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Research Article

Vertical Shaft Support Improvement Studies by Strata Grouting at Aquifer Zone

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The shaft lining failure which occurs in deep alluvium is a sudden coal mine hazard. The strata grouting is one of the treatment methods for the shaft lining failure. To investigate the impact of grout injection pressure on the shaft lining, the field measurement and the numerical analysis of the shaft lining stress variation during the grouting were conducted. To improve the strata grouting, the underground continuous impervious curtain (UCIC) is proposed as a new method by using the chain conveyor cutter technique without the impact on the shaft lining. The effects of the new method were also analyzed by means of the numerical methods. The results show that the strata grouting in the deep alluvium needs a high injection pressure, and in the horizontal direction, the shaft lining sustains the repeat tensile and compressive force during the grouting process. The negative influence of strata grouting on the stability of the shaft lining is obvious and serious. The UCIC built around the shaft lining can restrain the stress concentration induced by the aquifer drawdown. The triangular UCIC has a similar effect as that of the vertical one, and the small angle is better for preventing the shaft lining failure.

1. Introduction

Coal mining operation caused many problems such as ground settlement, shaft lining instability, surrounding strata deformation, aquifer leakage, rock burst, and water inrush [1–9]. Among them, serious shaft lining failures have often occurred in the eastern part of China, such as Datun, Xuzhou, Huaibei, Huainan, Yanzhou, and Yongxia, since 1987 [10]. The shaft lining failure which occurs in deep alluvium is a sudden coal mine hazard. The number of failure shafts and their large ranges have never been seen before in Chinese mining history and are also rare in the world. During the mining process, the failure of the shaft lining is a serious hazard to mining operation and mine safety. The main feature is that the part of the shaft lining which passes through the aquifer has the most serious deformation and failure even though under the condition of enough shaft pillars left around the shaft [11]. The settlements of the mining fields which happened near the shaft lining failure were about 0.2–0.5 m, and it increased with increasing the distance from the shaft. When shaft lining failure occurs, the inner shaft lining delaminates and spalls, longitudinal steel bows inward, transverse cracks form and intersect in the horizontal direction along circle, seepage occurs or even sand gushes, and mostly seriously, concrete blocks fall out and may damage the equipments in the shaft. In addition, the shaft bends up; cage guides, drainpipes, and pressure ventilation pipes are in longitudinal bending; and in serious cases, the cage is stuck due to torsional deformation [12]. Thus, the shaft lining failure has a serious impact on the operation of the coal mine and the safety [13].

After many years' researches, the mechanism of the shaft lining failures has become clear. The vertical additional force theory is described as follows. There is a thick bottom soil aquifer under the steady impermeable layer, and the aquifer is in direct contact with the weathered rock which is in the top of bedrock in all broken shafts. The special mining activities and the artificial drainage cause the water levels drop in the soil aquifer. According to the drop of water level in the aquifer, the stratum of aquifer deforms and then the effective stress increases in the aquifer. This can lead to consolidation of the soil strata and subsidence of the surface. During the process of strata settlement, the soil layer imposes a vertical additional force on the outer surface of the shaft. While the vertical stress increases gradually to its limitation, the shaft lining cannot resist the force and then fails. The failure mostly occurred near the interface between aquifer and bedrock, sometimes in the alluvium a few meters above the bedrock [14–17]. Many results of shaft lining destructive tests and the data of in situ experiment conducted in mining areas of Huaibei, Xuzhou, and so on, confirmed the existence of vertical additional force and its influence on the shaft lining failures [18–20]. Many researchers did a lot of work on the laboratory test and field test to verify this theory and made a great achievement.

As these subsidence might be related to the bottom aquifer drainage and consolidation settlement, the most important and difficult task is how to prevent the shaft lining from the effect of the aquifer drawdown in deep alluvium. The study on the mechanism of shaft lining failure and its treatment practices were started in Zhangshuanglou coal mine and Kongzhuang coal mine [20, 21]. Since 1995, in Yanzhou area, the strata grouting has been applied to the treatment for the shaft lining failure [22]. Cui and his research group conducted the treatment in Zhangshuanglou coal mine and applied the strata grouting method to repair the shaft lining failure in Baodian coal mine [23]. The strata grouting is a positive reinforcement technique to control the shaft lining failure [24–26]. However, the negative influence of the strata grouting on the shaft lining is obvious and large [27]. Moreover, due to the grouting process is in the soil layer, the effect of the injection pressure on the shaft lining depends on the actual formation conditions and the treatment effect cannot be guaranteed [28, 29]. It is necessary to establish a new method for the failure treatment which has the effect of the strata grouting and not the negative influence.

In this paper, grouting pressure impaction on the shaft lining is analyzed by means of field investigations and numerical methods. Then, the underground continuous impervious curtain (UCIC) is proposed as an improvement for the strata grouting, and the effects of the UCIC are analyzed by means of the numerical methods. After that, the different angles which the UCIC is constructed and the appropriate angle for the UCIC construction are discussed.

2. Analysis of Impaction of Grouting Pressure on Shaft Lining

Strata grouting for shaft lining treatment requires drilling into the strata around the shaft and grouting though the casing into the aquifer near the rupture location. The borehole must reach the predesigned locations in the bottom aquifer, and then the grout is injected into the soil to fill the soil pores, compact and compress the soil, and cement soil particles. Up to now, there are mainly two grouting methods for strata reinforcement: one is grouting behind the segment, and the other is grouting from the surface (Figure 1) [30].

The strata grouting in deep alluvium needs a high injection pressure. In the aquifer, the water pressure is high due to the confined aquifer, and the injection pressure needs to be higher than the water pressure. So, the risk of shaft lining failure is raised due to the influence of the injection pressure on the shaft lining. Though the strata grouting has the functions to restrain and release the additional vertical stress, it may cause the damage to the shaft lining inversely. In some cases, due to the improper control of the injection pressure and the uncertain distribution of the fracture, the leakage of grouting material or even more the failure would occur in the shaft lining (Figure 2). Therefore, the impact of grout injection pressure on the shaft lining needs to be investigated.

2.1. Field Measurements. Yang et al. conducted the field measurements in the main shaft of Baodian coal mine in order to obtain the distribution of strains of the shaft lining during the grouting process in 2000 [27]. The net diameter of the main shaft in Baodian mine was 6.5 m, and the thickness of the shaft lining was 1.0 m. The thickness of alluvium was 148.69 m, and it contained 3 aquifers. The bottom aquifer was important to the mine, and the water level was affected by mining. The failure location was at −136 to −144 m depth, and the grouting range was −93.5 to −149.0 m depth. The target layer of grouting was mainly the sand layer and the occasional clay layer. The initial grout injection pressure was 2–4 MPa, and the maximum pressure and the end pressure were less than 6 MPa. The sites of grouting holes Z1–Z10 and the layout of concrete strain meters $1^{\#}$–$8^{\#}$ in the inner shaft lining are shown in Figure 3. The strain meters were set at four measuring levels, the first level was at −92.5 m depth; the second one was −116.5 m depth; the third one was −129.5 m depth; and the fourth one was −148.5 m depth.

Figure 4 shows the horizontal circumferential strain curves of the measuring points during alternately grouting in −129 to −131 m depths (Z5 and Z7). From the curves obtained, when grouting was conducted in Z5, the strain meter $4^{\#}$ had the relative tensile strain at the third measuring level, and the other side strain meter $6^{\#}$ at the third measuring level had the relative compressive strain. On the other hand, when grouting was conducted in Z7, the relative tensile strain was measured in strain meter $6^{\#}$ and relative compressive strain was measured in strain meter $4^{\#}$.

Two tensile zones and two compressive zones were observed in the inner margin. Two tensile zones were generated at neighborhood and remote area of the grouting hole. The central angle of the compression zone or tensile zone was about 90°. From the results, it can be concluded that the shaft lining would bear the overload nonuniform horizontal stress by the improper selecting of grouting

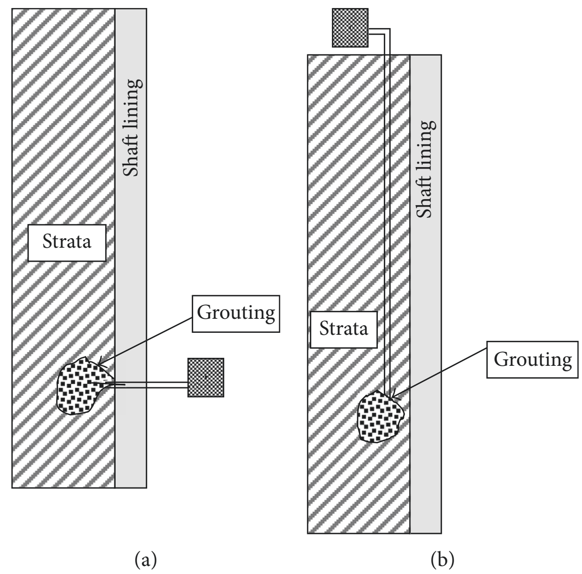

Figure 1: Sketch of the grouting method. (a) Grouting behind segment. (b) Grouting from surface.

Figure 2: Leakage and failure during the grouting.

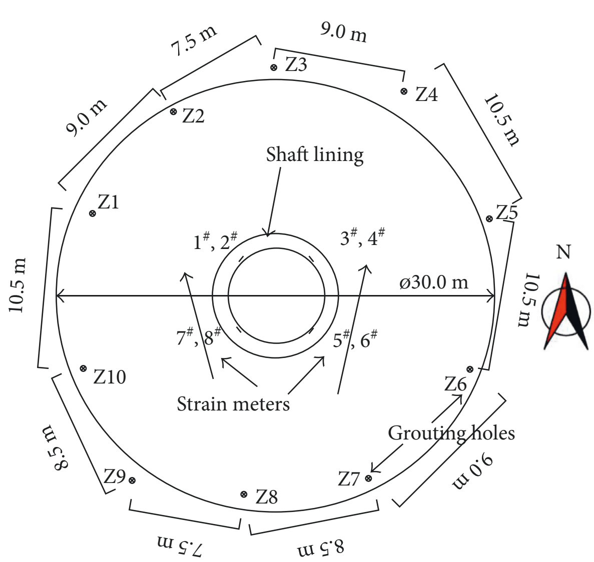

Figure 3: Sites of grouting holes and layout of concrete strain meters [27].

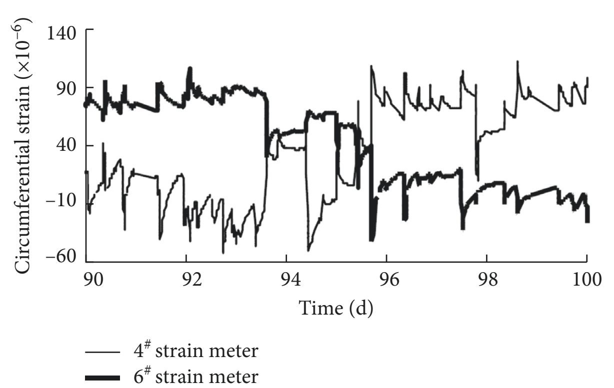

Figure 4: Circumferential strain curves during alternately grouting at the third measuring level [27].

positions or grouting orders. However, as the field measurements of the strain change during the grouting process, it is necessary to study about the stability of the shaft lining during the grouting process in detail.

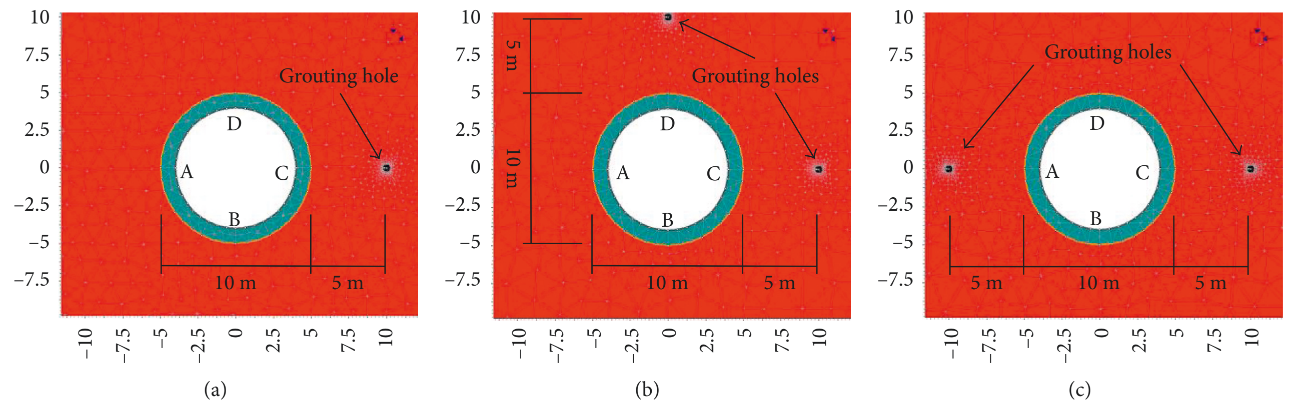

Figure 5: Geometry model of grouting around the shaft lining. (a) Single hole grouting. (b) Double holes grouting (90°). (c) Double holes grouting (180°).

Table 1: The mechanical parameters of the aquifer, the shaft lining and the interface [12, 27].

Element type	Shaft lining	Aquifer	Interface	
Elastic modulus (MPa)	20,000	42	Normal modulus (MPa)	100
Poisson's ratio	0.15	0.3	Shear modulus (MPa)	100
Interior friction angle	35°	20°	20°	
Cohesion (MPa)	35	0.04	0.03	

2.2. Simulation of Grouting Pressure Impaction. Finite element software is used to simulate the impact of grouting pressure during the grouting process. Phase^2 7.0 is a 2D elastic-plastic finite element analysis program for underground or surface excavations in rock or soil [31]. Three geometry models (Figure 5) are established, and the initial grouting pressures are set at 2 MPa, 4 MPa, 6 MPa, and 8 MPa. The mechanical properties of the aquifer, the shaft lining, and the interface used in these analyses are shown in Table 1 [12, 27]. As the stress accumulates around the inner lining, the values of the deviatoric stress (a condition in which the stress components operating at a point in a body are not the same in every direction. Also known as differential stress) along the circumference of the inner lining are used to evaluate the influence of grouting pressures on the shaft lining as shown in Figure 6.

From this analysis, some important results are obtained as follows:

(1) Single hole grouting (Figure 6(a)): The deviatoric stress is small in the shaft lining at the nearest point to the injected hole (at point C) and the opposite position (at point A). The stress in other areas is higher than these two points, and the peak stress is observed at points B (5.8 MPa) and D (4.7 MPa) near the 90° central angle to the lowest stress area. As the grouting injection pressure is increased, the stresses in zones A and C are decreased due to the tension effect, and the ones in zones B and C are increased due to the compression effect. The maximum peak value between points B and C is 5.4 MPa, and this is a danger part of the shaft lining.

(2) Double holes grouting (90°) (Figure 6(b)): The deviatoric stress is small in the shaft lining at nearest points to the grouting holes (points C and D) and the opposite areas A and B. The stress in other area is higher than these points and the peak stress appears in the area of AD (4.6 MPa), BC (4.6 MPa), and CD (2.7 MPa). As the grouting pressure increases, the stresses at points C and D and area AB increase slightly due to the tensile effect, and the stresses in area AD, BC, and CD are increased due to the compression effect.

(3) Double holes grouting (180°) (Figure 6(c)): The deviatoric stress is small in the shaft lining at nearest points to the grouting holes (points A and C), and in other areas, the stresses are higher than the two points. It can be seen that as the grouting pressure increases, the stresses at points A and C are increased due to the tension effect, and the stresses in other areas are increased due to the compression effect.

The minimum principal stresses in the shaft lining in the three models are shown in Figure 7. From the results obtained, tensile stress acts in the minimum principal stress plane during the grouting process. And as the grouting pressure is increased, the tensile stress increased in the zone for which the deviatoric stress is low. Although the deviatoric stress is low, it is still not safe for the shaft lining. Comparing the results of the three grouting positions in Figure 5, the minimum deviatoric stress is appeared in the zone near the injected hole; the peak stress in the second grouting position is less than that for two other grouting positions; when the injected holes are distributed in a row, much more peak stresses appear, and these have a large impact on the shaft lining. For example, in Figure 7(c), the points A and C of the shaft lining are easy to fail.

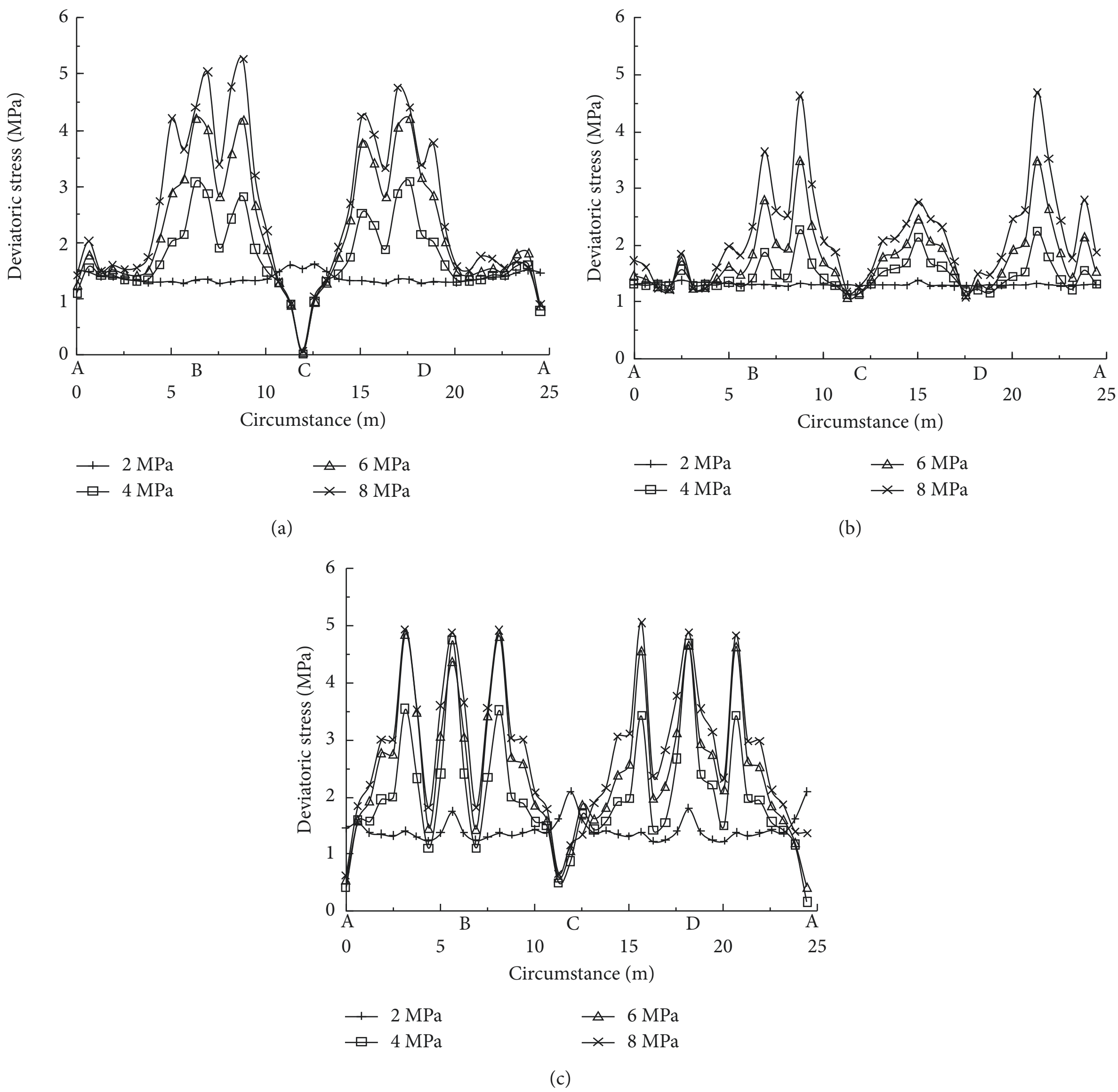

Figure 6: Deviatoric stress changes along the circumference of inner lining. (a) Single hole grouting. (b) Double holes grouting (90°). (c) Double holes grouting (180°).

The strata grouting in the deep alluvium needs a high injection pressure, and in the horizontal direction, the shaft lining sustains the repeat tensile and compressive force during the grouting process. And the grouting pressure is difficult to be controlled due to the complex geological conditions. The negative influence of the strata grouting on the stability of the shaft lining is obvious and serious. The risk of shaft lining failure due to the grouting method is high. Therefore, the grouting method is not a conclusive solution for shaft lining failure.

3. Measures for Improvements of Strata Grouting

3.1. Introduction of UCIC. Based on the results of an analysis of other methods and the mechanism of the shaft lining failure, a new method for shaft lining failure treatment which constructs the underground continuous impervious curtain (UCIC) is proposed. This new method is supposed to have an effect to reinforce the strata around the shaft such as the strata grouting, but the control of grouting range is easy; furthermore, the impact on shaft lining is lower than that of the grouting method. By using the chain conveyor cutter technique [32], the UCIC can be constructed uniformly in the strata as an underground wall that has the antiseepage capacity. This method for shaft lining failure has been developed based on the mechanism of shaft lining failure and from the existing treatment methods such as strata grouting and the previous shaft sinking method which is the concrete curtain method [33]. The concrete curtain method is to drill holes from the ground surface around the shaft zone and injects the concrete grout in order to form a cylinder

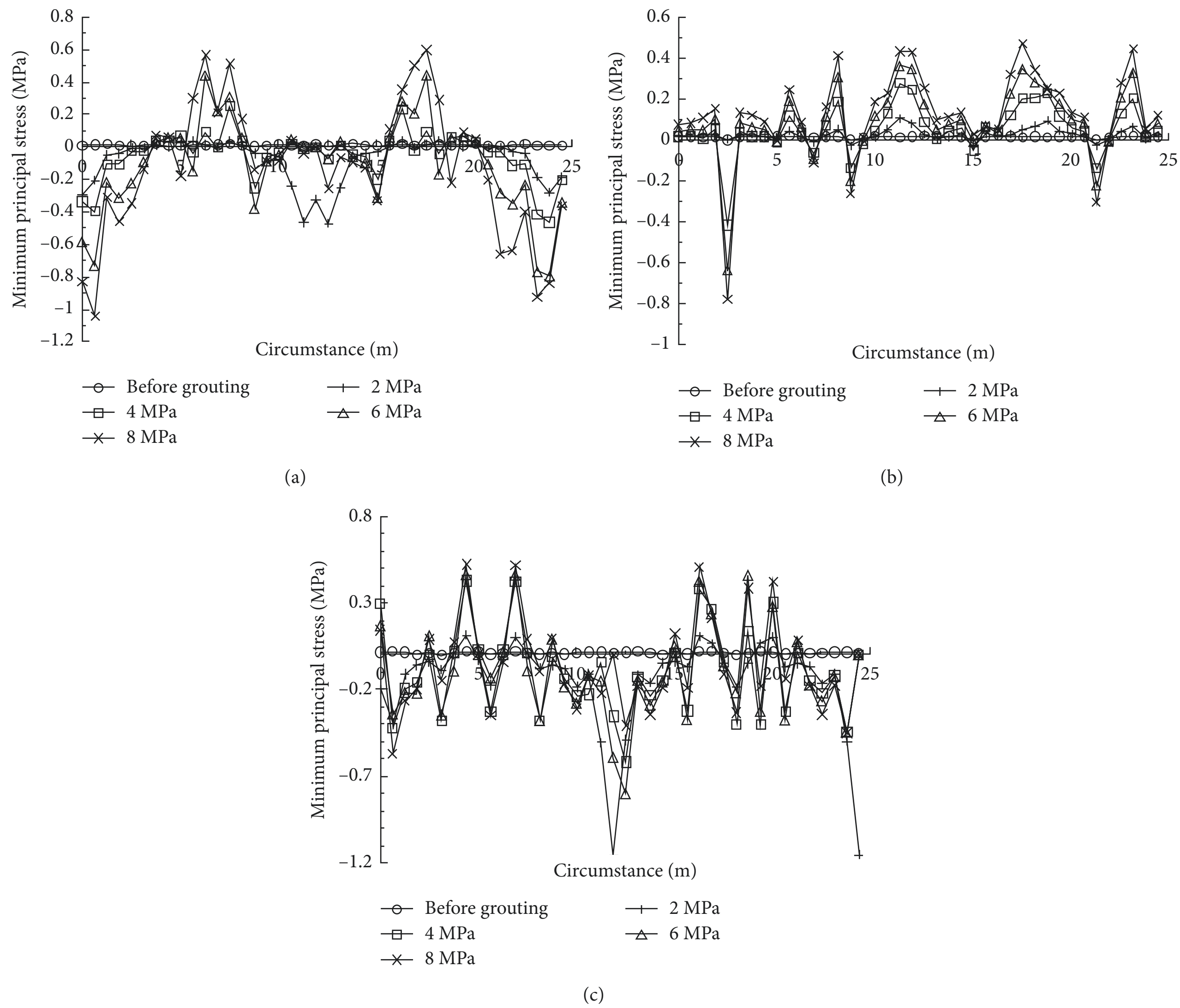

Figure 7: Minimum principal stress changes along inner lining. (a) Single hole grouting. (b) Double holes grouting (90°). (c) Double holes grouting (180°).

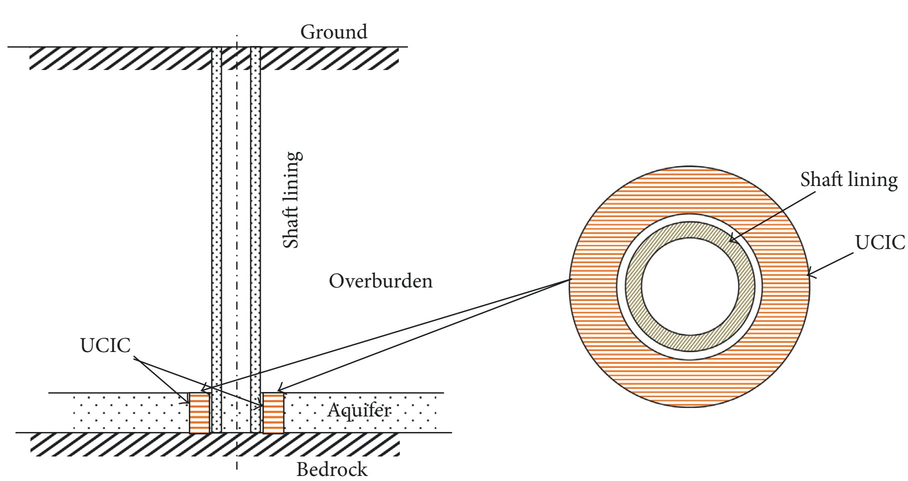

Figure 8: Sketch of the UCIC for shaft lining treatment.

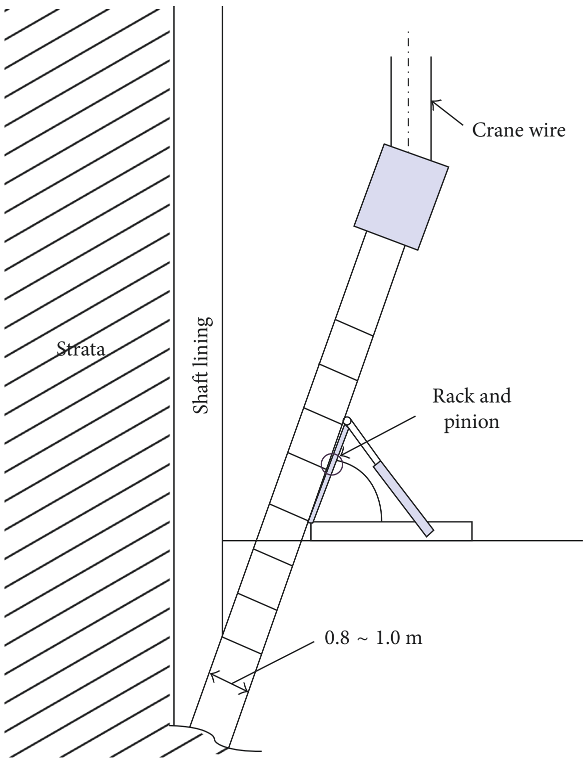

Figure 9: Field application schematic of the CCC.

concrete curtain around the shaft for supporting and waterproofing. From 1974 to 1980, this method was applied to about twenty shafts. However, the sinking depth of this method is less than 80 m, and it cannot be applied to the thicker alluvium shaft sinking.

The UCIC is designed outside of the shaft lining in a certain area, adopting the vertical cutting and mixing technique, chain conveyor cutter (CCC), and mixing cement grout with soil or concrete to be a wall, and the construction technique needs to be improved. The design of the UCIC is shown in Figure 8. The UCIC is a cylinder concrete curtain around the shaft, and it can be constructed uniformly by the CCC technique [32].

The CCC works in the gravity conditions, and when it is used for the shaft lining treatment, the angle of the CCC controlled by a rack and pinion as shown in Figure 9 is needed. In this research, the shaft passes through the deep aquifer layer which has a high water pressure. Therefore, the frozen method has to be applied as pretreatment in order to prevent the water outburst while excavating in the aquifer layer. For this reason, the construction procedure by the CCC is started after the aquifer is frozen.

3.2. Effect of UCIC. In order to clarify the effect of the UCIC for the improvement of the shaft lining, the effects of the UCIC are analyzed in different angles and widths by means of the numerical methods. Numerical simulation is an easy way to evaluate the different circumstances, and the results can be the theoretical guidance for the actual work. Finite element software, Phase^2 7.0, is used to simulate the reinforcement effect of the UCIC method. The analysis model used to imitate the geological condition is shown in Figure 10, and the mechanical properties used in the analysis are shown in Table 2. The parameters in this model are based on the geological data and the shaft construction data of Baodian coal mine where shaft lining failures occurred [12, 22, 23, 27]. The UCIC is assumed to be applied to this coal mine. In this simulation, the space between UCIC and shaft lining is left in order to eliminate the influence of the interaction between UCIC and shaft lining, and the appropriate angle for the UCIC construction is also discussed. The initial water level in the bottom aquifer is −25 m, and after the water level dropping, it changes to −45 m.

The numerical simulation is divided into two steps: The first step is to balance the stresses that act between the strata and the shaft lining under the initial stress, and the initial stress is generated by the gravity and the lateral pressure of strata. The second step is to drop the water level, and then the aquifer was consolidated interacting with the shaft lining by the additional stress.

The tilt directions of apply patterns are shown in Table 3. The influence of the angles of the UCIC is investigated in the analysis. The UCIC is constructed in the aquifer layer around the shaft lining. After the drop of water level, the effect of the UCIC on the shaft lining is discussed. As the stress accumulated around the inner lining, the values of the maximum principle stress in the shaft lining are used to evaluate the effect of the UCIC on the shaft lining.

The results of the effect of the treatment are shown in Figure 10. Figure 11 shows the maximum principal stress changes in the inner surface of the shaft lining as the UCIC was applied at different angles. It can be seen that a peak stress happens in the lower part of the bottom aquifer after the drop of water level. So, most of the shaft lining failures occur near this boundary. From those results, under the initial stress state, the maximum principle stress in the inner surface of the shaft lining increases with increasing the depth, and its magnitude changes dramatically near the boundary between the bottom aquifer and bedrock (180 m depth). The reason is that there is a big difference between their physical properties, so the stress occurs easily near this boundary. After the treatment, the stress consternation in the shaft lining near the boundary reduces. The UCIC built around the shaft lining can restrain the stress concentration (peak value decreases 15 MPa at least) induced by the aquifer drawdown obviously. According to the previous study, the reason of the stress concentration is that the settlement of the soil layer with drawdown has an obvious impact on the shaft lining. It can be concluded that the maximum principal stress can be decreased by using the UCIC to separate the shaft lining and the aquifer.

The vertical direction is 0°; the other angles are 15° and 45°. From Figure 11, the triangular UCIC constructed in the aquifer has the similar effect as that of the vertical one, and it can reduce the stress which affected the shaft lining through the aquifer layer. The stress concentration becomes smaller, and the stress reduces through the aquifer layer. However, from the practical point of view, the angle 15° instruction is better for preventing the shaft lining failure because of the few differences of the stress concentration.

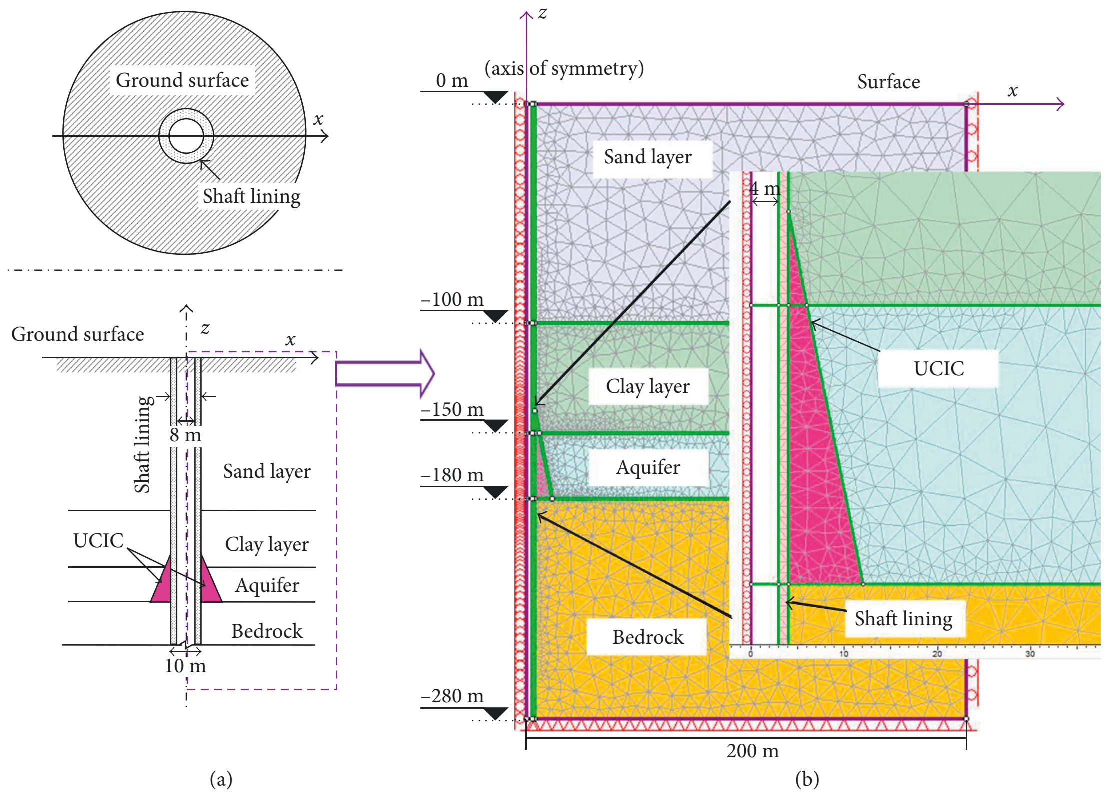

Figure 10: Axisymmetric model of shaft lining treatment with the triangular UCIC.

Table 2: Mechanical properties of strata layers and shaft lining.

Parameters	Sand layer	Clay layer	Aquifer	Bedrock	Shaft lining	UCIC
Young's modulus (MPa)	42	73.5	42	10,000	20,000	20,000
Poisson's ratio	0.3	0.3	0.3	0.25	0.15	0.15
Internal friction angle (°)	20	20	20	35	35	35
Cohesion (MPa)	0.03	0.035	0.04	11	35	35
Unit weight (MN/m^3)	0.021	0.021	0.22	0.027	0.03	0.03
Tensile strength (MPa)	0.06	0.07	0.075	6.0	16	10.5

Table 3: Apply patterns at different angles.

Patterns	Angles (°)	Height (m)		Base width (m)
		In aquifer	Above aquifer	
Pattern A	0	30	10	1
Pattern B	15	30	10	11.8
Pattern C	45	30	10	40

4. Conclusions

The strata grouting is one of the treatment methods for the shaft lining failure, and the impact of grout injection pressure on the shaft lining should be paid attention to and is investigated. The field measurement and the numerical analysis of the shaft lining stress variation during the grouting were conducted. An improvement method for the strata grouting is proposed. The effects of the new method were also analyzed by means of the numerical methods. The following specific conclusions can be drawn:

(1) The strata grouting in the deep alluvium needs a high injection pressure, and in the horizontal direction, the shaft lining sustains the repeat tensile and compressive force during the grouting process. The grouting pressure is difficult to be controlled due to the complex geological conditions. The negative influence of the strata grouting on the stability of the shaft lining is obvious and serious. The risk of shaft lining failure due to the grouting method is high.

(2) The underground continuous impervious curtain (UCIC) is proposed as a new method for improvement

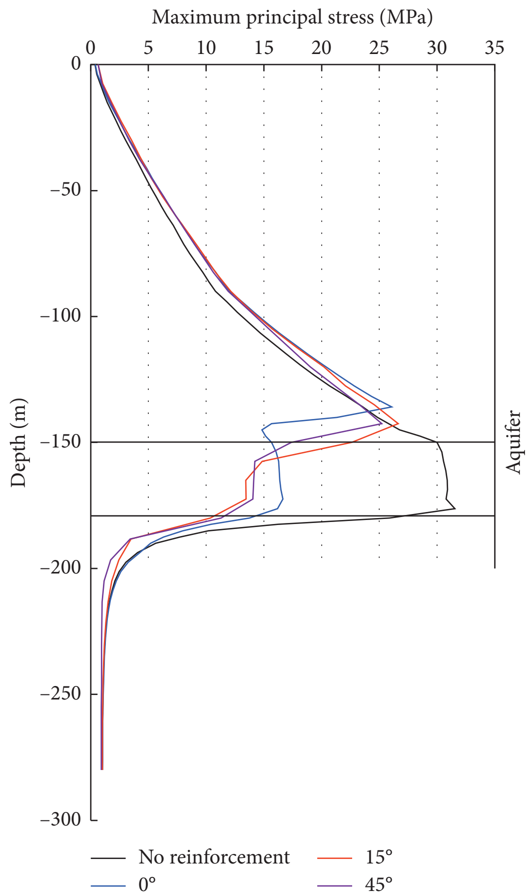

FIGURE 11: Maximum principal stress state after aquifer drawdown (UCIC in tilt direction).

of strata grouting; the UCIC is a cylinder concrete curtain around the shaft and can be constructed uniformly by using the chain conveyor cutter technique without the impact on the shaft lining.

(3) The UCIC built around the shaft lining can restrain the stress concentration induced by the aquifer drawdown. The triangular UCIC has the similar effect as that of vertical one and the small angle is better for preventing the shaft lining failure.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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