Application of Underground Continuous Impervious Curtain
to Shaft Lining Rupture Treatment in Eastern Chinese Coal Mines

by

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Abstract

Many problems result when coal mine shafts are built in complicated geological conditions and serious shaft lining ruptures have often occurred in the eastern part of China since 1987. Several types of treatment methods are used for shaft lining reinforcement, such as the grouting method, sets of wall reinforcement method and stress-relief slot method; based on analysis of these methods and the mechanism of shaft lining rupture, a new treatment method is proposed for shaft lining treatment with an underground continuous impervious curtain (UCIC). In this study, the mechanism of shaft lining rupture was analyzed using numerical simulation, the current treatment methods were also analyzed, and then the various conditions of the UCIC built around the shaft lining were analyzed and the effect of the UCIC method was discussed. The results show that the lowering of water level in an aquifer can result in shaft lining rupture, and the new method has the effect to reduce and transform the stress concentration, and is able to reinforce shaft lining rupture in actual application.

Keywords: Shaft lining, Rupture, Treatment method, Grouting, Coal mines, UCIC

1.   Introduction

Serious shaft lining ruptures have often occurred in the eastern part of China, such as Datun, Xuzhou, Huaibei, Yanzhou, Yingxia, Hebi, Dongrong, etc, since 1987[1]. 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

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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 ruptures have happened in these zones.

The result of a technical survey showed that, in all broken shafts there was a thick bottom aquifer under the steady impermeable layer and the aquifer was in direct contact with the weathered rock in the top of bedrock. Their geological conditions of hydrology and geology have some of the same characteristics. All the shafts passed through the deep topsoil in Quaternary materials and mostly the thickness was about 200 m. Quaternary strata are divided into upper, middle and lower groups; under the strata is the coal-bearing rock. The upper is the water-bearing stratum, the middle is a relatively impermeable layer, and the lower is the confined bottom aquifer. Before the shaft linings ruptured, the water pressure of the bottom aquifer around the shaft was significantly reduced and the larger subsidence occurred due to the influence of mining drainage.

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[2, 3]. 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[4, 5].

As these subsidences might be related to the bottom aquifer drainage and consolidation settlement, the most important and difficult task is how to protect the shaft lining from the impact of the aquifer drawdown in deep alluvium. The main treatment methods are the strengthening of shaft lining and the reinforcement of surrounding soil. Current researches are mostly focused on the causes, mechanism and solutions for these kinds of geotechnical issues in engineering projects and they have been hot topics in the last 20 years in shaft construction[6-12].

In this study, the mechanism of shaft lining rupture is analyzed using numerical simulation, the current treatment methods are also analyzed, the underground continuous impervious curtain (UCIC) is proposed as a new method against shaft lining rupture, and then the effect of the UCIC method is discussed and analyzed.

2.   Mechanism of Shaft Lining Rupture

2.1 Geological conditions

In this analysis, the Baodian coal mine was chosen as a typical example for the mines which are located in eastern China. This mine belongs to the Yanzhou Mining Group in Shandong province, and is a concealed coalfield in which the shafts pass through the Quaternary stratum and Jurassic stratum.

This coal mine was put into operation in June 1986. The total thickness of the Quaternary alluvium which the shaft passes through is 148 m, the cumulative thickness of the aquifer which has the ability of drainage is more than 20 m, the initial water pressure aquifer was 1.45 MPa, and by July 1995, the pressure had been reduced to 0.65 MPa. The average rate of depressurization in the aquifer was 8.4 m (water head)/a. At the end of June 1995, the auxiliary shaft lining had a rupture accident at a vertical depth of 126.7 m. After the accident happened, the cage guides,

drainpipes and pressure ventilation pipes showed longitudinal bending and the water stringed from the shaft lining and steel bars. The rupture was horizontal and extended 6.5 m. Then in July 1995, the main shaft lining had another rupture at a depth of 136 m ~ 144 m; in this rupture, the concrete lining collapsed and fell off in a large area. As the accident was more serious, the coal mine had to stop operation to reinforce the shaft.

2.2 Analysis model

As mentioned above, groundwater drawdown in the aquifer has happened before the shaft lining rupture occurred in the coal mine in which the rupture location was near the aquifer. In this study, the finite element analysis code, *Phase*^{2}, was used to show the impact of aquifer drawdown on shaft lining rupture. *Phase*^{2} 7.0 is a 2D elastic-plastic finite element analysis program for underground or surface excavations in rock or soil[13].

The analysis model used to imitate the geological condition is shown in **Fig. 1**. The axis *z* is the symmetric axis of the axisymmetric model and it is the central axis of shaft. The axis *x* indicates the direction of ground surface away from the shaft. In order to reduce the analysis burden, the model just focused on the part of the aquifer. The analysis boundary condition is set as follows; the lower boundary is vertically fixed, the lateral boundaries are horizontally fixed, the upper boundary is free, and both corner points in the lower boundary are fully fixed. It is an axisymmetric model and the elastic analysis is used. Axisymmetric modeling allows analyzing a 3-D excavation which is rotationally symmetric about an axis. The input is 2-dimensional, but the analysis results apply to the 3-dimensional problem[13]. The aquifer which is 30 m thick and near the shaft lining is assumed that the water level has decreased.

(a) Sketch of Shaft lining   (b) Axisymmetric model
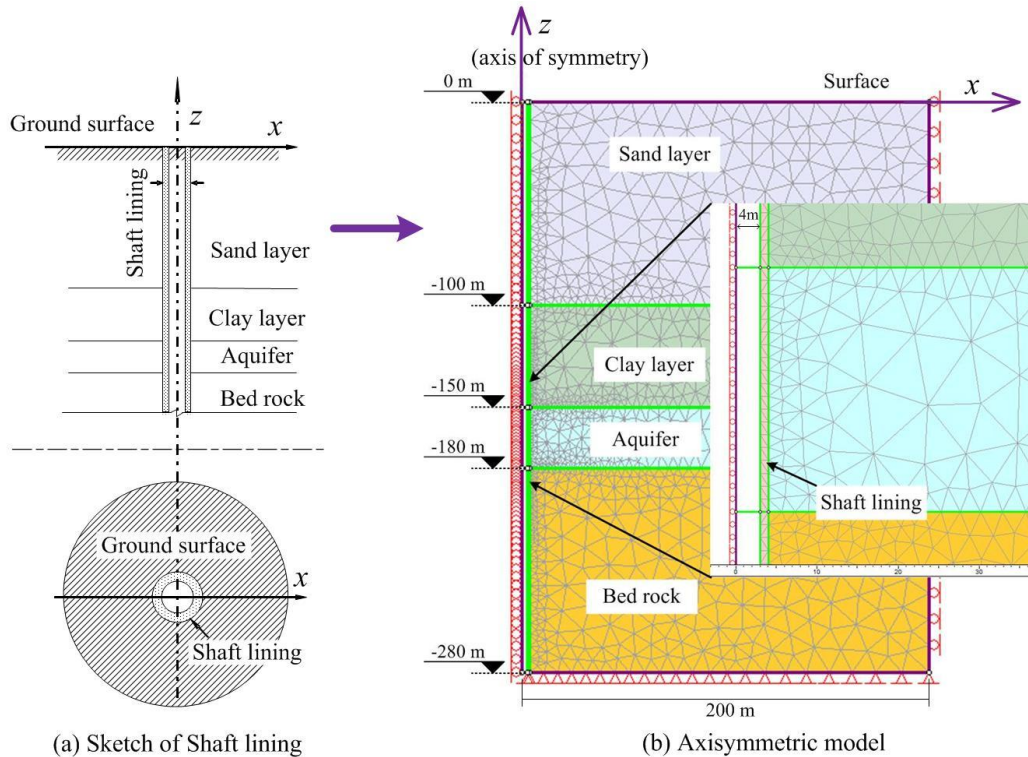
**Fig. 1** Axisymmetric model of numerical simulation for shaft lining rupture.

The mechanical properties used in the analysis are shown in **Table 1**.

Table 1 Mechanical properties used in the analysis.

Parameters	Sand layer	Clay layer	Aquifer	Bed rock	Shaft lining
Young's modulus (MPa)	42	73.5	42	1.0×10^4	2.0×10^4
Poisson's ratio	0.3	0.3	0.3	0.25	0.15
Internal friction angle (°)	20	20	20	35	35
Cohesion (MPa)	3.0×10^{-2}	3.5×10^{-2}	4.0×10^{-2}	11	35
Unit weight (MN/m^3)	2.1×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.7×10^{-2}	3.0×10^{-2}
Tensile strength (MPa)	6.0×10^{-2}	7.0×10^{-2}	7.5×10^{-2}	6.0	16

It is necessary to evaluate the risk of shaft lining rupture caused by the stress. In this research, strength factor is given out to evaluate the risk of shaft lining. Strength factor is a method for determining failure based on the Mohr-Coulomb failure criterion. As shown in **Fig. 2**, the ratio of the radius of the Mohr's circle when tangent to the failure criterion line to the radius of the Mohr's circle is drawn from the numerical results. If the value is less than 1.0, that means there is a risk of failure occurrence. The strength factor is expressed in the follow equation.

$$SF = R' / R \tag{1}$$
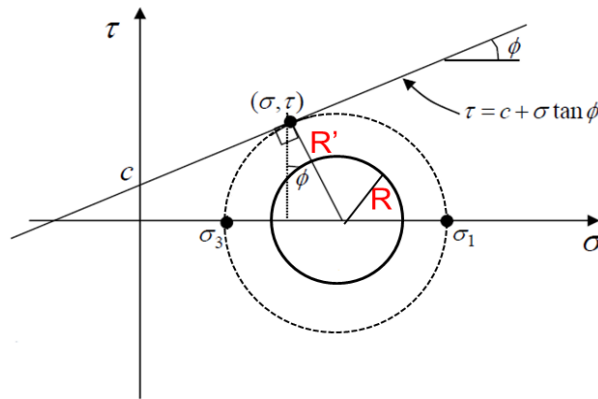
Fig. 2 Mohr-Coulomb failure criterion.

2.3 Analysis results and discussion
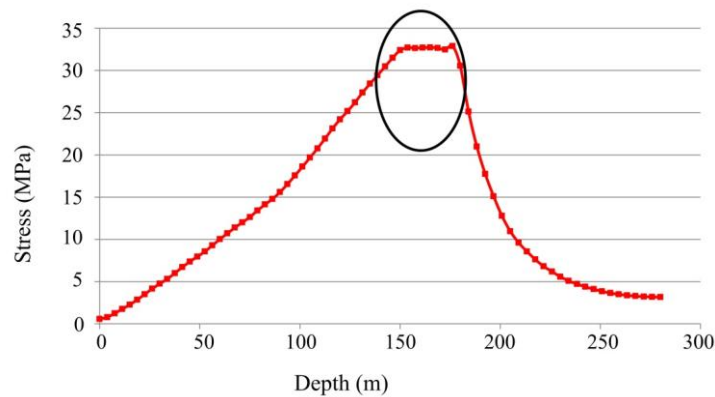
Fig. 3 Maximum principal stress condition in shaft lining after aquifer drawdown.

The maximum principal stress condition in the shaft lining after the aquifer drainage is shown in **Fig. 3**. The stress increases with the increases in the depth, and the stress peak occurs near the aquifer of a depth of 150~180 m. However, below the aquifer, the stress in shaft lining decreases with the increases in the depth.
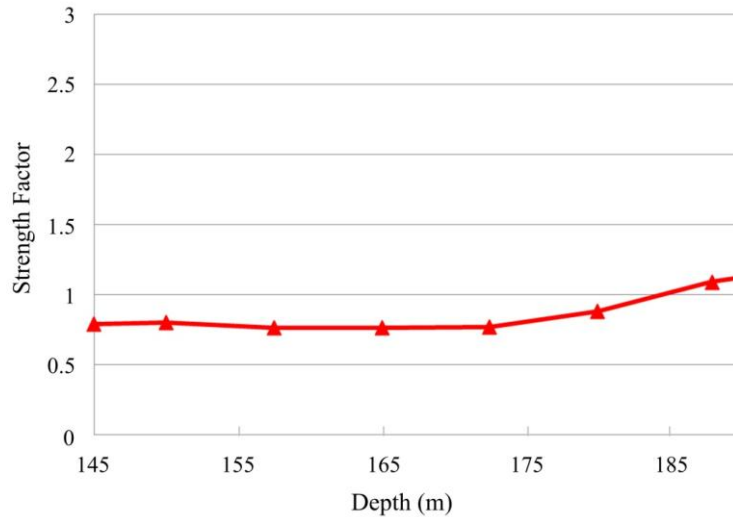

Fig. 4 Strength factor of shaft lining near aquifer after drawdown.

The strength factor of shaft lining near the aquifer which has a stress concentration is shown in **Fig. 4**. The result shows that there is a high risk of shaft lining rupture occurrence which is near the aquifer. Also, deeper than 180 m, the stability of shaft lining is raised and the risk of rupture is reduced.
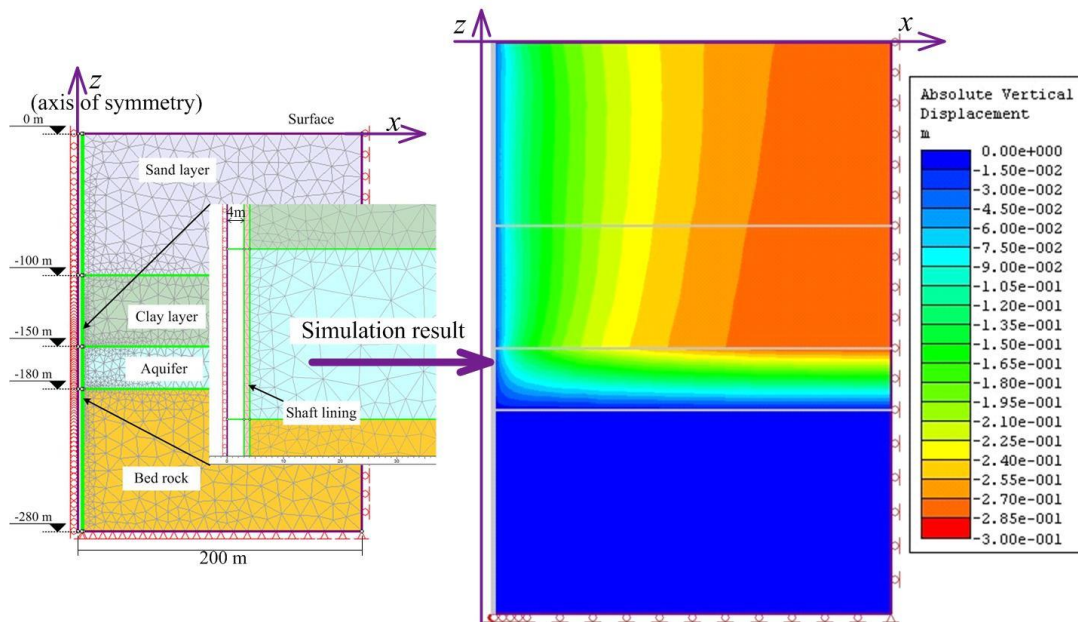

Fig. 5 Vertical displacement after aquifer drainage.

The subsidence of the strata, which is shown in Fig. 5, is considered to be the possible cause of stress concentration and lower safety of shaft lining. The axis z is the symmetric axis of the axisymmetric model and it indicates the direction of the vertical displacement. The axis x indicates the direction of ground surface away from the shaft. The vertical displacement happened after the aquifer drainage and was of downward displacement. For the depth less than 150 m, the displacement of each layer was obvious changed with the distance from the shaft lining.

Figure 6 shows the vertical displacement changes with distance to shaft lining at a 150 m depth. The displacement in the shaft lining was small and less than 0.05 m at this depth. Also, as the distance to the shaft lining increased, the displacement of each layer increased. The displacement 100 m away was about 5 times the displacement of the shaft lining. Also, at more than a 100 m distance, the change of displacement became small.
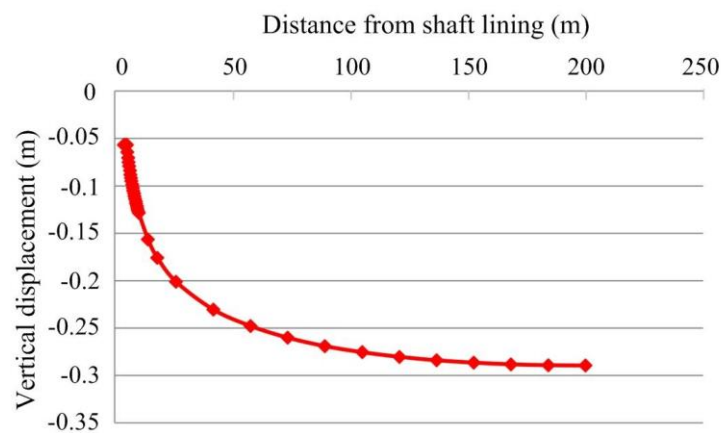

Fig. 6 Vertical displacement with distance to shaft lining (150m depth).

From the above analysis, the mechanism of shaft lining rupture can be described as follows: the lowering of water level causes voids appearing in the aquifer and the upper layer subsidence happens due to natural voids filling. Then, the stress concentration which happens in shaft lining is driven by the subsidence of the strata. As the subsidence happens in the upper of the aquifer and upper layer, the stress concentration reaches the maximum value in the shaft lining near the interface of the aquifer and bedrock. Therefore, shaft lining rupture is considered to occur at this location.

3.   Methods and Mechanism of Shaft Lining Treatment

As the interaction between the alluvium and shaft results the shaft lining rupture, there are two different ways of treatment: shaft lining reinforcement and strata reinforcement.

3.1 Shaft lining reinforcement

Shaft lining reinforcement is doing treatments on the shaft lining directly using methods such as the sets of wall method and stress-relief slot method.

3.1.1 Sets of wall method

This method is to reinforce the shaft lining directly, as shown in **Fig. 7**. Its mechanism is to improve the bearing capacity of shaft lining and against additional stress. It is quick to work on, but

the part of shaft lining without reinforcement will rupture as the increasing of additional stress. Therefore, this method has the initial function on anti-permeable and reinforcement and can not solve the problem from the root. Generally it is used in combination with other treatment methods.
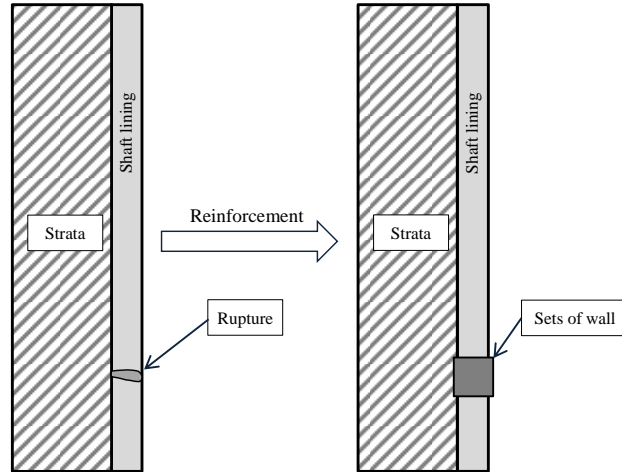

Fig. 7 Sketch of sets of wall.

3.1.2 Stress-relief slot method

This method is to cut a groove on the shaft lining and fill compressible materials into it, as shown in **Fig. 8**. Its mechanism is to unload additional stress by the materials' compression. It can prevent the stress concentration of the shaft lining up to the compression limit of the materials. As consolidation of the surrounding soil is a long term process, this method just plays a role in a short period.
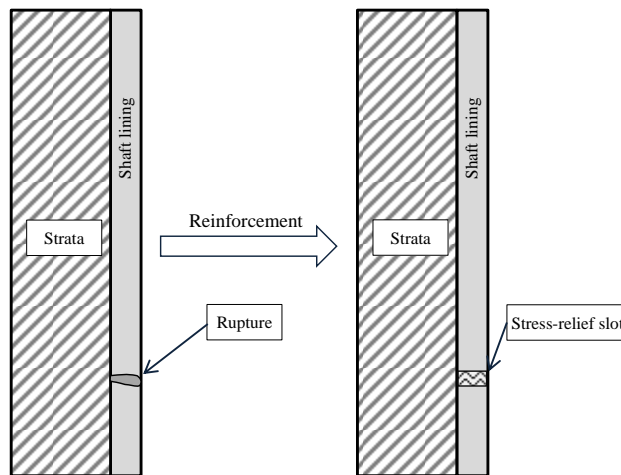

Fig. 8 Sketch of stress-relief slot.

3.2 Strata reinforcement

Strata reinforcement is mainly reinforcing the aquifer around the shaft lining by grouting. Up to now, there have been two grouting methods for strata reinforcement of grouting behind segment and strata grouting[14].

3.2.1 Grouting behind segment

This is a method of boring a hole in the shaft lining from inside to outside and injecting the grout into the soil behind the shaft lining for leaking stoppage and reinforcement, as shown in **Fig. 9a**. The main works and major operations are to be carried out within the shaft. Usually the work platform is temporary put up on the upper part of the cage and the skip. The merit is the broken parts can be observed and the reinforcement can be quickly carried out in the correct position. The drawbacks are the works are operated in the shaft and it is not safe and intermitting the mine production by occupying time and space. This method is mainly used for wall leakage control and combination with other reinforcement methods.
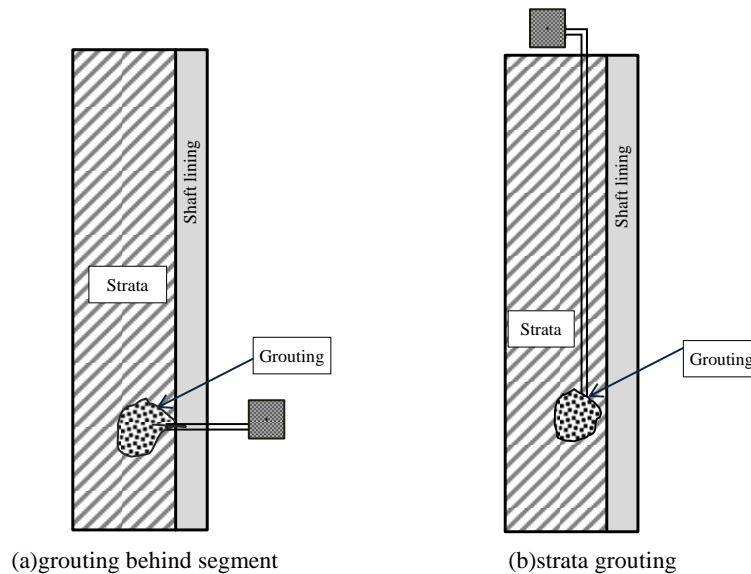

(a)grouting behind segment   (b)strata grouting

Fig. 9 Sketch of grouting method.

3.2.2 Strata grouting

Strata grouting is a method that requires drilling into the ground around the shaft and grouting through the casing into strata near the rupture location. Essentially, this method is drilling a hole around the shaft and must use directional drilling technology. The borehole must reach the precalculated position in the bottom aquifer and then the grout can be injected into the soil to fill the soil pores, compact and compress the soil and cemented soil particles.

Simulation and observation of strata grouting method shows that it has the functions to restrain and release the additional vertical force by stratum reinforcement[15]. It can improve the soil modulus of consolidation compression, thus the rate of additional vertical stress growth with time or water pressure drop can be reduced. This is called restrain function. In another aspect, the grouting makes the soil stratum move upward around the shaft, and the compressive stress within the shaft lining is reduced to some extent. This is called release function. Strata grouting is a positive reinforcement technique to control shaft lining rupture.

3.3 Comparison of different methods

The way of directing reinforcement shaft lining has the effect to enhance the strength of shaft lining for resisting additional forces or release the additional forces on the shaft lining. However, the basic cause of shaft lining rupture, additional force, is not eliminated. The additional force will increase with the bottom aquifer drainage and shaft lining rupture will occur again.

The way of reinforcing strata is to change the property of the strata, reinforcing the aquifer by grouting. Although, the grouting has the functions to restrain and release the additional vertical force, it may cause damage to the shaft lining on the opposite side. The shaft lining will bear the overload non-uniform horizontal stress by improper selecting of grouting range or grouting technology. The impact of grouting pressure on shaft lining is obvious and is a serious problem for shaft lining stability[16].

Therefore, a new method for shaft lining rupture treatment is proposed which is the underground continuous impervious curtain (UCIC). This new method is supposed to have the effect of preventing water flow and stress concentration in shaft lining, and furthermore, no impact or less than the grouting method.

4.   Underground Continuous Impervious Curtain for Shaft Lining Rupture
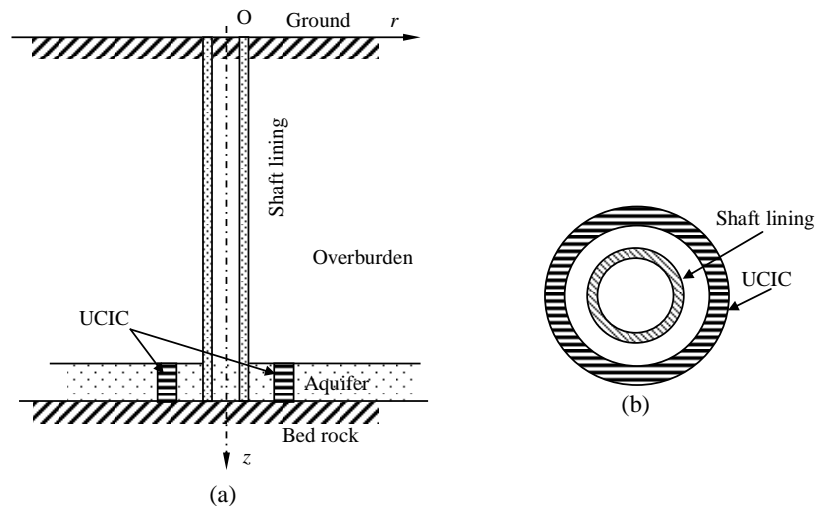
4.1 Reinforcement mechanism

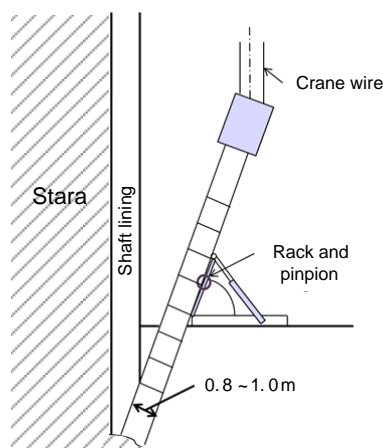**Fig. 10** Design of UCIC for shaft lining treatment.

Fig. 11 Field application schematic of CCC.

Underground continuous impervious curtain (UCIC) is an underground wall that has anti-seepage capacity. This method for shaft lining rupture treatment is based on the mechanism of

shaft lining rupture and borrows ideas from existing treatment methods, such as strata grouting[17]. The UCIC is constructed outside of the shaft lining in a certain area, adopting the vertical cutting mixing technique (CCC)[18], and mixing cement grout with soil or concrete to be a wall. The UCIC is designed as shown in **Fig. 10**. Also, the application schematic of the CCC is shown in **Fig. 11**.

The UCIC is assumed to construct in the bottom aquifer, can interrupt the connection with the seepage path, and eliminate the effect of bottom aquifer drainage to shaft lining. Furthermore, the UCIC has the strength to reinforce the aquifer around the shaft lining so that the effect of subsidence can be decreased and the additional force can be removed from this point.

4.2 Model for numerical simulation

In order to certify the UCIC has the effect of avoiding the stress concentration in shaft lining, which is considered to be caused by the aquifer drainage, the range of application and other changes of the UCIC were analyzed using numerical methods.
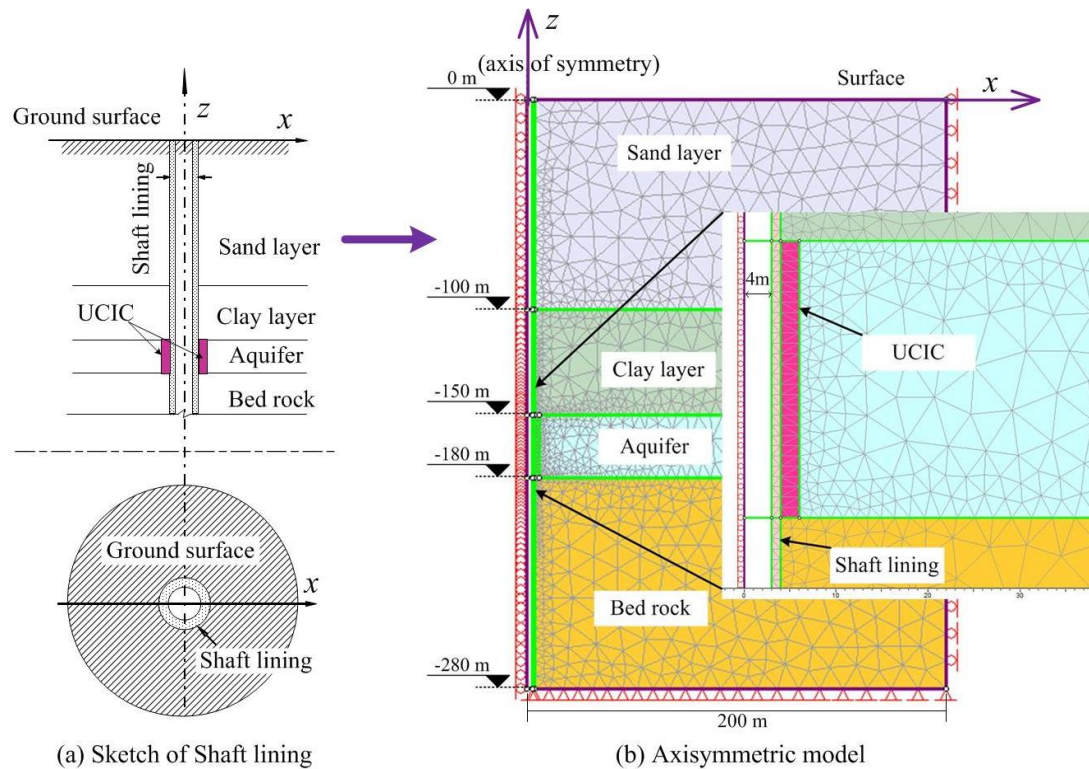

(a) Sketch of Shaft lining   (b) Axisymmetric model

Fig. 12 Axisymmetric model of numerical simulation for shaft lining treatment with vertical UCIC.

The analysis model is shown in **Fig. 12**. This model has the same geology layer like the former model, and the UCIC is built in the aquifer layer around the shaft lining. Under the situation of aquifer drainage, the effect of the UCIC on shaft lining was compared with no reinforcement situation. At first, the effect of UCIC was analyzed in different ranges in this model. After that, the actually constructed UCIC which is the triangular UCIC, shown in **Fig.13**, and the proper angle of inclination for the UCIC were also analyzed.
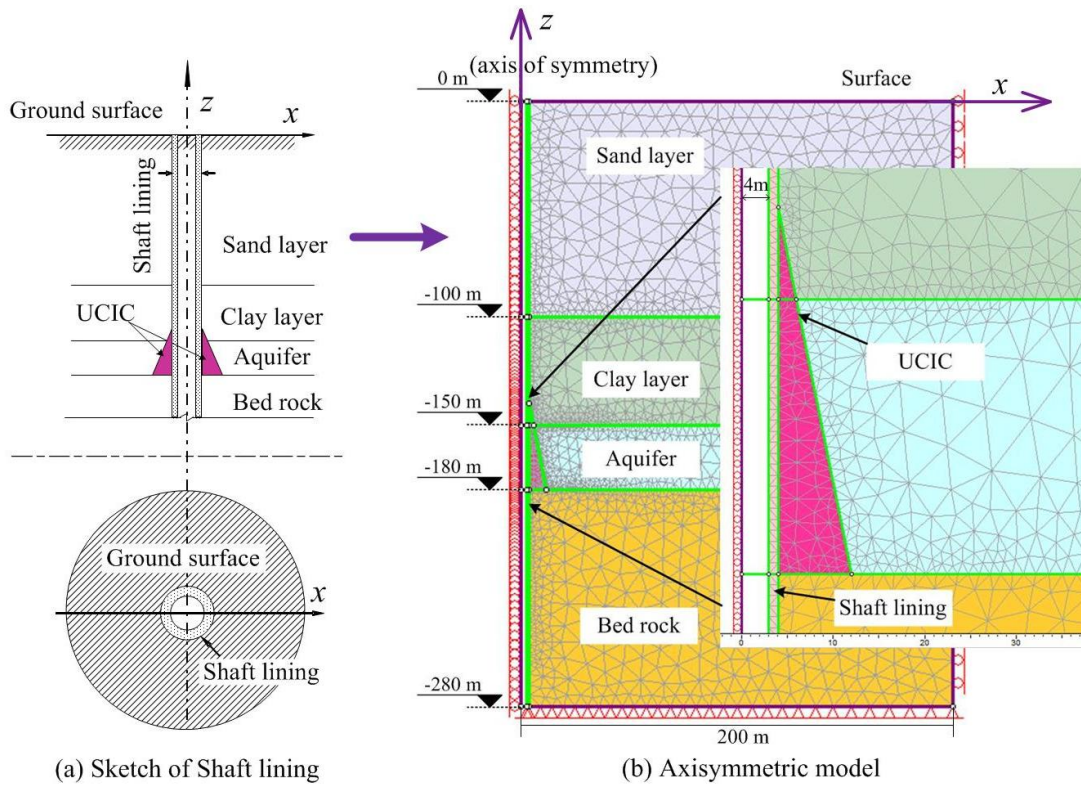
(a) Sketch of Shaft lining   (b) Axisymmetric model

Fig. 13 Axisymmetric model of numerical simulation for shaft lining treatment with triangular UCIC.

The mechanical properties of UCIC are shown in **Table 2**, and the other layers mechanic properties are the same as **Table 3**.

Table 2 Mechanical properties of UCIC.

Parameters	UCIC
Young' module (MPa)	2.0×10^4
Poisson's ratio	0.25
Angle of internal friction (deg)	35
Cohesion (MPa)	35
Unit weight (MN/m^3)	0.02
Tensile strength (MPa)	10.5

The applied range of UCIC used in analyses is shown in **Table 3**.

Table 3 Apply patterns of UCIC.

Patterns	Height (m)			Width (m)
	In aquifer	Above aquifer	Under aquifer	
Pattern A	30	—	—	1.0
Pattern B	30	—	—	5.0
Pattern C	30	10	10	1.0

The tilt direction of apply pattern is shown in **Table 4**. The different angle of the UCIC is examined in the analysis.

Table 4 Apply patterns at different angles.

Patterns	Angles (°)	Height (m)	
		In aquifer	Above aquifer
Pattern D	0	30	10
Pattern E	15	30	10
Pattern F	45	30	10

4.3 Analysis results and discussion

4.3.1 Effect of reinforcement by applying UCIC

The maximum principal stress state in shaft lining in different situations is shown in **Fig. 14**. From the figure, when the UCIC was built around the shaft lining, the stress concentration due to the aquifer was restrained, and the effect of UCIC was obvious. According to the previous study, the reason of the stress concentration is surrounding ground settlement due to the aquifer drawdown. It can be concluded that the UCIC has an effect to sever the connection between the shaft lining and the aquifer.
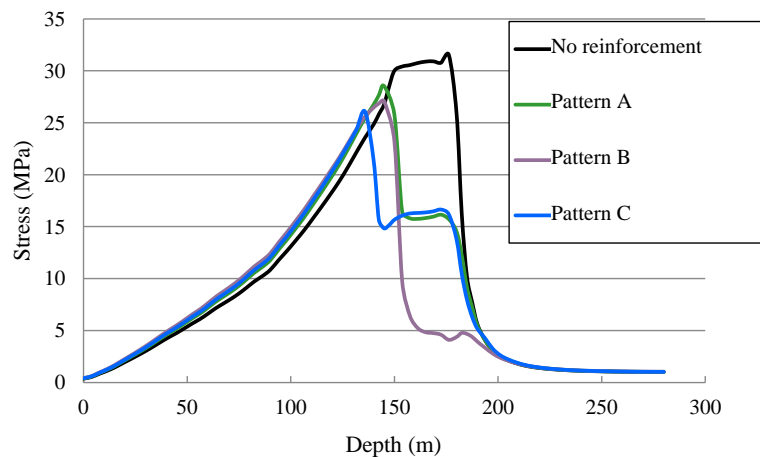
Fig. 14 Maximum principal stress state after aquifer drawdown.

However, in Pattern A, in which the width of the UCIC was 1m, stress concentration still occurred in the shaft lining near the boundary between the clay layer and the aquifer layer, but the stress became small. In Pattern B, the width was changed to 5m, the stress in shaft lining near the aquifer layer was greatly decreased, meaning the UCIC has an effect to strain the stress increases like in the bedrock layer, and the effect depends on the thickness of the UCIC. However, the stress concentration was the same as Pattern A. In Pattern C, the UCIC extended into the above layer and the under layer, the width was 1m, the stress concentration had a little relief, and the stress in the shaft lining became smaller. Furthermore, the stress concentration peak had a trend to move forward, meaning the existence of the UCIC also has an effect to transform the stress concentration to avoid ruptures occurring in the aquifer range, and then reduces the risk of water seepage in the shaft lining as the rupture location transforms into the impermeability layer.

Figure 15 shows the strength factor changes after the drawdown. In a no reinforcement situation, the strength factor of shaft lining through the aquifer layer is below the value of 1.0. In Pattern C, the strength factor raised to exceed the value 1.0, which means that the shaft lining was improved through the aquifer layer. Therefore, the UCIC should be built into the aquifer and also

the above layer, which can transform and release the stress concentration in the shaft lining and reduce the risk of shaft lining rupture.
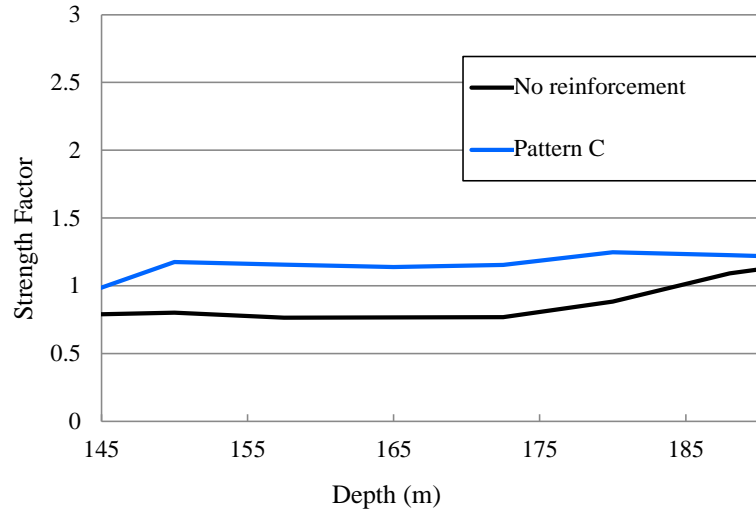

Fig. 15 Strength factor after drawdown.

4.3.2 Effect of UCIC at different angles

As shown in **Fig. 11**, the vertical UCIC cannot be constructed from the inside of the shaft by using CCC. So, the effect of tilt angles on the reinforcement by UCIC is discussed. **Figure 16** shows the maximum principal stress changes in shaft lining as the UCIC applying at different angles. The vertical direction is 0°, and the tilt angles are 15° and 45°. From this figure, it can be seen that different tilt angels have no obvious impact on the reduction of stress concentration in shaft lining and their effects of UCIC are almost the same as that of vertical one. However, from the cost points of view, the smaller tilt angle is the better because the area of UCIC becomes to be small.
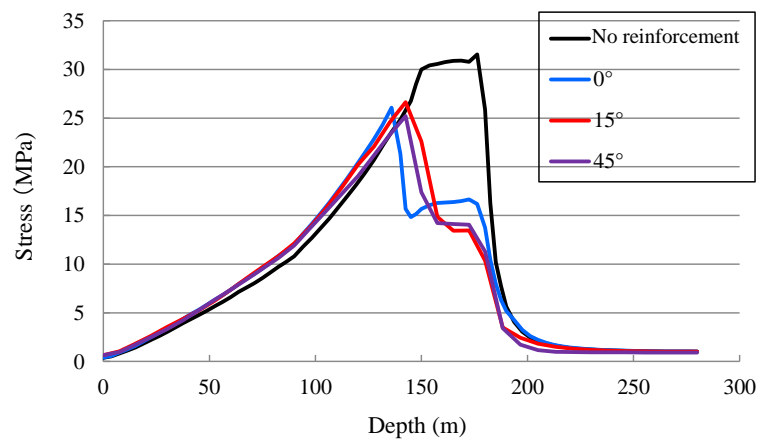

Fig. 16 Maximum principal stress state after aquifer drawdown (UCIC in tilt direction).

4.4 Summary

From the results of a series of numerical analyses, it can be seen clear that the application of UCIC can reduce the stress concentration in shaft lining while built in the bottom aquifer. The UCIC also has the effect to transform the stress concentration to avoid ruptures occurring in the aquifer range and then reduce the risk of water seepage in the shaft lining as the rupture location transforms into the impermeability layer. Therefore, it can be concluded that the UCIC is an effective method to reinforce the shaft lining and able to be used in actual application.

5.   Conclusion

In this study, the mechanism of shaft lining rupture was analyzed using numerical simulation and compared with the current treatment methods, the UCIC was proposed for the shaft lining, and then the effect of the UCIC method was discussed and analyzed. From a series of numerical simulations and analyses, the main results can be summarized as follows:

(1) Shaft lining rupture occurs near the interface of the aquifer and bedrock, and the stress concentration in the shaft lining is driven by the subsidence of strata. The lowering of water level causes voids to appear in the aquifer, and the upper layer subsidence happens due to natural voids filling.

(2) There are two types and four kinds of methods for shaft lining reinforcement. The way of direct reinforcement shaft lining: Sets of wall method and Stress-relief slot method. For the basic cause of shaft lining rupture additional force is not eliminated. The way of reinforcing strata: grouting behind the segment and strata grouting. The impact of grouting pressure on shaft lining is obvious and is a serious problem for shaft lining stability.

(3) The underground continuous impervious curtain (UCIC) as a new treatment method is proposed for the shaft lining rupture. The UCIC can reduce the stress concentration in shaft lining while built in the bottom aquifer. The UCIC also has the effect to transform the stress concentration to avoid ruptures occurring in the aquifer range and then reduce the risk of water seepage in the shaft lining as the rupture location transforms into the impermeability layer.

(4) The tilt UCIC applied in the aquifer had the same results as the simulation of vertical UCIC. Therefore, the UCIC is effective to reinforce the shaft lining and able to be used in actual application.

Acknowledgements

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