Design and Research of Pre-grouting technology for 1000m scale blind shaft

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Abstract. Based on the characteristics of high water pressure and large quantity water-inrush in water-rich dolomite formation around the 1000m level blind shaft of a mine in Yunnan province, pre-grouting was proposed to control water for safe and rapid tunneling. Three large chambers were set up as drilling platforms underground, and the pulping station was established on the surface, the red clay cement slurry was transported to underground grouting station through slurry pipeline. 496m long grouting section was designed and segmented downward manner was adopted. After pre-grouting, the water inflow in the pre-grouting section of the shaft is 7.86m³/h, which met the requirements of the national standard and the contracted maximum water inflow 10m²/h, excellent water control effect was obtained. scientific and reasonable pre-grouting design achieved safe and rapid tunneling of the 1000m level blind shaft.

1. Introduction
Deep mineral resources exploitation is an important issue for mining development of the next few years in China, and deep resource mining method will be more widely used in resource exploitation[1-2]. The vertical shaft is the “throat” part of the mine, and its construction period accounts for 30% to 40% of the entire mine construction period. Therefore, the vertical shaft construction is the key part of deep resource exploitation[3-4].

The hydrology and geological conditions of the deep bedrock formation in the vertical shaft are very intricate. With the increasingly depth of the shaft, and under high water pressure conditions, the probability of water inrush in the water-bearing formation increases sharply, which greatly threatens the safety construction of the shaft and even leads to mine flooding, causing huge economic and social losses [5-8]. Ji Dongli studied two design results of high-pressure pre-grouting in the working face of the main and auxiliary shafts of an iron mine [9]. Li Haiyan et al. studied the grouting and plugging methods of the working face with large quantity water in deep vertical shafts. They proposed that the shaft wall and the outside of slurry blocking pad should be grouting first, and the working face grouting should be carried out after the curtain is formed around the shaft wall[10]. He Wen et al. studied the aqueous sodium silicate chemical slurry based on the microfractures and porosity found in the deep bedrock of shaft [11].

The depth of the shaft under construction usually reaches or exceeds 1000 m [12]. When the shaft exposes deep aquifers, the exposing hydrostatic pressure is usually greater than 10 MPa. In this case, the grouting of the working face often fails to achieve the expected grouting effect, resulting in a lot of time and money wasted. As the advantages of mature technology, reasonable economy, and the ability to form permanent curtains, the pre-grouting technology has become the most widely used construction
method for the vertical shaft passing through a thick aquifer.

In recent years, the pre-grouting technology has been widely used in the vertical shaft in China, but for the blind vertical shaft, due to the limitation of the construction conditions, the relevant practice has not been carried out in China.

In this study, through the design of the number of shafts, drilling grouting chambers, etc., we successfully implemented pre-grouting in the thousand-meter-level blind vertical shafts, and its implementation is of great significance for the prevention and control of water in blind vertical shafts in China.

1.1 Project Overview

A mine of Yunnan is located in Zhaotong City in the northeast of Yunnan Province, which is a large mine with large reserves and high grade. The mining area is located in the Grand Canyon of the Luoze River, and the Luoze River flows through the surface of the mining area, presenting the landscape of alpine valleys. The mining area has more than 60 years mining period, all of which are underground mining. Currently, the main mining middle sections are +910 middle section, +760 middle section, +670 middle section.

In order to achieve the purpose of continuous replacement of deep resources, the 92-line blind shaft was designed at the east side of the surface river. The shaft depth is 960 m, the initial elevation is +910 m, and the shaft bottom elevation is -50 m. In April 2013, when the shaft was constructed to the elevation of +794 m, the aquifer was exposed, and when the construction was elevated to the position of +741 m, the water inflow amounted to 32 m³/h, and then the working face grouting treatment was carried out. However, the working face grouting effect was unsatisfied, as the depth of the shaft continues to increase, the amount of water inrush continued to increase. When tunneling to the elevation of +694 m, multiple mine flooding accidents occurred due to excessive water inrush. The shaft can no longer continue to dig. In that case, it was decided to adopt strong drainage measure by adding pumps. When the strong drainage construction reached the elevation of +670 m, it was decided to continue grouting in the working face. The grouting was carried out in a combined manner until the end of grouting in the working face in December 2013. After the grouting at the working face, the water blocking rate only reached 50%. The 92-line blind shaft has been digging from the elevation +794 m to +670 m. It took a total of 9 months to dig 124 m, and the effect of grouting and water blocking was extremely unsatisfactory, causing huge economic losses and construction time waste. Considering that the shaft can no longer continue normal tunneling, it was finally decided to abandon the 92-line shaft.

Fig.1 The space position diagram of the shaft
In view of the urgency of the continuous replacement of deep resources, the construction of the blind shaft needs to be restarted quickly, and finally the 112-line was selected to restart the vertical shaft construction, the position diagram of the 112-line blind shaft and the 92-line blind shaft is shown in Figure 1. The 112-line blind shaft has a diameter of 5.7 m and an excavation diameter of 6.5 m. The elevation of the shaft head position is +910 m, the bottom elevation of the shaft is -50 m, and the depth is 960 m. The 112-line blind shaft is designed as a blind mixed shaft, which will be used as a key line for deep resource development after completion.

The blind vertical shaft of 112-line started construction in 2016. Due to the continuous development of mineral resources in the +670 middle section of the elevation in recent years, a large number of roadways and chambers have been developed in the middle section of the +670 section. The shaft above the elevation +670 m of the blind shaft of 112-line has been drained, forming a descending funnel.

| Table 1. 112 line shaft design parameters |
|------------------------------------------|
| Shaft | Wellhead elevation (m) | Bottom elevation (m) | Shaft depth (m) | Shaft diameter (m) | excavation diameter (m) |
| 112 line blind shaft | 910 | -50 | 960 | 5.7 | 6.5 |

When the 112-line blind shaft was constructed to below the elevation of +670 m, it began to expose the gushing water and then multiple grouting on the working face and grouting behind the wall were carried out. When the shaft was constructed to the elevation of +481 m, the water inflow of the shaft was as large as 50 m³/h. To ensure the safe and rapid excavation of the shaft and prevent the occurrence of casualties and equipment loss caused by water inrush, it was decided to suspend the excavation of the shaft and carried out pre-grouting to control water at the elevation of +481 (the remaining excavation workload of the shaft is 531m).

1.2 Hydrogeology and engineering geology conditions of the shaft

In order to ascertain the hydrogeology and engineering geological conditions of the shaft of the 112-line blind shaft, an exploration borehole was designed at the position of the shaft. Since the elevation above the +670 m elevation has been drained, the initial elevation of the exploration borehole is designed to be +670 m, the bottom elevation is designed to be -55 m, and the investigation borehole design depth is 735 m.

The exploration results show that the shaft site is located in the east wing of the Shimenkan fold structure, and multiple fault structures are developed in this area. The degree of karst development on this site is relatively weak. Except for the local development of small eroded crystal caves, there is no karst phenomenon, such as karst caves, at the shaft site.

The strata at the shaft site are, from top to bottom, the weak weathering dolomite in the 3rd sub-section of the Upper Devonian Zaige Formation, the weak weathering dolomite in the 2nd sub-section of the Upper Devonian Zaige Formation, and the weak weathering dolomite in the 1st subsection of the Upper Devonian Zaige Formation.

During the drilling process of the investigation hole, the water gush was exposed for many times. When drilling to the height of -50 m (hole depth 730 m), the water inrush of the single hole of the drill hole reached 123.3 m³/h, and the water pressure of the hole of the drill hole reached 1.93 MPa. The rig cannot stand normally, the drilling tool is pushed out, and the investigation hole is forced to terminate.

2. Design schemes

2.1 Overall design

In order to ensure the water blocking effect of the pre-grouting of the shaft, a reliable curtain needs to be formed around the shaft. This water control design introduces ground pre-grouting technology.

The shaft head of 112-line is set in the tunnel of the middle section of +910, and large chambers such
as lifting chambers and hoisting sheave chambers are arranged around the shaft head. Therefore, it is extremely difficult to arrange other large drilling chambers and grouting chambers around the shaft head. The addition of drilling chambers and grouting chambers around the shaft head will greatly reduce the stability of the rock mass and will adversely affect the long-term operation of the shaft. Considering that the blind shaft has been excavated and built up to +481 m elevation, in order to reduce the drilling workload, it was finally decided to arrange a drilling and grouting chamber and a grouting chamber around the downhole +670 middle shaft as a construction platform for drilling and grouting.

The ground pulp station was set at the plane of surface elevation +910, the grouting station was designed at the grouting tunnel interior in underground elevation +670 middle section, and ground and underground are connected by slurry pipeline.

In order to prevent the blasting and drilling construction from damaging the existing shaft and to ensure the stability of the chamber group (drilling nest chamber, grouting chamber, and shaft), the drilling nest chamber and grouting chamber are designed to be far away from blind shaft.

The grouting material uses clay cement slurry. The upper part of the borehole is the casing section, and the lower part is the grouting section. After the borehole is formed, the descending section pre-grouting method is used to treat the aquifer around the shaft to form a grouting curtain to achieve the purpose of controlling water.

Drilling equipment adopts TSJ-2000 type rig, grouting equipment adopts BQ-350 type grouting pump.

2.2 Drilling design
For the prevention and control of grouting water in vertical shafts, pre-grouting holes are usually arranged outside the shaft excavation diameter. After the pre-grouting of the borehole is completed, a reliable shaft curtain is formed around the shaft, thereby ensuring the safe and rapid tunneling of the shaft.

![Fig 2. The intersection schematic diagram of the grouting curtain](image)

Figure 2 is a schematic plan view of the borehole layout around the shaft. The boreholes are evenly arranged. Assuming that the slurry is homogeneously diffused in the bedrock, the red shaded area in the figure is the slurry diffusion area; the purple shaded area is the curtain circle area; \( R \) is the radius of the shaft.
falling point; \( r \) is the diffusion radius of the slurry; \( c \) is the hole spacing; \( h \) is the thickness of the grouting curtain circle; \( \theta \) is the angle formed between two adjacent grouting holes.

### 2.2.1 Intersection thickness analysis

Grouting to control water must form an effective grouting curtain, while ensuring a certain thickness of the intersecting circle. Intersection thickness is the key for grouting to block water.

According to Fig. 2:

\[
\begin{align*}
    c^2 &= 2R^2(1 - \cos \theta) \\
    \frac{1}{4}h^2 + \frac{1}{4}c^2 &= r^2 \\
    \theta &= \frac{2\pi}{n}
\end{align*}
\]

The final calculation can be obtained as:

\[
h = \sqrt{\frac{4r^2 - 2R^2(1 - \cos \frac{2\pi}{n})}{n}}
\]

It can be known from Formula 1 that the thickness \( h \) of the intersecting circle is proportional to the diffusion radius \( r \) of the slurry, inversely proportional to the diameter \( R \) of the falling point of the borehole, and directly proportional to the number of boreholes.

First, the slurry diffusion radius \( r \) is analyzed. Due to the slurry type and solidification characteristics, the slurry diffusion radius is a finite value. Therefore, when the slurry type is selected, the degree of increase in the slurry diffusion radius is limited; then the drop point diameter is analyzed. In order to ensure a sufficiently large intersection thickness, the drop point diameter \( R \) must take a smaller value.

In the actual engineering construction practice, the drop point diameter of the grouting hole is usually 2~4 larger than the borehole excavation diameter; Finally, the number of boreholes is analyzed. The more the number of drill holes, the greater the thickness of the circle. However, the increase in the number of drill holes must result in an increase in the amount of engineering workload, so the number of drill holes must be designed reasonably.

### 2.2.2 Number of holes

It can be deduced from Formula below:

\[
n = \frac{2\pi}{\arccos \left(1 - \frac{h^2}{4r^2 - 2R^2}\right)}
\]

The excavation diameter of the 112-line blind shaft is 6.5 m. The diameter of the drilled hole in this design is larger than the borehole diameter of 3 m. Therefore, the diameter of the drilled hole is 9.5 m. Considering the impact of blasting on the grouting curtain damage, and to ensure that the shaft curtain is not damaged by water pressure and reserve a certain safety distance, this design curtain thickness is 13 m; according to actual engineering experience, the diffusion radius of the red clay cement slurry is designed to be 10 m. The final calculation can get \( n = 6.16 \), so this design arranges 6 holes.

### 2.2.3 Design of drilling nest chamber

In order to ensure the smooth construction of the TSJ-2000 drilling rig, a tunnel must be drilled underground, and the specifications and dimensions of the tunnel must meet the actual needs of the construction. In order to save the amount of blasting work in the chamber, and to ensure the stability of the chamber as much as possible, in this paper, three drilling nest chambers are designed, and two grouting holes are designed for each drilling nest chamber. And the roadways are designed to connect the main roadway and the drilling nest chamber.

The top of the drilling nest chamber is designed with inverted wedge anchors as lifting beams, which are used for the drill tower installation. The chamber is also designed with water sinks and sedimentation tanks. The height of the drilling nest chamber is designed to be 18 m, the bottom of the drilling socket
is roughly square, and the specification is 10 m*10 m.

2.2.4 Drilling engineering design
In order to ensure that the borehole enters the grouting drilling target area in the casing section, and at the same time, based on the actual situation of the rock layer, the length of the borehole casing section is designed to be 254 m (elevation +670~+416 m). In order to ensure the effect of shaft pre-grouting, the grouting stop depth exceeds 30 m of shaft depth. Therefore, the drilling depth is 750 m, the grouting length is 496 m, and the starting and ending depths are from 254 to 750 m (elevation +416~ -80 m).

| project                      | parameters  | remarks     |
|------------------------------|-------------|-------------|
| casing section/m            | 254         | elevation 670m~416m |
| grouting section/m-m        | 254~750     | elevation 416m~80m |
| grouting section length/m   | 496         |             |
| circle diameter /m          | 28          |             |
| falling circle /m           | 9.5         |             |
| number of holes             | 6           |             |
| hole spacing /m             | 4.75        |             |

2.3 Grouting design

2.3.1 Grouting volume design
Sufficient slurry injection volume is the basis for ensuring the quality of grouting. The slurry injection volume can be calculated using the following formula:

\[ Q = A \pi \sum_{i=1}^{n} R_i^2 H_i \eta \beta /m \]

Where: \( Q \) is the slurry injection volume (m³); \( A \) is the slurry super-diffusion consumption coefficient; \( R \) is the effective diffusion radius of the slurry from the center of the shaft (m), \( R = r + L \); \( r \) is the grouting hole radius of the grouting section (m); \( L \) is the radial diffusion distance of the slurry; \( H \) is the height of the grouting section; \( n \) is the average fracture rate of the rock layer; \( \beta \) is the filling factor of the slurry; \( m \) is the rate of slurry stone.

The designed slurry injection volume is shown in Table 3.

| project                        | single cement grout /m³ | cement clay grout /m³ | total /m³ |
|-------------------------------|-------------------------|-----------------------|-----------|
| rock cap section              | 400                     | 17231                 | 18633     |
| bedrock section               | 60                      | 60                    | 1402      |
| fixed pipe section            | 942                     | 942                   |           |
| broken zone                   |                         |                       |           |
| total                         | 1402                    | 17231                 |           |

2.3.2 Grouting section height
The division of the grouting section height depends on many factors such as the location, thickness, grouting level, slurry performance and grouting pump performance of the aquifer. The designed grouting section of red clay cement slurry should not exceed 80 m. According to the geological profile of the engineering survey hole and the corresponding geological report, the section height is divided during construction. Grouting pressure is one of the factors that affect the diffusion range of the slurry. If the grouting pressure is too small, the diffusion range of the slurry will be reduced and the curtain thickness cannot be reached. When the grouting pressure is too large, the diffusion range of the slurry will expand, causing slurry waste. In this design, the final pressure of the grouting in the rock cap section is 1.5 to 2.0 times the hydrostatic pressure; the final pressure of the grouting section is 2.0 ~ 3.0 times the
hydrostatic pressure.

Table 4. The segment high division and final grouting pressure

| grouting section | start-stop depth/m~m | elevation/m~m | grouting section/m | final design pressure/MPa |
|------------------|---------------------|--------------|-------------------|-------------------------|
| rock cap section | 254~274             | +416~+396    | 20                | 7.6~10.1                |
| 1                | 274~330             | +396~+340    | 56                | 11.2~16.8               |
| 2                | 330~405             | +340~+265    | 75                | 12.7~19.1               |
| 3                | 405~474             | +265~+196    | 69                | 14.1~21.1               |
| 4                | 474~550             | +196~+120    | 76                | 15.6~23.4               |
| 5                | 550~628             | +120~+42     | 78                | 17.2~25.7               |
| 6                | 628~696             | +42~+26      | 66                | 18.5~27.8               |
| 7                | 696~750             | -26~+80      | 54                | 19.6~29.4               |

3. Construction practice

3.1 Chamber
As this construction is the first downhole construction of TSJ-2000 water source drilling rig, the reasonable design of the chamber is extremely important.

Fig.3. The schematic diagram of the drilling chamber

3.2 Drilling
In the case of high-water pressure and large amount of water, the hole drilling in this construction adopted the methods of adjusting the proportion of mud, heavier drilling tools, enhanced drainage, and frequent grouting. The drilling depths all exceed the design requirements. The deflection of the borehole directly affects the final grouting water blocking effect. Through the directional technology, the maximum deflection rate of the grouting section of the shaft in this construction is 2.88‰, which meets the design requirements. The drop points on the grouting ring diameter and different depths are also generally uniform, further ensuring the quality of the grouting project.

3.3 Grouting
This grouting construction mainly uses red clay cement slurry. Through 24 times of grouting, we successfully controlled the gushing water of the gushing stratum, smoothly passed through the deep water gushing stratum and finally constructed to the design depth. The whole shaft was grouted 112 times, with a total grouting volume of 15314.246 m³, reaching 82.19% of the total grouting volume of 18633 m³.
4. Grouting effect evaluation
The shaft construction on 112-line is the first pre-grouting construction of a thousand-meter blind vertical shaft in Devonian water-rich dolomite formations in China. The evaluation of the grouting effect directly determines the success or failure of deep resource development.

The blind shaft of 112-line has been safely and smoothly drilled to the design depth (-50 m elevation). The shaft flooding method was used to measure the water inflow volume in the blind shaft, and the remaining water inflow volume in the pre-grouting section of the blind shaft was finally measured to be 7.86 m³/h (with the Matou gate was closed), which meets the requirements of national standards and the contract of not exceeding 10 m³/h. According to the survey report of the investigation hole, the water inflow from the shaft will be as large as 314.8 m³/h, and the water plugging rate of the pre-grouting section is calculated to be 97.5%, which means the effect of grouting and water blocking is excellent.

5. Conclusion
(1) For the prevention and control of pre-grouting water in blind vertical shafts, drilling nest chambers and grouting chambers can be set up as drilling and grouting working faces, pulping stations can be set up on the ground to make slurry, and the red clay cement slurry is transported to the underground for grouting.

(2) The number of shaft pre-grouting holes affects the quality and cost of the project. The designed number of holes should be calculated according to the parameters such as the thickness of the circle intersection, the radius of diffusion, and the diameter of the landing point circle.

(3) Pre-grouting process is used for the prevention and control of the shaft of the thousand-meter-level blind vertical shaft. After grouting with red clay cement slurry, the remaining water inflow is 7.86 m³/h, which meets the requirements of national regulations and contract agreement. Scientific and reasonable pre-grouting design achieves safe and rapid tunneling.

(4) The pre-grouting of the 112-line blind shaft is the first pre-grouting water controlling construction in China and even the world. The successful practice of this project is of great reference significance to the construction of the shaft water prevention and control in China.

Author
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Acknowledgments
Youth Project of Technology Innovation and Entrepreneurship Special Fund Project in Tiandi Technology Co., Ltd. (No. 2019-TD-QN010).

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