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Construction technology and parameter calculation of air drilling with raise boring machine

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Abstract. Based on the characteristics of raise boring technology and air drilling technology, the construction equipment and process of raise boring with air as circulating medium are studied. Raise air drilling equipment includes the hydraulic control system, the air-cooled cooler and the air compressor. The drilling process is that the bit is cooled by the high-pressure air, at the same time, the broken rock debris generated in the drilling process are discharged to the ground, and the high temperature hydraulic oil is cooled by the air-cooler cooler. By the study above, the problems are solved effectively such as heat dissipation, cooling and rock debris collection and discharge in the process of construction with raise boring machines without drilling fluids. Based on the basic assumption and the aerodynamic theory, the circulation system pressure of the raise air drilling is studied, the calculation method and formula of the annular pressure drop, bit pressure drop and rod pressure drop are presented. The research results can provide theoretical guidance and technical support for the application of raise air drilling technology.

1 Introduction

The drilling method with raise boring machines has played an important role in the fields of mining, water & electricity, transportation and municipal administration since its application to underground engineering construction in the 1980s [1]. The scale of underground engineering construction is increasingly expanding with the rapid development of China's national economy. A considerable number of new mine shafts have been planned in the west, especially in Inner Mongolia and Shaanxi. There are more and more large-scale construction projects such as highways and railways in the central and western regions. According to incomplete statistics, there are up to 362 planned extra-long railway tunnels with a length of over 10 km, totalling 5,359 km, and 38 with a length of more than 20 km, totalling 993 km. Air and escape shafts must be provided for every 7 kilometers according to design requirements. Such works should be completed with complete mechanical shaft construction technology and mature mechanical sinking equipment. Raise boring machines have become a solution for high-efficiency construction of deep and large shafts with their characteristics such as safety, reliability, flexibility, energy conservation and environmental protection [2,3].

The construction of vertical and inclined shafts faces great difficulties in water utilization when highway and railway tunnels or metallurgical mines are located in areas with harsh natural climates such as gobi, high-altitude areas, high and cold areas and areas with severe water shortage and drought [4]. In the conventional method of raise boring with drilling fluids, the normal implementation of the process and the normal operation of the project can hardly be guaranteed in case of the failure to cool the hydraulic oil, reamer bits and hobs, unsmooth lifting and discharge of broken rock debris and other problems due to insufficient water supply.

As a special underbalanced drilling technology [5], air drilling, with compressible air as the circulating drilling fluid, is characterized by high rate of penetration, low formation damage, strong resistance to leakage, low cost, environmental protection and other advantages. It has been widely applied in the field of oil and gas exploration and development in both China and foreign countries [6,7]. However, the research of air drilling technology and equipment based on the drilling method with raise boring machines is not yet mature.

This paper studies the construction technology and parameters of raise boring with air cooling and slag discharge, which can solve the problems such as heat dissipation, cooling and rock debris collection and discharge in the process of construction with raise boring machines without drilling fluids. It is of great significance for expanding the scope of application of the drilling method with raise boring machines and realizing safe and rapid construction of shafts.

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2 Research on the construction technology of raise air drilling

2.1 Composition of raise boring system

The drilling technology with raise boring machines, including top-down pilot drilling and bottom-up ream drilling, mainly relies on raise boring machine, drilling tool and auxiliary equipment systems [8]. The boring machine system is composed of a drilling cramp, a power system and a control system. The drilling tool system is composed of drill rods, drill bits and hobs, etc. and the auxiliary system is composed of a circulation system, a cooling system and a slag discharge system [9].

Key links that require water sources in the construction process of the raise boring method include:

(1) Cooling system, which is used to cool the hydraulic system of the boring machine and the reamer bit and hob. The cooling water pump pressurizes the clear water to cool the hydraulic oil through the hydraulic cooler. The cooling water then flows back to the cooling pond for cooling and recycling. During ream drilling, part of the clear water enters the drill rod via the valve and arrives at the reamer bit, and then cools the reamer bit and hob after atomization. For small-diameter hole drilling, it can also flow directly into the annular space and arrive at the reamer bit by gravity, and then cool the rock breaking hob after atomization.

(2) Circulating system: The method of direct flushing with pressurized fluids is adopted during pilot drilling with a raise boring machine. The circulating pump pressurizes drilling fluids in the circulating pool, which are jetted out from the central tube of the drill power head, the center hole of the drill rod and the water hole of the pilot bit via the control valve, carrying rock debris broken by the pilot bit. In the annular space between the drill rod and the pilot hole wall, the rock debris is discharged to the ground at a certain flow rate. The circulating fluid after separation returns to the circulating pool and the rock debris is separated and carried away.

2.2 Raise air drilling equipment and technology

Raise air drilling equipment mainly includes the hydraulic control system of the raise boring machine, the air-cooled cooler, the air compressor, the slag collector installed at the inlet of the shaft and the bit cooler installed on the reamer bit.

The raise air drilling process includes the following steps:

2.2.1 During pilot drilling

Cool the pilot bit with the high-pressure air from the air compressor and meanwhile discharge the broken rock debris at the bottom of the hole to the ground; cool the high-temperature hydraulic oil from the hydraulic control system of the raise boring machine with the air-cooled cooler.

With the direct fluid circulation technology, the high-pressure air from the air compressor flows to a position below the pilot bit for its cooling through the central hole of the main axis of the raise boring machine and the axial center hole of the drill rod. Carrying the rock debris produced during drilling, the high-pressure air enters the annular slag discharge channel between the shaft and the drill rod and flows to the wellhead on the ground along the channel. After reaching the wellhead, the debris enters the slag collector and is collected and discharged under the combined action of its gravity and the flowing air, thus preventing the boring machine from being damaged by splashing debris and reducing dust pollution on the construction site effectively. The high-pressure air flow process during raise air drilling is shown in Figure 1.

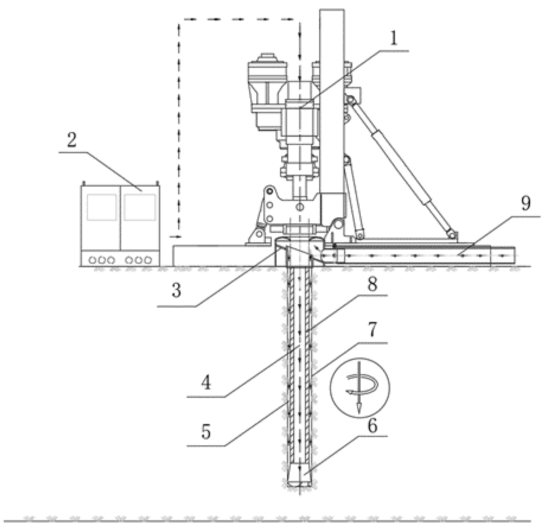

Figure 1. Schematic diagram of pilot drilling in raise air drilling
1- Raise boring machine; 2- Air compressor; 3- Slag collector; 4- Axial center hole of drill rod; 5- Annular slag discharge channel; 6- Pilot bit; 7- Pilot hole; 8- Drill rod; 9- Slag discharge pipe

The direct circulation system is provided with two channels, namely the center hole channel of the drill rod and the annular slag discharge channel. The limitation of the structure and size of the drilling tool results in the small and fixed cross-sectional area of the two channels, the high up-hole velocity of high-pressure air and the low interaction between debris particles and between debris particles and high-pressure air.

2.2.2 During ream drilling

Cool the reamer bit with the high-pressure air from the air compressor, and cool the high-temperature hydraulic oil from the hydraulic control system of the raise boring machine with the air-cooled cooler.

The high-pressure air from the air compressor flows to the inner cavity of the air duct splitter below the reamer bit through the central axle hole of the main axis of the raise boring machine, the axial center hole of the drill rod and that of the reamer bit. The air duct splitter divides the high-pressure air evenly into 6 puffs which are jetted out from the nozzles of air ducts to cool the hob on the reamer bit and meanwhile accelerate the falling of the slag generated during drilling. Figure 2 shows the cooling of the hob on the drill bit by high-pressure air in the process of raise air drilling.

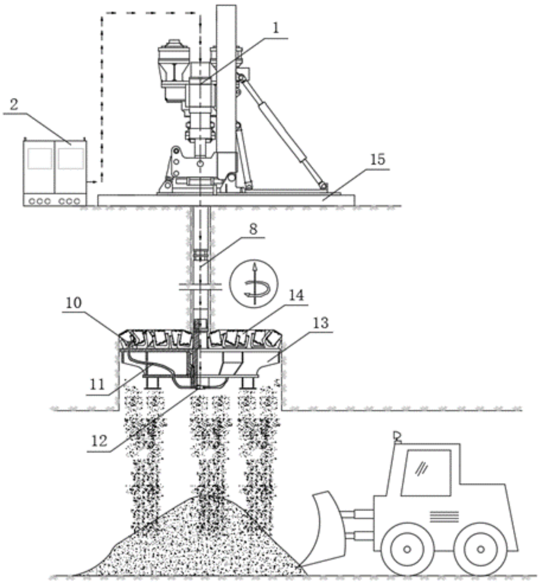

Figure 2. Schematic diagram of ream drilling in raise air drilling
1- Raise boring machine; 2- Air compressor; 8- Drill rod; 10- Air duct nozzle; 11- Air duct; 12- Air duct splitter; 13- Reamer bit; 14- Hob; 15- Steel beam of the boring machine

3 Calculation of raise air drilling parameter

The raise air drilling parameter mainly refers to the pressure of the circulation system, which is the theoretical basis for the layout of drilling equipment such as air compressors [10,11].

3.1 Basic hypotheses of the theoretical model

As the process of raise air drilling is very complicated, it is difficult to establish and solve a theoretical model that is completely in line with reality [12]. Therefore, the following basic hypotheses are required to set up a relatively simplified and accurate calculation model: fluids are all steady and uniform one-dimensional flow; the mass force of debris particles and high-pressure air is ignored; the aerothermodynamic process in the isodiametric section is a constant temperature; and the air satisfies the ideal gas equation of state.

3.2 Calculation of the pressure of circulation system

During pilot drilling with the raise boring method, the air enters the axial center hole of the drill rod through the central axle hole of the main axis of the raise boring machine and then enters the annular space between the drill hole and the drill rod through the water hole of the bit. For the calculation of the pressure of the circulation system, the outlet of the annular space is regarded as the starting point for pressure calculation and the inlet of the drill hole is regarded as the end point, and the annular pressure drop, bit pressure drop and rod pressure drop are calculated successively in the sequence of reverse flow based on the difference of fluid types in the drill rod and the annular space [13-15].

3.2.1 Calculation of the annular pressure drop

Based on the equation set for gas flow in the annular space, for the annular infinitesimal section with equal diameter,

$$\mathrm{d}p=\gamma_{\mathrm{mix}} g\left[1+\frac{fv^2}{2g\left(D_{\mathrm{h}}-D_{\mathrm{p0}}\right)}\right]\mathrm{d}z \tag{1}$$

Substitute parameters such as the coefficient of friction resistance in the annular space and the gravity density and velocity of the two-phase flow of debris particles and high-pressure air into equation (1), and separate and integrate the variables. The pressure at the outlet of the annular pressure is p_0, and the pressure p_b at the bottom of the hole is

$$p_{\mathrm{b}}=\left[\left(p_0^2+bT_{\mathrm{av}}^2\right)\mathrm{e}^{\frac{2ah}{T_{\mathrm{av}}}}-bT_{\mathrm{av}}^2\right]^{0.5} \tag{2}$$

Where T_{av} refers to the average temperature of the two-phase flow in the annular space, K; and h refers to the depth of the drill hole, m.

3.2.2 Calculation of bit pressure drop

The flow area, the pressure loss and the flow velocity increase when the air passes through the water hole of the bit. The air velocity will exceed the velocity of sound when the bit pressure drop exceeds a certain level. Two cases - hypersonic flow and subsonic flow are considered respectively in the calculation of bit pressure drop.

(1) Hypersonic flow

The velocity of air passing through the drill bit reaches the velocity of sound when the upstream pressure of the bit is greater than 1.89 times the downstream pressure. The drill rod pressure has nothing to do with the annular pressure under hypersonic jetting conditions. The upstream pressure p_a of the bit is

$$p_{\mathrm{a}}=\frac{Q\rho_{\mathrm{g}}g}{A_{\mathrm{n}}}\left[\frac{T_{\mathrm{a}}R}{sg^2M_{\mathrm{g}}k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{1-k}}\right]^{0.5} \tag{3}$$

Where, Q is the air flow rate, m^3/s; ρ_g is the gas density in the standard state, kg/m^3; A_n is the total area of bit nozzles, m^2; T_a is the temperature of air upstream of the bit, K; R is the universal gas constant; s is the density of air, kg/m^3; M_g is the relative molecular mass of air; and k is the specific heat capacity of air, J/(kg·K).

(2) Subsonic flow

The velocity of air passing through the drill bit is constant as subsonic velocity when the upstream pressure of the bit is less than 1.89 times the downstream pressure. The drill rod pressure is associated with the annular pressure under subsonic jetting conditions. The upstream pressure p_a of the bit is

$$p_{\mathrm{a}}=p_{\mathrm{b}}\left[1+\frac{R(k-1)\left(Q\rho_{\mathrm{g}}g\right)^{2}T_{\mathrm{b}}}{2sg^{2}M_{\mathrm{g}}kA_{\mathrm{n}}^{2}p_{\mathrm{b}}^{2}}\right] \tag{4}$$

Where, T_b is the temperature of air downstream of the drill bit, K; and other letters have the same meaning as above.

3.2.3 Calculation of rod pressure drop

Based on the equation set for gas flow in the drill rod, for the infinitesimal section of the rod with equal diameter,

$$\mathrm{d}p=\gamma\left(1\text{-}\frac{fv^{2}}{2gD_{\mathrm{i}}}\right)\mathrm{d}h \tag{5}$$

Substitute the coefficient of friction resistance, the gravity density and velocity of high-pressure air and other parameters into equation (5), and integrate from the bottom of the hole. The corresponding pressure is the upstream pressure of the drill bit. The pressure p_i at the inlet of the hole is the sum of the pressure at the bottom of the hole and the rod pressure drop, i.e.

$$p_{\mathrm{i}}=\left[\frac{P_{\mathrm{a}}^{2}+b'T_{\mathrm{av}}^{2}\left(e^{2a'h/T_{\mathrm{av}}}-1\right)}{\mathrm{e}^{2a'h/T_{\mathrm{av}}}}\right] \tag{6}$$

4 Conclusion

(1) Raise air drilling equipment mainly includes the hydraulic control system of the raise boring machine, the air-cooled cooler, the air compressor, the slag collector installed at the inlet of the shaft and the bit cooler installed on the reamer bit.

(2) During pilot drilling, the high-pressure air passes through the main axis of the boring machine, the drill rod, the water hole of the bit and the annular space between the drill hole and the rod successively, discharging the broken rock debris at the bottom of the hole to the ground. During ream drilling, the high-pressure air passes through the main axis of the boring machine, the drill rod and the air tube splitter below the bit successively, cooling the rock breaking hob. The high-temperature hydraulic oil from the hydraulic control system of the raise boring machine is cooled with the air-cooled cooler.

(3) According to the analysis on the pressure of the circulation system, the annular pressure drop, the bit pressure drop and the rod pressure drop are calculated respectively in the sequence of reverse flow based on the structure and fluid type of the drill rod and the annular space.

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