Selection and application of the minimum gas injection volume of air drilling with raise boring machine

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Abstract. Gas injection volume is the key parameter of air drilling with raise boring machine, and the determination of the minimum gas injection volume is one of the key technologies to improve the drilling speed and shorten the drilling period. Based on the characteristics of raise boring technology, the construction technique of raise boring with air as circulating medium is studied, and the double-channel structural characteristics of direct circulation system are discussed. On the basis of summarizing and analyzing the principle and characteristics of the calculation methods, the minimum gas injection volume required for rock carrying in the engineering of air drilling with raise boring machine is calculated by using the minimum velocity method. The research results provide a basis for the design of drilling parameters and are of great significance for expanding the application range of raise boring method and realizing the safe and rapid construction of shaft.

1 Introduction

As the 21st century is the century of underground space, the safe and efficient construction of underground engineering has become a key focus [1]. As a mechanized shaft construction method, the drilling with raise boring machines can make full use of the equipment and natural conditions and has the advantages of fewer operators, higher safety, and faster construction speed compared to the common method and mine shaft drilling method [2].

Since the 1980s, China has started to develop raise boring machines and technology. Through more than 30 years of development, the drilling method with raise boring machines has been applied from coal mine and metal mine to hydroelectric power generation, pumped storage power station, highway and railroad tunnel. The raise boring technology has become an important method for shaft construction in underground engineering [3].

The drilling technology with raise boring machines includes top-down small-diameter pilot hole drilling and bottom-up large-diameter reaming drilling. The raise boring machine drives the rotation of the drill rod, which transfers energy to the drill head. Then the rock is crushed through the rolling cutter and a pilot or reaming hole can be formed. The purpose of the pilot hole is to transport the drill rod to the lower level tunnel so that the reaming bit can be connected. The quality of the drilled pilot hole is critical to the success of the drilling project and is the key to the construction of the drilling with raise boring machines [4].

With the successful development of large raise boring machines such as the ZFY5.0/600 [5], the scope of application of the drilling method with raise boring machines has been greatly expanded [6-8]. However, as an integrated mechanized drilling method, its scope of application is limited by technology and equipment so that this method cannot solve all shaft drilling problems. There are a large number of construction projects planned in the central and western regions of China, such as highway and railroad tunnel, and metallurgy mining. When the shaft is located in an area with the Gobi Desert, high altitude, extreme cold, severe water shortage, and drought, it is very difficult to use water for construction [9]. For the conventional drilling method with raise boring machines, the drilling fluid needs to be used as the circulating medium. If some problems such as cooldown failure of the hydraulic oil and the rolling cutter of the drill head, and poor discharge of crushed rock fragments from the lift occur due to insufficient water supply, it will be difficult to ensure the normal implementation of the drilling process with raise boring machines and the normal operation of the project. Therefore, further researches need to be conducted to solve the technical problems related to raise boring by means of air.

As a special underbalanced drilling technology [10], air drilling uses compressible air as the circulating fluid for drilling, which has the advantages of high mechanical drilling speed, low formation damage, strong resistance to leakage, low cost, and good environmental protection. Owing to these, air drilling has been widely used in domestic and foreign oil and gas exploration and development [11]. However, researches on air drilling technology and equipment based on the drilling method...
with raise boring machines are still not enough.

Based on the direct fluid circulation technology used in the air drilling system with raise boring machines, this paper focuses on the calculation of the minimum air injection volume, which is applied to the design of drilling parameters for actual engineering construction. While cooling and rock fragment collection can be achieved during the drilling process, the mechanical drilling speed can be accelerated and the drilling cycle can be shortened so that the project cost can be reduced.

2 Air drilling circulation system with raise boring machines

The air drilling system with raise boring machines uses direct fluid circulation technology and highly-compressed air as the circulating medium for drilling, that is, the highly-compressed air produced by the air compressor flows through the central axis hole of the spindle of the drilling rig and the axial hole of the drill rod, and reaches the bottom of the drill head to cool down the drill head. The highly-compressed air carries the rock fragments generated during drilling into the annular space between the drill hole and the drill rod and flows along the annulus toward the surface wellhead. A slag collection device is installed at the surface wellhead to collect and discharge the rock fragments, thus effectively preventing the rig from being damaged by splashing rock fragments and reducing dust pollution at the construction site. The process of highly-compressed air flowing in direct circulation drilling is shown in Figure 1.

![Figure 1. Direct air circulation](Image)

1- slag collection device; 2- central axis hole of the drill rod; 3- annular slag discharge channel; 4- drill bit of pilot hole; 5- pilot hole; 6- drill rod; 7- slag discharge pipe

The direct circulation system has a two-channel structure, that is, it has a central-hole channel and an annular-space channel in the drill rod, with different form dimensions and fluid composition. The following assumptions need to be made when studying the process parameters: the fluids are all constant and uniform one-dimensional flow; the two channels are in a turbulent and completely rough zone; the thermodynamic process of the gas in the isometrical section is constant temperature; the circulating gas satisfies the ideal gas equation of state.

3 Analysis of minimum gas injection volume for air drilling with raise boring machines

The air injection volume is a key parameter of the air drilling technology with raise boring machines. During drilling, the main function of air circulation is to transport the rock fragments generated at the bottom of the borehole out of the well. If the air injection volume is insufficient and the upward and downward velocity in the annulus is too low, the rock fragments will fall back to the bottom of the borehole and gradually accumulate to form a "blockage," which will prevent the drilling operation from proceeding normally. Therefore, in designing drilling parameters, it is necessary to reasonably determine the minimum air injection volume required to carry rock fragments and use this as a criterion to select air compressors and other equipment.

3.1 A key point of rock-carrying air in the annular space

The outer diameter of the stabilized drill rod is larger than the outer diameter of the conventional drill rod, so the annulus suddenly becomes larger as the air carries the rock fragments up and down the annulus to the joint of the stabilized drill rod and the conventional drill rod. Because the air is highly compressible, the air will significantly expand in this space. Due to the energy principle, there is a large loss of energy in the rock-carrying air and a sudden decrease in pressure, density, and velocity. By dividing the annular space into three sections, which are the joint, the lower part of the joint, and the upper part of the joint, the rock-carrying capacity of the air can be analyzed. It is found that the air lifting force at the joint is the smallest. Therefore, this point is called the key point of rock-carrying air in the annulus, which is the minimum air injection volume. The air volume required to satisfy the "key point" is the air volume required to satisfy the circulating system.

3.2 Method of calculating the minimum air injection volume

Generally, there are three calculation methods developed by domestic and international scholars on the minimum gas injection volume.

3.2.1 Method based on minimum kinetic energy criteria for air

The minimum kinetic energy method is concluded from air drilling engineering practice. It assumes that the air and rock fragments in the borehole are homogeneous mixtures. The minimum air injection volume can be calculated based on the area of the annular space and the return velocity of the rock-carrying air under standard conditions. This method does not take into account the interaction between the air and rock fragments.
3.2.2 Method based on the minimum pressure at the bottom of the hole

According to the minimum pressure method, the lower the bottom pressure is, the greater the rock-carrying capacity. Assuming that the kinetic energy of the air at the bottom of the hole is equal to the kinetic energy of the air in the standard state and the return velocity in the standard state is used, that is, the required rock-carrying capacity can be met, the minimum air injection volume can be obtained through the analytical solution. This method is relatively simple to apply in the field, but few factors are considered.

3.2.3 Method based on the settling velocity of rock fragments

Taking into consideration the interaction between air and rock fragments, the minimum velocity method proposes the concept of the critical settling velocity of rock fragments. That is, when the rock fragments are in the still air, they will sink under the action of gravity; during the sinking process, the fragments will encounter air resistance; the resistance will increase with the sinking speed until the resistance and gravity balance, at which point the fragments will keep sinking at a uniform speed.

3.3 Selection of minimum injection volume for air drilling with raise boring machines

The method based on the settling velocity of rock fragments is theoretically advanced. The minimum velocity method is used to calculate the minimum air injection volume for air drilling with raise boring machines. Therefore, as long as the flow rate of air is higher than the settling velocity of rock fragments, the rock fragments can be kept back in the annulus, thus avoiding blockage and achieving safe drilling operations.

4 Application example of air drilling projects with raise boring machines

4.1 Project overview

A hydropower station project in the upper reaches of the Yellow River in Qinghai Province required the construction of two outgoing vertical shafts. In order to solve the problems of slagging, drainage, and ventilation during the excavation process, the construction method using raise boring machines to drill into the slag pilot shaft and the direct drilling method to expand so as to form the vertical shaft was adopted. In this method, the construction safety, quality, and progress of the slag pilot shaft were directly related to the achievement of shaft construction objectives. The raise boring machine ZFY3.5/400 was used to drill downward to form a Φ295mm pilot hole and then to drill upward to form a Φ1.4m pilot shaft. The drilling parameters and requirements for the pilot shaft are shown in Table 1.

| Project name | Pilot hole diameter | Pilot shaft diameter | Depth | Deflection rate |
|--------------|---------------------|----------------------|-------|----------------|
| 1#shaft      | 295mm               | 1.4m                 | 155.63m | ≤1%            |
| 2#shaft      | 295mm               | 1.4m                 | 108.18m | ≤1%            |

The outgoing vertical shaft project was located on the right bank of the downstream side of the arch dam, with a ground elevation of 3217.70. The lithology of the area was mainly Middle to Upper Triassic (T₂3-Ss), and the upper part had the tertiary red layer (R₃). The geological structure was relatively simple, mainly consisting of faults, fractures, and metamorphic sandstone layers. Since the outgoing shaft was located on the high slope of the right bank of the dam, it was difficult to ensure enough water for construction, and the tertiary red layer above the shaft was prone to collapse when it encountered water. Therefore, the air drilling method with raise boring machines was used to construct the pilot shaft, as shown in Figure 2.

4.2 Determination of the minimum gas injection volume

4.2.1 Basic drilling parameters

In this project, the drilling started from the pilot hole. The diameter of the pilot hole D₀ is 295mm. The outer diameter of the drill rod Dᵢ is 254mm. The mechanical drilling speed Rᵢ is 1.4m/h. The rotation speed of the drill head N is 20r/min. The sandstone particle shape coefficient Cᵣ is 0.85. The sandstone density ρₘ is 2600kg/m³. The air density at the key point ρₐ is 4.5kg/m³. The concentration of the rock fragments in the annular space Cₚ is 0.02.

4.2.2 Calculation of minimum air injection volume based on the minimum velocity method

The equivalent diameter of rock fragments is

$$D_{eq} = \frac{R_p}{60N} = \frac{1.4}{60 \times 18} = 0.0013 \text{(m)}$$  \hspace{1cm} (1)

The settling rate of rock fragments is
The transportation speed of rock fragments is
\[ v_r = \frac{\pi}{4} \left( D_d^2 - D_t^2 \right) \frac{R_t}{\rho_a A} \times 3600 \]
\[ = \frac{3.14 \times 0.295^2 \times 1.4}{4 \times 0.02 \times \left( \frac{3.14}{4} \times (0.295^2 - 0.254^2) \right) \times 3600} \]
\[ = 0.075 \text{ (m/s)} \]

The minimum velocity of rock-carrying air is
\[ v = v_r + v_u = 3.013 + 0.075 = 3.088 \text{ (m/s)} \] (4)

Therefore, the minimum air injection volume required at the key point is
\[ Q_r = \frac{60\pi}{4} \left( D_o^2 - D_t^2 \right) v_u \]
\[ = \frac{60 \times 3.14}{4} \left( 0.295^2 - 0.254^2 \right) \times 3.088 \]
\[ = 3.274 \text{ (m}^3/\text{min)} \]

5 Conclusion

(1) When the drilling method with raise boring machines is used in the construction process, highly-compressed air shall be used as the circulating medium, which can increase the mechanical drilling speed and shorten the drilling cycle. The direct circulation system has a two-channel structure, including a central-hole channel and an annular-space channel in the drill rod, with different form dimensions and fluid composition.

(2) The minimum air injection volume can be calculated based on the minimum velocity method, which is theoretically advanced. As long as the flow rate of air is higher than the settling velocity of rock fragments, the rock fragments can be kept back in the annulus so that blockage can be avoided and safe drilling operation can be achieved.

(3) The minimum air injection volume required for effective rock carrying is calculated based on the actual practice of raise boring engineering, which provides theoretical guidance and basis for the design of drilling parameters.

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