Numerical Analysis on Shaft Lining Stability during Aquifer Quick Drainage in Eastern Chinese Coal Mines

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Abstract

In recent years, shaft lining ruptures have occurred in deep alluvium for many times in the eastern Chinese coal mines, which caused huge losses to the coal mines. Stability of the shaft lining in deep alluvium is affected by complex factors, one of which is unstable bottom aquifer. This paper, based on the previous studies with long-term drainage of bottom aquifer, researches the influence of the aquifer on shaft lining's stability in the condition of a large number of pumping in a short time. First, according to the documents, the engineering geological and hydrogeological conditions of Baodian coal mine, which has shaft lining ruptures once, have been gained. Then the paper analyzes the stress of shaft lining under the limit state when the pore pressure in aquifer gets down in a short time. As the result, the shaft lining may be unstable under that condition. Finally, with the finite element software *ADINA*, the authors simulate a large number of pumping of bottom aquifer in a short time in conditions of fluid-structure interaction of water and soil. The results show that the concentrate area of shear stress transfers to the junction of bedrock and aquifer under the initial drainage. Also, the shear stress of inner shaft lining increases, and the faster of pumping speed, the more it increases at the initial drainage. Besides, the numerical simulation of drainage verifies that the pore pressure does not always reduce but corresponds with *Mandel-Cryer* effects: the pore pressure decreases after the first increasing. Therefore, the numerical simulation has perfectly interpreted the effects of quick drainage of bottom aquifer in deep alluvium on the stability of shaft lining.

Keywords: aquifer quick drainage, shaft lining stability, stress analysis, numerical simulation

1. Introduction

Environment damage caused by coal mining operation has got more and more attention. A large number of problems emerged during the coal extraction such as shaft deformation, surrounding rock deformation, aquifer leakage, rock burst, and water inrush (Jaiswal and Shrivastva, 2012; Sari et al., 2004; Li, 2006). Furthermore, serious shaft lining failures have often occurred in the eastern part of China, such as Datun, Xuzhou, Huaibei, Yanzhou, Yingxia, Hebi, Dongrong, etc, since 1987 (Gu, 2000). The geological conditions of all these spots are almost the same. All these shaft linings pass through deep topsoil of Quaternary strata, for which the composition of the bottom aquifer is complex; before shaft lining rupture, the water head of the bottom aquifer fell dramatically and large scale subsidence occurred. During the water head fall, the soil layer applies additional force to the outer shaft lining. As the additional force increases with the effect of other joint forces, the condition of shaft lining gradually goes into a plastic state, and then can be ruptured. As the maximum additional stress occurs in the bottom aquifer and near the bedrock surface, most of the failures have happened in these zones (Cui and Cheng, 1991; Zhou and Cheng, 1995; Bi et al., 1997; Yang et al. 1997; Yang and Fu, 1999; Jing and Wang, 2000; Liu et al., 2007).

For the mechanism of shaft lining rupture, there are a few hypotheses that have been proposed by some researchers such as the construction quality hypothesis, the tectonic movement hypothesis, the earthquake hypothesis, and the vertical additional force hypothesis (Yang et al. 1997; Jing and Wang, 2000). In these hypotheses, the vertical additional force hypothesis plays a dominant role and it is described below. Shaft lining bears the horizontal underground pressure, the self-weight (including equipment weight) and the vertical additional force. The research results of shaft lining destructive tests and the in site experimental data in mining areas of Huaibei, Xuzhou, etc. confirmed the existence of vertical additional force and its impact on the shaft lining rupture (Cui and Cheng, 1991; Yang and Fu, 1999). Researches on analysis of shaft lining stability have been conducted in recent years and some measures including water-resistant key strata have been applied (Liang et al., 2009; Wang et al., 2010a; Sui et al., 2010; Pu et al., 2008; Wang et al., 2010b).

However, stability of the shaft lining in deep alluvium is affected by complex factors, one of which is unstable bottom aquifer. This paper, based on the previous studies with long-term drainage of bottom aquifer, researches the influence of the aquifer on shaft lining's stability in in the condition of a large number of pumping in a short time.

2. Geological Conditions

As the geological conditions are similar in eastern Chinese coal mines, in this analysis, the Baodian coal mine was chosen as a typical example for the mines which are located in eastern China. This coal mine belongs to Yanzhou Mining Group in Shandong Province. The coalfield of this coal mine is buried in the Quaternary stratum and Jurassic stratum. This coal mine was commenced in June 1986 and the production is over 3 million tons per year. The mining level is now below -430 m from the surface and the fully mechanized long wall mining system is adopted for coal extraction.

The geological conditions of the alluvium which the Baodian auxiliary shaft passes through are shown in Table 1. The total thickness of the Quaternary alluvium in which the shaft passes through was about 148 m, the cumulative thickness of the aquifer was more than 20 m. The middle group has a good impermeability and can effectively block the vertical recharge of Quaternary aquifer. The lower group has three small sand layers, and in this study, the lower group is considered the bottom aquifer which has the water level drawdown.

The initial water pressure in the aquifer was 1.45 MPa, and by July 1995, the pressure had been decreased to 0.65 MPa. The average of water discharge pumped up in each year of this coal mine is shown in Fig. 1 (Liu et al., 2007). From 1991 to 2000, the average water discharge was about 563.40 m3/h. The permeability coherent K of the bottom aquifer was 2.52-5.39 m/d (average 3.955 m/d). The variation of water level in the bottom aquifer of Baodian coal mine from 1985 to 2000 is shown in Fig. 2 (Liu et al., 2007). This figure shows that the water level in the bottom aquifer dropped dramatically and persistently. The water level in the bottom aquifer dropped more than 20 m from 1985 to 1995 when the first shaft lining failure occurred.

Table 1 Geological condition of alluvium in Baodian auxiliary shaft

Soil group	Depth /m	Thickness /m	Description
Upper	6.54	6.54	Humid soil, yellowish-brown clay
	15.80	9.26	Sandy clay
	19.90	4.10	Yellow gravel
	23.50	3.60	Sandy clay, silty sand
Middle	46.10	22.60	Yellow sandy clay, clay
	59.40	13.30	Clay with fine sand interbed
	63.40	14.00	Clay
	87.67	24.27	Clay with coarse sand interbed
	93.58	5.91	Clay
Lower	106.18	12.60	Clayey coarse sand
	116.45	10.27	Sandy clay
	128.05	11.60	Clayey silty sand
	140.00	11.95	Clay
	148.60	8.60	Fine sand, silty sand

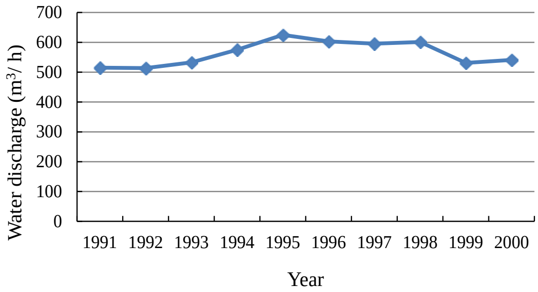

Fig. 1 Water discharge in past ten years of Baodian coal mine

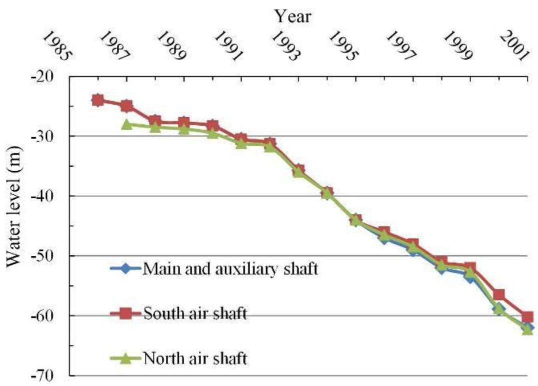

Fig. 2 Variation of water level in bottom aquifer

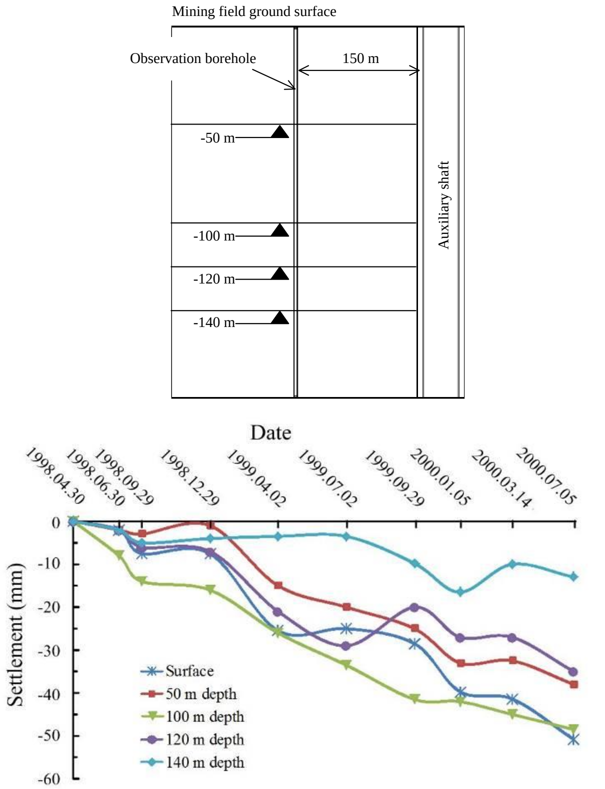

Fig. 3 Settlement at different depths

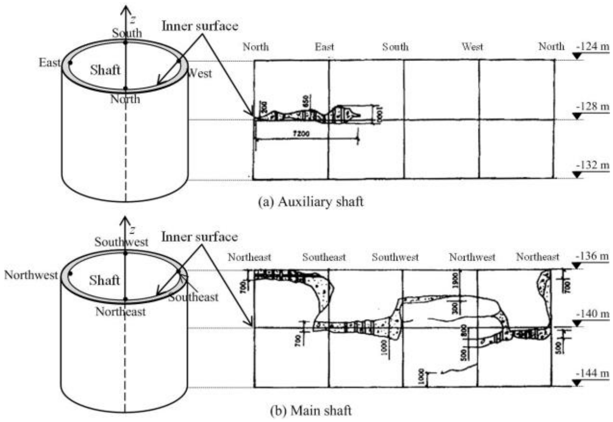

Fig. 4 Failure sketches of two shafts

Because of the drop of water level in aquifer, this layer was consolidated and compressed, which could cause the ground subsidence around the shaft. Fig. 3 shows the settlement at different depths of the industry square in Baodian mine from May 1998 to July 2000 (Liu et al., 2004). The observation borehole was located at 150 m from the shaft. The settlement in 100 m depth was greater than any other depths before July 2000. This depth was just the upper location of the aquifer layer. This meant that a large settlement had been occurred in the aquifer layer and that caused the subsidence of ground surface. The obvious settlement of ground surface in the mining field was occurred in just two years and the last one was over 51 mm. The average settlement of the ground surface was about 24 mm/year.

On June 5, 1995, it was found that the cage guides in the auxiliary shaft deformed torsionally at a depth of -140 m. The cage guides, drainpipes and pressure ventilation pipes in the shaft bended in the longitudinal direction due to the shaft lining failure. On July 12, 1995, it was found that the main shaft lining had another failure at a depth of -136 m~ -144 m. At that time, the concrete lining collapsed and fell off in a large area. The sketches of the failure parts in two shafts are shown in Fig. 4 (Liu and Zhang, 1995). The crack in the shafts was distributed in horizontal direction and its maximum width was over 1.0 m.

3. Numerical Simulations

3.1 Numerical model

The influence of aquifer quick drainage on shaft lining stability was analyzed by means of finite element analysis software, *ADINA*. During the structural-pore pressure coupling process, the multiphysics problem is characterized by the coupling between the pore pressure and the deformation of a porous material consisting of a solid skeleton and pore fluid. Mechanical deformation changes the pore pressure and change in the pore pressure causes mechanical deformation (Multiphysics Capabilities of ADINA, 2015).

Considering the focus of this study is the influence of aquifer quick drainage on the shaft lining stability, the pore pressure change caused by drainage and the stress change in shaft lining are the important factors. Therefore, in this simulation, the structural-pore pressure coupling method was adopted, without changing the actual load types, in order to get the simulation results.

As the process of overburden deformation and change of shaft lining stress was very complicate, the following assumptions were made:

[1] Shaft lining and strata were treated as the symmetrical distribution belonging to the space axial-symmetry.

[2] Concrete shaft lining, the surrounding strata were homogeneous and isotropic. There was an interface between the surrounding strata and shaft lining, which means the friction occurs in the interface. According to the references (Tang et al., 2004; Xu et al., 2002), the friction coherent was set as 0.75.

[3] Drainage faces were only in outer edge of the aquifer. The aquifer unit was treated as the porous material.

The basic model used in the analysis is shown in Fig. 5. This model was used the typical geological conditions of Baodian coal mine. The net diameter of main shaft was 8 m and the thickness of shaft lining was 1.0 m. The dimensions of the entire model were 420 m ×420 m wide and 220 m high, and it consists of four layers: an aquifer, a top soil, a water-resisting layer and a bedrock layer. From the above assumptions, the four strata layers were defined Mohr-Coulomb material and the shaft lining was defined the elastic material.

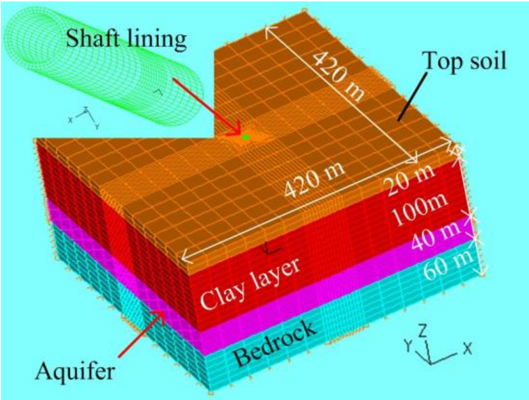

Fig. 5 Numerical analysis model

Table 2 Mechanical properties used for numerical simulation

Parameters	Top soil	Clay layer	Aquifer	Bedrock	Shaft lining
Thickness /m	20	100	40	60	1
Young's modulus /MPa	42	73.5	42	10,000	20,000
Poisson's ratio	0.3	0.3	0.3	0.25	0.15
Internal friction angle /°	20	20	20	35	35
Cohesion /MPa	0.03	0.035	0.04	11	35
Unit weight /MN/m^3	0.021	0.021	0.022	0.027	0.03
Tensile strength /MPa	0.06	0.07	0.075	6.0	16
Permeability coefficient /m/s	—	—	5.775×10^{-10}	—	—

According to the conditions of engineering geological and hydrogeological in Baodian coal mine, the parameters of strata and shaft lining are shown in Table 2 (Zhao, 2009).

The analytical boundary conditions were set as follows:

[1]The lower boundary was fixed in vertical direction.

[2]The lateral boundaries were fixed in horizontal direction, the upper boundary was free.

[3]The both corner points in the lower boundary were fully fixed.

3.2 Simulation tests

In order to find the influence of aquifer drainage on the shaft lining stability, during the simulation, the constant flow pumping method was used to instead of the drainage process. There are two steps in the numerical simulation of aquifer drainage:

[1] The first step is the initial stress equilibrium of soil and shaft lining under the undrained condition. The initial stress is the soil weight and lateral pressure under gravity.

[2] The second step is the aquifer drainage under the initial stress state, which can make the soil consolidation under self-weight.

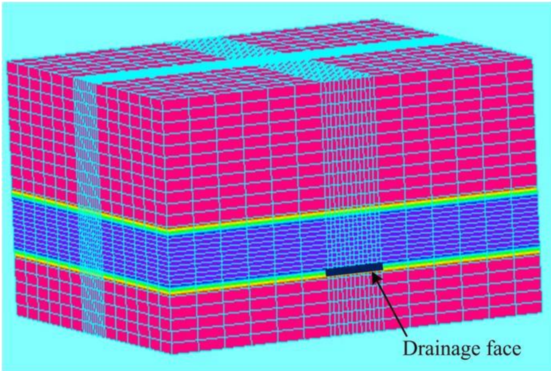

Fig. 6. Initial pore pressure.

Fig. 6 shows the pore pressure in aquifer and the principle stresses under the initial stress state. In initial state, the pore pressure is uniform distribution in aquifer. The drainage face was set at the edge of the bottom aquifer. The maximum shear stress in shaft lining is recognized around the aquifer and bedrock zone as shown in Fig. 7(a).

Considering the ratio of the actual mining area to the simulation area is 209, the average water discharge can reduce to 2.7 m^3/h (64.8 m^3/d). As a result of lacking of correlation parameters such as observation well data and effective radius, and also the poor recharge conditions of bottom aquifer, the simulated water discharge in this simulation was set as the 8%-10% of the average water discharge, and then we take 5.8 m^3/d for the average value. In this simulation tests, the 5 times, 10 times, and 12 times water discharge were also simulated in order to clarify the influence of aquifer quick drainage better.

3.3 Result analysis

Fig. 7 shows the maximum shear stress in shaft lining. The location of maximum shear stress of shaft lining transfers from the bedrock layer to the aquifer layer following the changes of the drainage status. This shows the aquifer drainage can change the stress state of shaft lining.

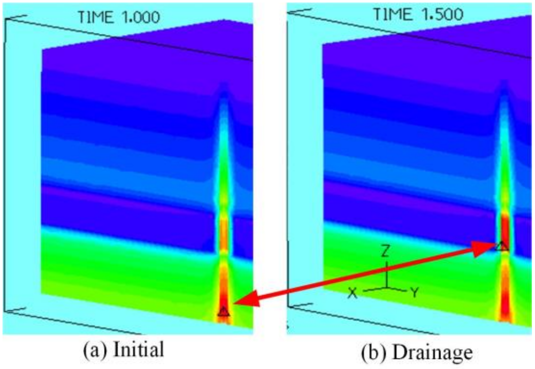

Fig. 7 Location change of maximum shear stress in shaft lining

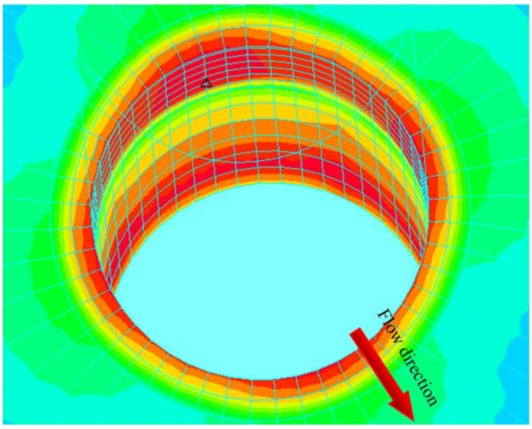

Fig. 8 Maximum shear stress condition during drainage

Fig. 8 shows the Maximum shear stress condition during drainage. The maximum shear stress appears in the inner shaft lining and the position is farthest in the shaft lining to the flow direction. It can be said that the part of shaft lining which is facing the direction of flow is the much more affected part. In other words, the facing part of shaft lining is the weak part and liable to failure.

Fig. 9 shows the maximum shear stress condition during drainage. Four circumstances of drainage conditions show in this figure, and the conditions of maximum shear stress in the shaft lining have the same trends. Following the increase of the drainage in a short time, the value of maximum shear stress in shaft lining has a sudden increase, and at the beginning of early drainage, it reaches to the maximum, and then trends to constant. Obviously, the larger drainage, the value of maximum shear stress becomes much greater.

Fig. 10 shows the pore pressure condition during aquifer quick drainage in four circumstances. The pore pressure curves in the figure also have the same trends. At the beginning of the drainage, the pore pressure in the aquifer has a sudden increase and then begins to reduce. And the larger drainage, the gradient becomes much larger. The pore pressure does not always reduce but corresponds with *Mandel-Cryer effects*: the pore pressure decreases after the first increasing (Selvadurai and Shirazi, 2004).

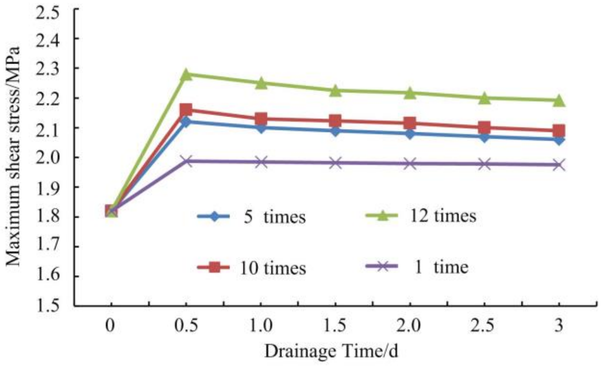

Fig. 9 Maximum shear stress condition during drainage

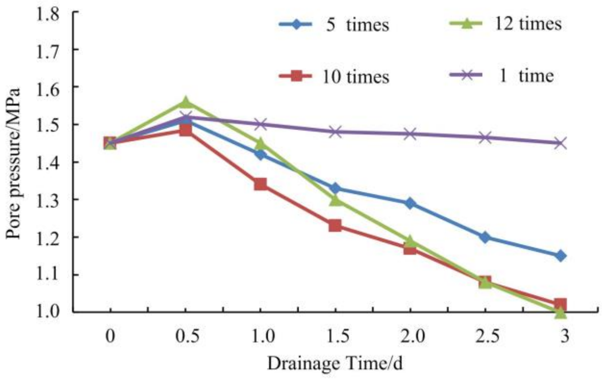

Fig. 10 Pore pressure condition during drainage

4. Conclusions

According to the above analyses and simulations, the following results can be obtained.

[1] During the short term aquifer drainage, the location of the maximum shear stress in inner shaft lining transfers from bedrock layer to aquifer layer, and the shear stress in inner shaft lining increases.

[2] Following the increase of the drainage in a short time, the value of maximum shear stress in shaft lining has a sudden increase and then trends to constant, and the pore pressure in the aquifer has a sudden increase and then begins to reduce. The larger drainage, the shear stress in shaft lining increases drastically at the initial drainage, and the gradient of pore pressure curves becomes much larger.

[3] As the maximum stress initiates around the

interface of bottom aquifer and bedrock, when pore pressure has an obvious change, the shear stress in inner shaft lining reaches to maximum. Therefore, the early drainage stage is a dangerous period to the stability of the shaft lining.

Acknowledgements

The authors are grateful for financial assistance provided by the Basic research program of Jiangsu province (Natural Science Foundation) (No. BK20130179).

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