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# Treatment effect investigation of underground continuous impervious curtain application in water-rich strata

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ABSTRACT

Serious shaft lining failures often occur when shaft linings are constructed by passing them through the deep topsoil of Quaternary strata. This approach also leads to the formation of an aquifer at the bottom. Based on the theory of the additional stress which is the main reason for these failures, this study focuses on the treatment effect of underground continuous impervious curtain (UCIC) in terms of different factors, namely, the location, shape, range, and width, by using numerical simulation. Results show that the UCIC can reduce the stress concentration in the shaft lining formed in the bottom aquifer. The UCIC can also reinforce the shaft lining at different angles and can be applied in actual situations. The strength factors of the inner surface of the shaft lining increase after the UCIC are used. The material strength and width of the UCIC show an obvious effect on the stability of the shaft lining. Results proved that the UCIC could effectively strengthen the stability of the shaft lining when it was built in the aquifer or built in the aquifer and above and below the layer.
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## 1. Introduction

Serious shaft lining failures often occur in shafts constructed more than 10 years ago in eastern China (since 1987 [1–4]). All these shaft linings are constructed in similar geological conditions and have passed through the deep topsoil of Quaternary strata, approximately 100 m to 200 m thick; furthermore, an aquifer more than 20 m thick is found at the base of the deep topsoil [5–7]. The main cause of these shaft lining failures is the additional stress concentration induced by the drawdown of the aquifer caused by mining operations [8–15]. Countermeasures for shaft lining failures and treatments, such as the set of wall method [16,17], stress-relief groove, and strata grouting methods [18,19], have been applied but in a limited manner because of complex and unique geological conditions. In serious cases, some shafts experience a second failure after the first treatments [20–22].

On the basis of the above-mentioned background, this study develops and suggests the application of an underground continuous impervious curtain (UCIC) around the shaft lining. This study also discusses the method employed and its suitability in establishing a guideline for its application.

UCIC is an anti-seepage underground wall. This method has been developed on the basis of the mechanism of shaft lining failure and existing treatment methods, such as strata grouting [23–25] and previous shaft sinking methods [26]. If the water pressure in the aquifer is high, the risk of water outburst will be high and the freezing method should be applied first to prevent water inflow [27]. The UCIC design is shown in Fig. 1. Ikuta et al. invented a new technique to construct the underground wall, which was called the vertical cutting mixing technique (CCC) [28]. The UCIC uses this technique to reinforce the aquifer around the shaft lining such that subsidence can be decreased and the additional force can be removed.

## 2. Analysis of UCIC for shaft lining treatment

### 2.1. Introduction

To clarify the effect of UCIC in improving shaft lining performance, different factors, namely, the location, shape, range, and width, were analyzed using the finite element software Phase$^2$. The geological conditions at the Baodian coal mine that lead to shaft lining failure were adopted in this simulation. The initial water level in the bottom aquifer was −25 m. Thereafter, the water level dropped to −45 m. An axisymmetric model was used (Fig. 2). The mechanical properties used in these analyses are shown in Table 1.

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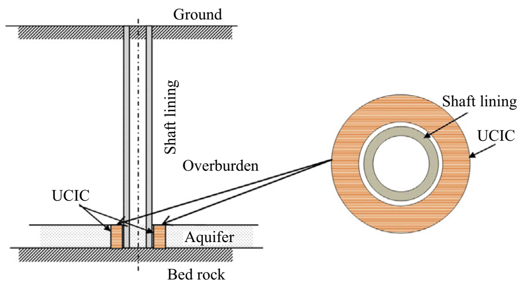


**Fig. 1.** Sketch of UCIC for shaft lining treatment.

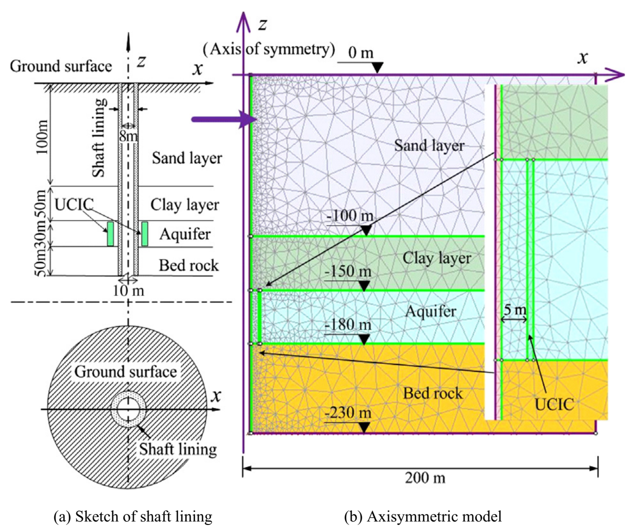


**Fig. 2.** Analytical model of UCIC.

The strength factor based on the Mohr–Coulomb failure criterion was applied to evaluate the risk of failure of the shaft lining. This factor represents the ratio of the shear strength of the material to the pure shear stress borne by the material.

### *2.2. Effect of UCIC disconnection with shaft lining*

The UCIC was constructed 5 m away from the shaft lining, and the width was 1 m. Two ranges of the UCIC construction were considered. The UCIC was constructed only in the aquifer in Treatment 1 but was constructed both in the aquifer and clay layer in Treatment 2.

Fig. 3a shows the changes of the maximum principal stress in the inner surface of the shaft lining. A peak stress caused by shaft lining failures occurred in the lower part of the bottom aquifer after drawdown. This change is in accordance with the additional stress change in the shaft lining (Fig. 3b), which is caused by the physical property difference between two adjacent layers. After the treatment, the stress concentration in the shaft lining near the boundary decreased. Thus, Treatment 2 (peak value decreased by 6 MPa) is better than Treatment 1 (peak value decreased by 3 MPa).

### *2.3. Effect of UCIC adjacent to shaft lining*

In this study, the UCIC was constructed to come into contact with the shaft lining. The numerical analysis model of the vertical UCIC (rectangle) is shown in Fig. 4a, and the distribution of the vertical UCIC is shown in Table 2. The model of the triangular UCIC constructed at different angles is shown in Fig. 4b, and the tilt directions of the applied patterns are shown in Table 3.

The maximum principal stresses in the inner surface of the shaft lining for the first three patterns are shown in Fig. 5. The maximum principal stress near the aquifer layer dramatically decreased, and stress concentration occurred near the boundary between the clay and aquifer layers. Furthermore, the peak stress in Pattern B is smaller than that in Pattern A. Thus, the thickness of the UCIC also has an obvious influence on its effectiveness as a treatment technique. The UCIC built around the shaft lining can restrain the stress concentration (peak value decreased 15 MPa at least) induced by the aquifer drawdown.

In Pattern C, the maximum principal stress became small. The construction of UCIC also transformed the stress concentration to prevent shaft lining failures from occurring in the aquifer range. The UCIC then reduced the risk of water seepage in the shaft lining as the failure location transformed into the impermeability layer.

Fig. 6 shows the strength factor of the shaft lining after drawdown. The strength factor through the aquifer layer considerably increased in Pattern C compared with patterns without reinforcement. Therefore, the UCIC should be built into the aquifer and the neighboring layer to release the stress concentration and reduce the risk of shaft lining failure.

Fig. 7 shows the maximum principal stress in the inner shaft lining when the triangular UCIC was constructed at different angles. The stress concentration becomes milder, and the stress decreases through the aquifer layer. An angle of 15° inclination is better for preventing shaft lining failure.

Therefore, UCIC is effective in reinforcing the shaft lining. Instead of leaving a gap around the shaft lining (peak value decreased 6 MPa at most), the UCIC built adjacent to the shaft lining (peak value decreased 15 MPa at least) has better effects.

### *2.4. Influence of ranges and materials on effect of UCIC*

The ranges and materials of the UCIC were considered in the analysis. Young's modulus of Material 1 is shown in Table 1 and that of Material 2 were set 10 times large than Material 1.

Fig. 8a–d shows the strength factors when the UCIC was built in the aquifer and 10 m above and/or below. Fig. 9 shows the strength factor of the UCIC constructed using different materials. The effect of the UCIC is analyzed as follows:

**Table 1**
Mechanical properties of strata, shaft lining, and UCIC.

| 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 | 0.30 | 0.30 | 0.30 | 0.25 | 0.15 | 0.15 |
| Internal friction angle (°) | 20 | 20 | 20 | 35 | 35 | 35 |
| Cohesion (MPa) | 0.030 | 0.035 | 0.040 | 11.000 | 35.000 | 35.000 |
| Unit weight ($MN/m^3$) | 0.021 | 0.021 | 0.022 | 0.027 | 0.030 | 0.030 |
| Tensile strength (MPa) | 0.060 | 0.070 | 0.075 | 6.000 | 16.000 | 16.000 |

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