]. At present, there are several approaches to prevent shaft failure in the world such as creating a stress-relief slot, casing reinforcement, grouting the surrounding strata, installing a wall ring, and injecting water to stabilize water levels (water injection method)[9-11]. Among these prevention and control measures, water injection method is a new approach to prevent shaft failure in recent years and does not affect mine production.

Water injection method to prevent shaft failure has been tested and applied in Jining No.3 and Dongtan coal mines, and achieved the expected results in recent years[12-14]. Previous studies have shown that the symmetric arrangement of the water injection boreholes was most beneficial to the shaft stability[15]. However, considering the existence of the building, it was difficult to increase the number of water injection boreholes in pairs, and the cost increased. As the water injection effect weakened with time, a single or singular number of water injection boreholes needed to be added, and the eccentric water injection became a measure that has to be adopted. However, eccentric water injection might cause uneven stress on the shaft wall that lead shaft failure. Therefore, it was necessary to study the feasibility and influence of eccentric water injection on shaft wall stability to provide a new way for water injection. In this paper, the influence of eccentric water injection on shaft stability was studied by numerical simulation method.

2. Model establishment and mechanical parameters

According to the strata of the Jining No.3 coal mine, a geomechanical model near ventilation shaft was established. For the convenience of simulation calculation, the strata and shaft wall are reasonably simplified in the process of modelling. The thickness of the loose alluvial stratum near the ventilation shaft was 176.8 m. Considering the size and unit of the model, gravity of topsoil covering 76.8 m was simplified as vertical stress acting on the model surface. The ventilation shaft wall was a double-layer concrete structure. For the convenience of calculation and did not affect the calculation result, the inner and outer shaft wall thicknesses were combined into one layer of shaft wall. The thickness of the shaft wall was 1 m, the net diameter of the shaft was 6.5 m, and the strength of the shaft wall was C30-C40. According to the lithology and thickness of strata near the ventilation shaft, the strata were divided into seven layers: aquifer sand layer I, claypan I, aquifer sand layer II, claypan II, aquifer sand layer III, claypan and bedrock weathering zone. The simplified shaft geomechanical model was shown in Figure 1. The length, width and height of the numerical simulation model were 200 m, 200 m and 100 m, the number of model elements was 220 416, and the number of nodes was 23 5984. The numerical simulation model was shown in Figure 2. The parameters of the shaft wall, strata and interface were shown in Table 1 and Table 2.

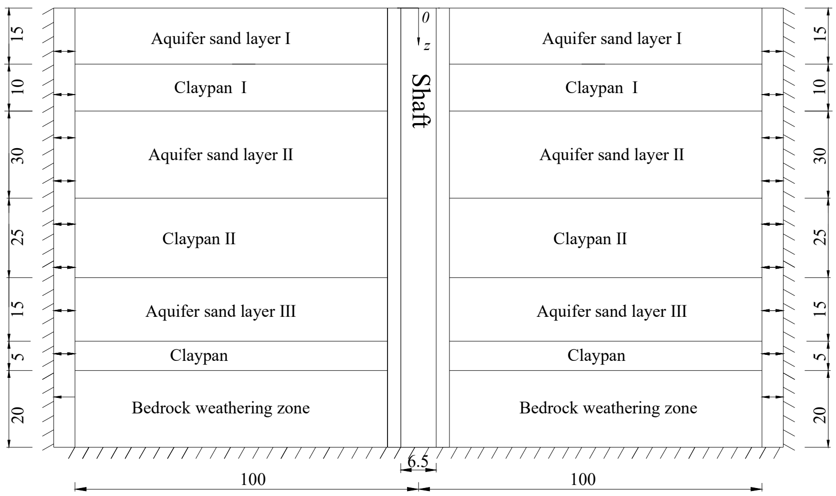


Figure 1. The simplified shaft geomechanical model

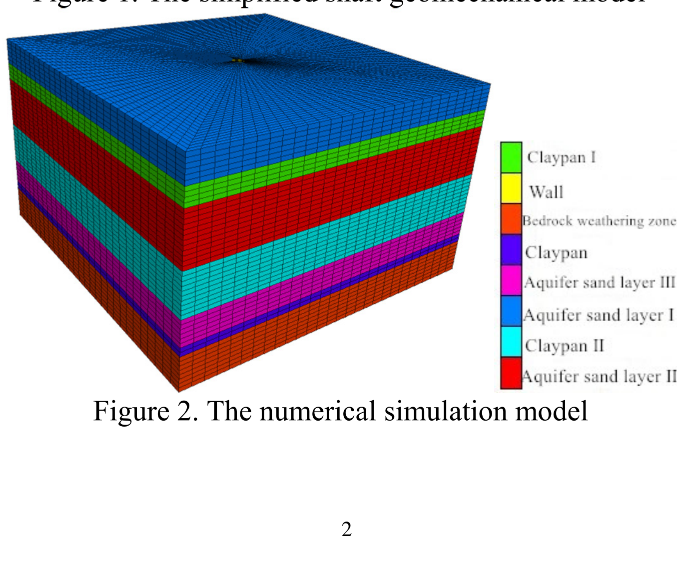


Figure 2. The numerical simulation model

Table 1. The parameters of shaft wall and strata

Lithology	Dry density ($kg \cdot m^{-3}$)	Poisson's ratio	Bulk modulus (MPa)	Shear modulus (MPa)	Friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)
Aquifer sand layer I	1650	0.4	100	20	30	0.008	0.006
Claypan I	1600	0.3	80	35	25	0.03	0.05
Aquifer sand layer II	1700	0.4	100	20	30	0.008	0.006
Claypan II	1650	0.2	80	35	25	0.035	0.05
Aquifer sand layer III	1800	0.4	100	20	30	0.008	0.006
Claypan	1730	0.3	80	35	25	0.04	0.07
Bedrock weathering zone	2500	0.25	15000	10000	35	6	1.88
Wall	2500	0.25	15000	12500	35	6	2

Table 2. The parameters of interface

Lithology	Normal stiffness (MPa)	Tangential stiffness (MPa)	Friction angle (°)	Cohesion (MPa)
Interface	100	100	20	0.03

3. Simulation method and steps

3.1. Simulation method

The model material adopted Coulomb-Mohr elastoplastic. The gravity of topsoil covering 76.8 m was simplified as vertical stress acting on the surface of the model, and the left and right boundaries of the model and the bottom boundary were fixed. According to the regulations, the tensile stress was positive and the compressive stress was negative. The water injection process was simulated by compiling the Fish language and changing the water pressure value of the bottom unit according to the single well water injection head distribution formula (1). In the process of water injection, monitoring points were set at the outer shaft wall of x=3.75 and x=-3.75 to monitor the vertical stress on the shaft wall with different buried depths.

$$h = h_0 - \frac{Q}{2\pi kM} \ln \frac{r}{r_0} \qquad (1)$$

In the formula, M is the thickness of aquifer, m; k is the permeability coefficient; r_0 is the radius of injection well, m; h is the head value at the center line of injection well, m; Q is the flow rate at the cross section, m^3/s.

Water injection head and flow rate referred to the data obtained from single-hole water injection tests during water injection tests of Q_L-4 and Z1 boreholes. When water injection pressure was 0.1 MPa, the average water injection rate in Q_L-4 borehole was 14.25 $m^3 \cdot h^{-1}$, and the water level elevation in Q_L-3 borehole rose approximately 4 m. When water injection pressure was 0.3 MPa, the average water injection rate in Q_L-4 borehole was 20.64 $m^3 \cdot h^{-1}$, and the water level elevation in Q_L-3 borehole rose approximately 8 m. When the injection pressure was 1 MPa, the average flow rate in Z1 borehole was 23.23 $m^3 \cdot h^{-1}$, and the water level elevation in Q_L-3 borehole rose approximately 10 m.

3.2. Simulation scheme and steps
Considering that the ventilation shaft of Jining No.3 coal mine has been 12 years from the initial treatment, the water level of bottom of aquifer sand layer has dropped by nearly 15 m, and the shaft wall has accumulated a certain compressive stress. Therefore, the simulation process is divided into two steps:

The first step was that the water level of bottom of aquifer sand layer dropped by nearly 15 m and the water pressure of aquifer sand layer before water injection was 1.5 MPa. At the same time, the accumulated compressive stress on the shaft wall has already existed. The stress state of shaft wall and surface subsidence near the ventilation shaft were analysed when the pressure of bottom of aquifer sand layer was 1.5 MPa by numerical simulation method, then the simulation results were compared with the monitoring results on-site to verify the correctness of numerical simulation method.

The second step was to simulate the influence of single-hole water injection on shaft wall stability and formation deformation near the ventilation shaft with different injection pressures (0.1 MPa, 0.3 MPa, 1 MPa) and injection position distances from the shaft (30 m, 50 m, 70 m), and to obtain reasonable engineering parameters for single-hole eccentric water injection.

4. Simulation results and analysis

4.1. Analysis of shaft wall stress and formation deformation before water injection
According to the monitored data of surface subsidence near industrial square, the surface subsidence from initial treatment to before injection was approximately 150 mm. The simulation results of the first step of the numerical simulation were shown in Figure 3 and Figure 4.

It can be seen from Figure 3 and Figure 4 that the vertical compressive stress on the alluvial wall increased with buried depth, reaching the maximum near the bottom of the aquifer layer. The accumulative settlements of the strata were close to 150 mm that close to the measured value on-site, indicating the simulation results by numerical simulation method were accurate.

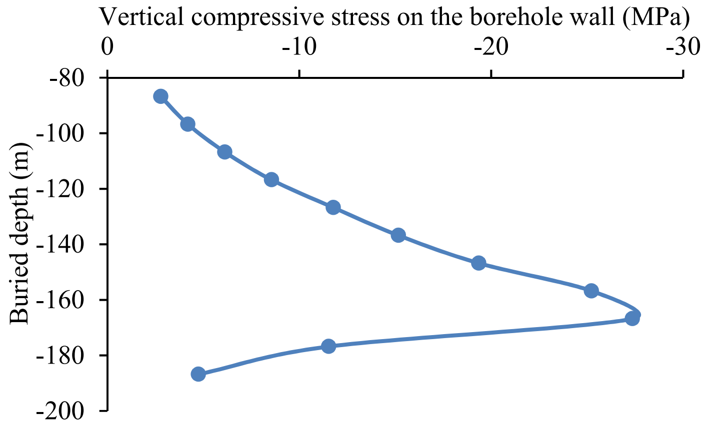
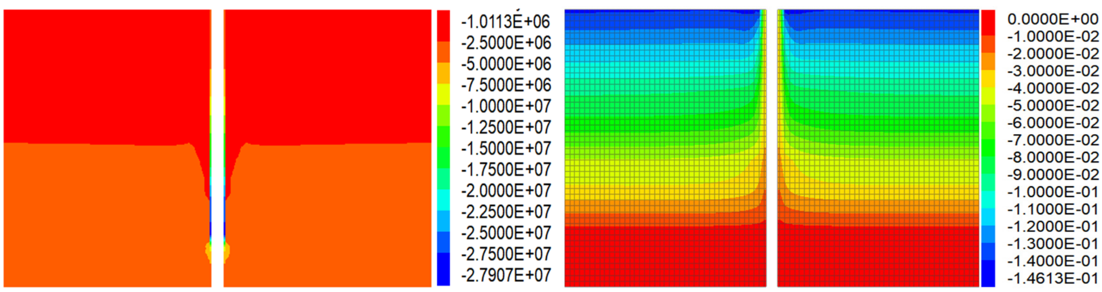


Figure 3. The relationship between vertical stress on shaft wall and buried depth



(a) Vertical pressure stress (b) Surface subsidence

Figure 4. Shaft stress and formation deformation before water injection

4.2. Analysis of eccentric water injection effect

Previous high-pressure water injection test of Z1 borehole has shown that a sudden stop of water injection could cause shaft wall stress to rebound sharply, which was likely to lead to shaft failure[11]. Therefore, the influence of eccentric water injection on shaft wall stability was studied to obtain optimal parameters by setting injection pressure and injection position distance from the shaft. Due to the influence radius of the Q_L-3, Q_L-4 and Z1 boreholes was over 100 m, the head loss was small more than the influence range of 100 m. For convenience of calculation, the water pressure over 100 m away from the injection borehole could be regarded as the same as that at 100 m.

4.2.1. Influence of different water injection pressure on shaft wall stability

Taking 0.3 MPa injection pressure as an example, the distribution of water injection pressure was shown in Figure 5. When injection position was 50 m away from the shaft, the vertical compressive stress on the shaft wall under different water injection pressure was shown in Figure 6, and variation of surface subsidence under different water injection pressures was shown in Figure 7.

It can be seen from Figure 6 that when injection point was 50 m away from the shaft, the vertical compressive stress on the shaft wall was the smallest when 1 MPa water injection pressure was used, and the vertical compressive stress on the shaft was the largest when 0.1 MPa water injection pressure was used. Compared with that before water injection, the maximum vertical compressive stress on the shaft wall decreased about 0.3 MPa when 0.1 MPa water injection pressure was used; the maximum vertical compressive stress on the shaft wall decreased by about 1.7 MPa when 0.3 MPa water injection pressure was used; the maximum vertical compressive stress on the shaft wall decreased by about 2.8 MPa when 1 MPa water injection pressure was used, which indicated that the larger the water injection pressure was, the less the vertical compressive stress on the shaft wall was, and the approach of water injection could effectively prevent shaft failure.

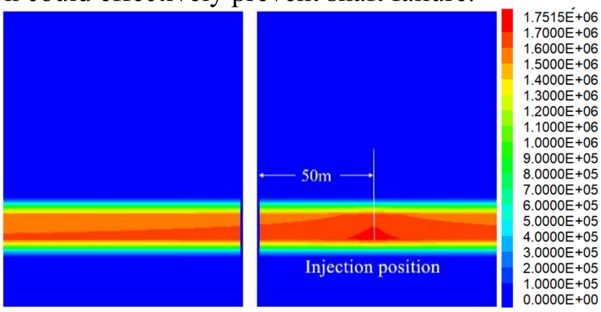
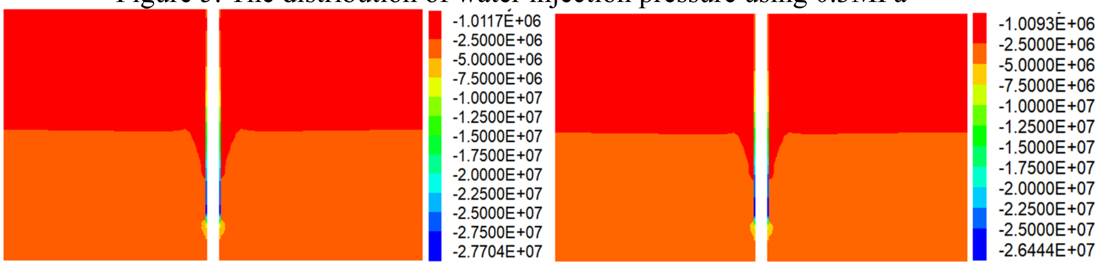


Figure 5. The distribution of water injection pressure using 0.3MPa



(a) 0.1MPa (b) 0.3MPa

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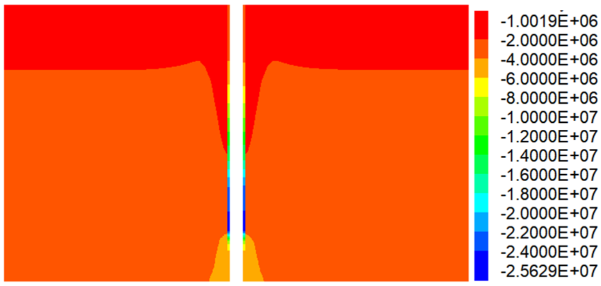
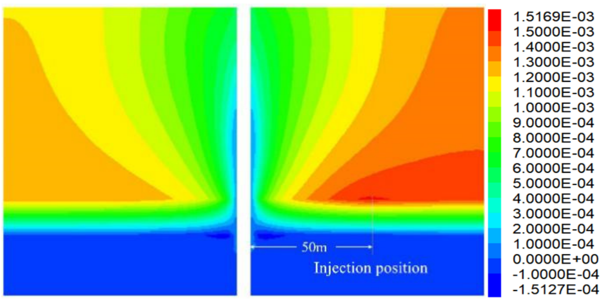


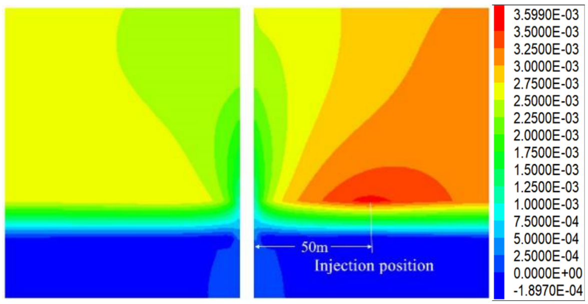
(c) 1MPa

Figure 6. Variation of vertical stress on shaft wall under different water injection pressure

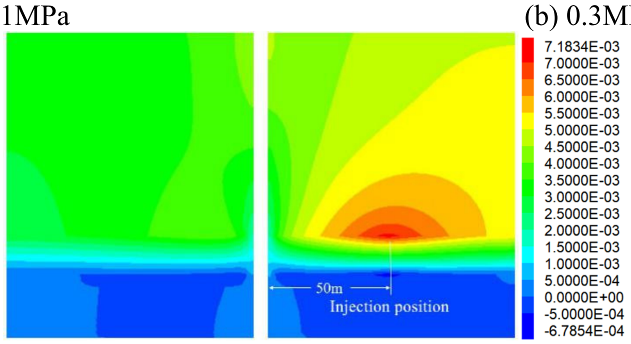
It can be seen from Figure 7 that the deformation of the alluvial strata slightly uplifted during the water injection, and the uplift of strata was diffused in a circular shape from the water injection point. Taking the position distance from the shaft 50 m as an example, the maximum uplift was approximately 1.52 mm when 0.1 MPa was used for water injection while that was approximately 7.18 mm when 1 MPa was used. It was also found that the closer the distance from the shaft was, the larger the formation uplift was, and the uplift value of the strata decreased gradually with the increased distance from the shaft.



(a) 0.1MPa



(b) 0.3MPa



(c) 1MPa

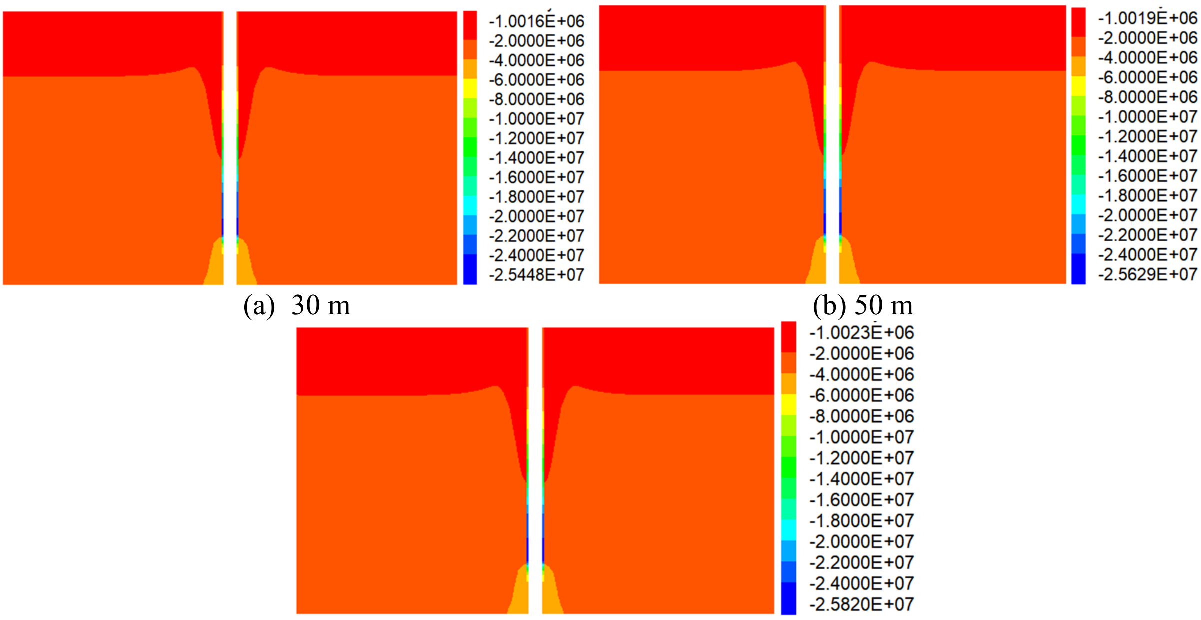
Figure 7. Variation of surface subsidence under different water injection pressures

4.2.2. Influence of injection position distance from shaft on shaft wall stability

Taking the water injection pressure of 1 MPa as an example, the stress on the shaft wall was shown in Figure 8 when the injection distance from shaft was 30 m, 50 m, 70 m, respectively.

It can be seen from Figure 8 that the vertical compressive stress on the shaft wall was the smallest when injection position was 30 m away from the shaft, which was 25.4 MPa while the vertical compressive stress on the shaft wall was the largest when injection position was 70 m away from the shaft, which was 25.8 MPa. However, pre-industrial tests have shown that high-pressure water injection with close distance (about 30 m) from the shaft, the shaft wall stress rebound occurred when the water injection stopped suddenly, which posed a threat to the stability of the shaft. Therefore, the water injection effect was relatively better at 50 m and 70 m away from the shaft.

When using 0.1 MPa injection and the water injection position was 50 m away from the shaft, the vertical compressive stress on the shaft wall of injection side wall at the buried depth of 166.8m was 1.2 KPa smaller than that of opposite side; when water injection position was 70 m away from the shaft, the vertical compressive stress on the shaft wall of injection side at the buried depth of 166.8m was 6.6 KPa smaller than that of opposite side. When using 0.3 MPa injection and the water injection position was 50 m away from the shaft, the vertical compressive stress on the shaft wall at the buried depth of 166.8 m was 0.19 KPa smaller than that of opposite side; when water injection position was 70 m away from the shaft, the vertical compressive stress on the shaft wall of injection side at the buried depth of 166.8 m was 3.4 KPa smaller than that of opposite side. When using 1 MPa injection and the water injection position was 50 m away from the shaft, the vertical compressive stress on the shaft wall at the buried depth of 166.8 m was 10.82 KPa smaller than that of opposite side; when water injection position was 70 m away from the shaft, the vertical compressive stress on the shaft wall of the water injection side at the buried depth of 166.8m was 30.76 KPa smaller than that of opposite side, which indicated that the farther away from the shaft was, the weaker the lateral transfer of water pressure was. The water level difference between the water injection side and the opposite side of the shaft wall was the dominant factor that caused uneven stress on both sides of the shaft wall.



(a) 30 m (b) 50 m

(c) 70m

Figure 8. Surface subsidence under different water injection pressures

Considering the influence of injection pressure and injection distance from the shaft, according to the simulation results, there was no obvious adverse effect on the shaft wall when 0.3 MPa low pressure water injection was used with 50 m away from the shaft. Therefore, it was indicated that the water injection pressure of 0.3 MPa with the water injection position 50 m away from the shaft could meet the requirements of eccentric water injection.

5. Conclusions

In this paper, the numerical simulation method was used to study the influence of eccentric water injection on shaft stability by setting injection pressure and injection position distance from the shaft. The following main conclusions were reached:

(1) According to stratigraphic characteristics near the ventilation shaft, a numerical model of the eccentric water injection of the shaft was established. By simulating the stress on the shaft wall and formation compression before water injection, it was concluded that the surface subsidence basically

coincided with monitoring results on-site, which verified the reliability of the numerical simulation results.

(2) By simulating the influence of injection pressure (0.1 MPa, 0.3 MPa, 1 MPa) on shaft stability, it was concluded that the larger the injection pressure was, the smaller the vertical compressive stress on the shaft was, and the larger the strata uplift was. The uplift of strata was diffused in a circular shape centering on the water injection point during water injection, and the approach of water injection could effectively prevent shaft failure.

(3) By simulating the influence of injection position distance from the shaft (30 m, 50 m, 70 m) on the shaft stability, it was concluded that the farther the injection distance was, the larger the vertical compressive stress on the shaft wall was. The farther the injection point away from the shaft was, the weaker the lateral transfer of water pressure was. The water level difference between the water injection side and the opposite side of the shaft wall was the dominant factor that caused uneven stress on both sides of the shaft wall.

(4) Considering the influence of injection pressure and injection position distance from the shaft by simulation, and based on the pre-industrial test results, there was no obvious adverse effect on the shaft wall when 0.3 MPa low pressure water injection was used with 50 m away from the shaft. It was indicated that the water injection pressure of 0.3 MPa with the injection position 50m away from the shaft could meet the requirements of eccentric water injection.

Acknowledgments
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