Development and Application of the special drilling rig for oblique guide hole

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Abstract. For the construction conditions of long-distance inclined drilling in roadway or chamber, a new type of self-moving hydraulic top-drive drilling rig is developed independently. Follow the research steps of the overall design, the key-parts design, the hydraulic system design, the industrial test. The main functional organization of the oblique-guide-hole drilling machine includes the power head, the feeding device, the power source, the drill pipe delivery installation, the rig control system, the hydraulic transmission system. The special oblique-guide-hole drilling rig realizes the construction requirement of any inclined drilling of 0–90°, at the same time, it can meet the technical requirements of the directional drilling assembly, that is the combination of down-hole motor, non-magnetic drill collar and Wireless while drilling. The track of long-distance oblique drilling is precisely controlled. The field test of the special oblique-guide-hole drilling rig is at Changlongshan Pumped Storage Power Station in Zhejiang, China. The actual guide hole has an inclined length of 289.5m, and the deviation slope of the borehole is controlled within 2.86‰. It is successfully completed the anti-shaft guide hole in the lower section of the 1# diversion system high-pressure pipeline safely, quickly, and efficiently.

1. Introduction

The pressure pipelines of pumped storage power stations in China are normally arranged in the pattern of long-stance and large-dip-angle inclined shaft, with a slope angle ranging from 45° to 60°. In the past, the pilot shaft of the pressure pipeline in pumped storage power stations was mostly constructed by climbing method. The climbing construction mode requires the workers to enter the face of tunnelling, where the working environment is harsh and the risk is high [1-2]. At present, for most pressure pipe shafts, the method of directly drilling into the guide hole through the reverse drilling rig is adopted, leading to difficulty in controlling the guide hole trajectory. The deviation slope of most guide holes is more than 1%, and many of them are beyond the excavation boundary line of the pressure pipe, which makes it very difficult to excavate. In addition, backfill concrete is needed, which creates unnecessary waste [3]. Aiming at the technical problems existing in the construction of long-distance inclined guide hole, a set of special drills for inclined guide hole is developed.

Considering the small construction space and high directional requirements of inclined hole in roadway of pumped storage power stations, this drill adopts the function of power head rotation, dip angle adjustment mechanism of borehole and precise adjustment of dip angle lock mechanism to realize directional drilling of inclined guide hole. The development of special drill is carried out...
according to the following development ideas: overall design of drill, design of key parts, design of hydraulic system of drill, industrial test.

2. Overall design and technical parameters of drilling rig

The overall design of the drill rig is determined through empirical calculation and comparison of performance parameters with similar foreign models. The drill rig is composed of shackle device on the drill pipe, walking mechanism, guide rail, power head, dip angle adjustment mechanism, hydraulic system and control system. All parts of the drill rig (including pump station of hydraulic system, power head, drill frame, guide frame, etc.) are installed on the steel track chassis, so as to realize the compact layout of inclined hole drill [4-5].

Among them, the power head is responsible for driving or driving the rotary work of the drill tool, the shackle device on the drill pipe is responsible for realizing the mechanical unscrew of the drill tool, and the dip angle adjustment mechanism and the dip angle lock mechanism are responsible for controlling of drill angle. The control console, rig walking control console, circuit switch and mud valve are all located in the driller room on the side of the frame at the front of the driller, which is very convenient for driller to control.

As shown in Fig. 1, the drill hole angle ranges between 0 ° and 90 °, equipped with a drill pipe (Φ89mm), the hole diameter reaches 190 mm. Concrete drill parameters are as follows:

**Table 1. Parameters of inclined holes drilling rig.**

| Serial number | Parameter             | value       |
|---------------|-----------------------|-------------|
| 1             | Motor drive power     | 90 kW       |
| 2             | maximum hoist capacity| 500 kN      |
| 3             | Power head rotary torque | 1 600 N·m |
3. Key parts design

3.1. Power head design
The power head of the inclined hole drill rig should have three functions: ① Drive drill pipe to rotate back; ② Bears the reaction force generated during drilling; ③ serve as the channel for mud to enter into drill pipe [6].

The power head is driven by the direct gear box of low-speed and high-torque hydraulic motor [7-9].

1) Related factors of power and torque required by power head [6]

\[
P = P_x + P_m + P_g
\]

(1)

where \( P \) is the power required by power head, kW; \( P_x \) is the power required by drill rig to cut rock, kW; \( P_m \) is the power consumed by the friction between the drill bit and the bottom of the hole, kW; \( P_g \) is the power required to drive drill pipe to rotate back, kW.

2) According to the construction conditions of the inclined guide hole, roller bit or drag bit is usually adopted, so the power required for the drill bit to cut rock is [10].

\[
P_x = \frac{m \cdot \delta \cdot h^{0.75} \cdot n \cdot F}{3 \times 10^4}
\]

(2)

where \( m \) is the number of hard alloy or scrapers on the drill bit; \( \delta \) is the compressive strength limit of rock, MPa; \( h \) is the biting depth of each scraper, cm; \( n \) is the rotating speed of the bit, r/min; \( F \) is the area of the detritus at the bottom of the hole, cm².

3) power consumed by the friction between the bit and the bottom of the hole [10]

\[
P_m = \frac{B \cdot f \cdot C \cdot n \cdot (R^3 - r^3)}{1432 \times (R^2 - r^2)}
\]

(3)

where \( B \) is a coefficient, ranging within 1.1~1.3; \( f \) is the friction coefficient between bit and rock \( n \) is the rotation speed of the bit, r/min; \( C \) is bit pressure, kN; \( R \) is the outer radius of the bit, cm; \( r \) is the inner radius of the bit, cm.

4) Power required to drive drill pipe to rotate back

The power required by the drill pipe to rotate back includes the gravity power of the rotary drill pipe, the friction between the drill pipe and the hole wall, and the additional power after applying the drilling pressure [8-10].

\[
P_g = C \cdot r \cdot d^2 \cdot L \cdot n^{1.7}
\]

(4)

\[
P_g = 1.15 \times 10^{-8} \cdot r \cdot L \cdot n^{1.6}
\]

(5)

where \( r \) is mud density, kg/m³; \( L \) is the length of drill pipe, m; \( d \) is the diameter of drill pipe, m; \( n \) is the rotary speed of drill bit, r/min; \( C \) is a coefficient, which is set to 18.8×10⁻⁸ for drilling inclined and straight hole.
According to the above formulas, the power required by the power head of this drill can be calculated to be \(P=110\)kW.

The formula of the speed and torque of hydraulic motor of power head is as follows:

\[
n = \frac{1000Q\eta}{q_0} \tag{6}
\]

where \(n\) is the rotary speed of motor, \(r/min\); \(Q\) is the flow rate at motor inlet, \(mL/s\); \(\eta\) is the volume efficiency of the motor, \(q_0\) is the motor displacement, \(mL/r\).

\[
T = \frac{Pq_0\eta_m}{2\pi} \tag{7}
\]

where \(T\) is the torque of motor, \(N\cdot m\); \(P\) is the pressure during operation, \(MPa\), \(q_0\) is the motor displacement; \(\eta_m\) is the mechanical efficiency of the motor.

The calculation formula of hydraulic pump capacity is as follows\(^6\):

\[
q_0 = \frac{1000Q^2}{nQ_n} \tag{8}
\]

where \(q_0\) is the displacement of the pump, \(mL/r\); \(Q\) is the actual output flow of the pump, \(m^3/s\), \(Q_n\) is the theoretical flow of the pump, \(m^3/s\); \(n\) is the rated rotary speed, \(r/min\).

According to the above formulas, the rotary speed of power head motor of this drill rig can be calculated to be \(n=65\)r/min, torque is \(T=20000\)N\cdot m, the hydraulic pump displacement is \(q_0=2100\) mL/r.

In the process of borehole construction, due to the complex and diverse geological conditions, the risk of in-hole accidents is very high. In order to enhance the ability to deal with accidents, the actual capacity of the power head should be appropriately increased. Therefore, the selected power head model is MS35, the hydraulic pump displacement is 3494mL/r, the maximum speed is 100r/min, the output power of the power head is 182kW, the maximum output torque of the power head is 38888N\cdot m, and the maximum rotary speed of the power head is \(n=48\)r/min.

Hydraulic power head can realize stepless adjustment of power head torque and speed, which can meet the requirements of drilling rig speed and torque in different formations. The development of full hydraulic feed system can meet the requirements for feeding force adjustment in different formations and drilling depths, and is of great significance to the realization of the overall performance of the drill rig.

Through the comparative analysis of three driving modes, namely the drive mode of hydraulic motor via the reducer and then the gearbox, direct drive mode of hollow low-speed high torque motor, drive mode of low-speed high-torque hydraulic motor via gear box, the drive mode of low-speed high-torque hydraulic motor via gear box is adopted, and the drive mode of the hydraulic motor via 2 gears is designed. The overall structure of the power head was shown in Fig. 2.

The power head adopts the combination of hydraulic shift and mechanical shift, which can ensure the rotation speed to be adjusted from 0r/min to 180r/min. Power head float adopts the floating structure of main shaft, which effectively protects the thread of drill pipe and extends the service life of drill pipe. The power head box is a strong force-bearing part, bearing the torque required for drilling. It is made by welding of high strength steel plate, and the welding stress is eliminated through annealing to ensure sufficient strength and stiffness.
3.2. Transmission case design
Since the low-speed high-torque transmission washing system is selected, which meets the requirement of low-speed high-torque power output during directional drilling of inclined hole, and simplifies the structure of the transmission box. It adopts two-speed transmission to meet the requirements of low-speed and high-speed drilling, and meets the requirements of various working conditions by combining the stepless variables of the pump [11].

The transmission ratio of two gears: \( i_1 = 1.318 \) and \( i_2 = 0.758 \)

1. Design calculation of a pair of gears with transmission ratios of 1.318: pinion speed \( n_1=48 \), main gear speed \( n_2=36.418 \); the transmission ratio \( i=1.318 \); the torque transferred by the input shaft \( T_1=38888N \cdot m. \); the motor is driven by straight gear, and the main engine is designed with 8 degrees of low speed; the pinion teeth \( Z_2=29 \).

2. When transmission type is reduced-speed transmission: gear meshing type is external gearing; the spiral angle type is straight teeth; the gear modification mode is no modification at tooth; control mode of tooth surface pitting: no pitting of tooth flanks is allowed; the gear is made of carburized quench steel 20CrMnT, and the quality control grade for heat treatment of the gear material is MQ-intermediate; the service life is designed to be 3 years; total design life is 25920h.

3.3. Feeding device
The feeding device of drill is fully-hydraulic, which can realize stepless adjusting of feeding force. If the conditions permit, the feeding process should be increased as much as possible to achieve long stroke continuous feeding, so as to reduce the auxiliary time in drilling, improve efficiency and prevent drilling accidents from happening. Sufficient feed force and large rotary torque should be set.
The adjustable range of tilting angle of feeding mechanism should be adapted to the design depth and different construction conditions, and the tilting angle must be adjusted easily. The feeding mechanism should be coordinated with the whole machine to increase its adaptability [12].

The chain wheel of the motor chain typed feeding mechanism is directly driven by the motor. The rotating moments of the motor in both rotation directions are the same, and its maximum lifting force is the same as the maximum feed. There are no restrictions on the design of the feeding stroke, and there are certain advantages in the construction of the guide hole, which enables the construction of the long-distance pilot hole. Therefore, of the small drills with feed force less than 200kN, many adopt the motor - roller chain drive mechanism.

Hydraulic cylinder feeding mechanism directly drives the power head to push and pull using hydraulic cylinder, without the intermediate force component, thus the structure is simple and the work is reliable, not only the manufacturing cost is low, but also the construction efficiency is high. However, its disadvantages are also obvious. Since piston rods or cylinder blocks need to be extended, the cylinder manufacturing is difficult, and the size of the drill rig is normally large, which is not convenient to be transported.

Since the maximum pulling force of the large-scale directional drilling rig is large, the above oil cylinder and chain drive cannot meet the requirements of its operation, and its chain or oil cylinder must be specially manufactured. In addition, it is very difficult to manufacture the oil cylinder with big cylinder diameter and long-stroke. As the gear transmission mode enjoys advantages such as large transmission force, small size, easy lubrication, good abrasion resistance and long service life, the large-scale directional drill generally adopts gear rack transmission.

Through comparative analysis of motor chain feeding mechanism, hydraulic cylinder feeding mechanism and gear rack feeding mechanism, the gear rack feeding mechanism is finally adopted.

The feeding gear shaft structure is a double bearing supporting form, which effectively avoids the instability of the cantilever structure, improves the bearing capacity of the feeding device. In addition, it is able to meet the needs of long-distance transmission and the manufacturing cost is relatively low.

In the feeding device, four motor reducer-gear devices are arranged symmetrically, and the whole structure is under uniform stress.

3.4. Drill pipe conveying and installation device

Through analysis of the working condition of the inclined guide hole drilling, the automatic conveying and installation device is designed. The process is trial-manufacture, then assembling and debugging, finally structure improvement. Considering the heavy weight of drill pipe, screw drill pipe and drill collar as well as the difficulty of installation, the automatic conveying and installation device of drill pipe is designed, which realizes the automatic installation and disassembly of drill pipe.

Lifting device can realize the rotating lifting of drill pipe, improve the efficiency of drilling and reduce the labour intensity of workers, shorten the auxiliary time for lifting and lowering drill pipe, and improve the comprehensive drilling efficiency of inclined guide hole. The maximum lifting force is designed to be 500kN.

The bracket device is driven by oil cylinder. When drilling, cylinder piston shrinks to the position lower than the drill frame table; when the bracket drills, the piston protrudes above the drill surface. This device improves the accuracy of alignment of drill pipe in the process of loading and unloading the drill rig and reduces the damage of tool joint thread. Different bracket support can be replaced according to different drill pipe.

The front and rear clamps of the automatic screw-on and screw-off device of the drill pipe are installed on the same bottom plate, with two double-acting oil cylinders being adopted respectively to achieve clamping/loosening of the drill pipe. The front clamp has the function of clamping and guiding straightening drill pipe, and adopts the oil cylinder to clamp the drill pipe, which has good alignment performance. When unloading, the joint thread of drill pipe is less worn, and the roller guide sleeve exerts a small abrasive action on the drill pipe surface in the process of drilling. Under the action of oil cylinder, the screw-off mechanism drives rotation of the rear clamp, thus can easily
remove the first button of drill pipe. The automatic screw-on and screw-off device of the drill pipe can move along the guide rail in response to an emergency of drill pipe stuck, and thus the capacity of the drill to deal with accidents is improved.

4. Hydraulic system design of drill rig

The drilling, speed adjustment, braking, lifting and other functions of this drill are all completed by hydraulic transmission. Through analysis, evaluation and comparison of the system and components, a comprehensive and coordinated zonal control of hydraulic transmission is realized by the electromagnetic valve. The clamping, walking, angle adjusting, crane rotation and supporting arm of the rig are also completed by the hydraulic system. During drilling, 4 motors are responsible for feeding and 2 motors are responsible for rotation.

Since the function of this drill is diversified and complex, we must consider a set of hydraulic system to control the action of various mechanisms accurately and harmoniously. Therefore, the design scheme of electro-hydraulic proportional valve control combined with variable system of remote transmission is adopted. The electro-hydraulic proportional valve is a kind of element. The working principle is that the proportional electromagnet in the valve produces the corresponding action according to the input voltage signal, causes the working valve spool to produce the displacement and the size change of valve orifice, thus completing the output of pressure and the flow output that are proportional to the input voltage [13-15]. Compared with the switch valve, the proportional valve can simply carry out remote automatic continuation of oil pressure, flow rate and direction.

The hydraulic system of drilling machine adopts the combined design scheme of electro-hydraulic closed circuit and open load sensing circuit. The main power station motor drives the power separation box directly, forming three working circuits. The function of power head rotation and power head push-pull are realized based on closed circuit, and controlled by electric proportional handle. Lifting device, clamping shackle and other auxiliary actions of drill area realized based on open load sensing circuit, and the flow rate is stepless adjustable. The clamping shackle is electromagnetically controlled. The main rig is driven and positioned under the oil supply from the power station on the main rig, with open load sensing circuit adopted [16]. When walking, the drill can be controlled by the controlling handle. Manual valve control is used in lifting device.

5. Field tests

The high-pressure pipe of the water diversion system of the pumped storage power station in Changlongshan of Zhejiang China arranged in the one-tunnel and two-machine layout, which is composed of high-pressure pipe, bifurcation pipe and high-pressure branch pipe, adopting steel pipe lining. The diameter of the excavation section is 6.5m. The central elevation of the middle flat segment is 1210m, and that of the lower flat segment is 947m. The pipe diameter of the lower segment of inclined shaft is 6.3m, which is reduced to 4.8m at the end of lower segment. The pipe diameter of the lower horizontal segment is 4.8m, which is connected with the branch pipe. The turning radius of 4 turning section of high-pressure pipeline is 30 m, with turning angle of 53 °. The underground water level of the high-pressure pipeline section is high, the water head height of natural groundwater is 30 to 300m, and the groundwater is mainly dominated by bedrock fissure water.
The diagram of inclined guide hole drilling is shown in Fig. 3. Field construction drawing of drill is shown in Fig. 4. The borehole diameter in design is 190mm, while the that in actual construction is 190mm. The dip length of drill hole in design is 298.58m, while that in actual construction is 289.5m, with dip angle of 53°. The adaptability of the drilling process is verified by industrial field experiment with random dip hole of 0 to 90°.

The curve of partial slope change of inclined hole is shown in Fig. 5. The drill partial slope of special drilling rig for inclined hole is within 2.86‰. The hole trajectory is straight and smooth without any significant changes in the dog-leg angle, the hole diameter is regular and the hole wall is flat, which is basically consistent with the borehole trajectory curve designed by the inclined guide hole, guaranteeing the installation and lowering of the drill pipe of the reverse shaft in the inclined guide hole.
6. Conclusions

We draw the following conclusions from this study of the special drilling rig for oblique guide hole:

(a) The special drill for inclined hole is running smoothly. The function and action of the power head, power source, feed device, drill pipe conveying and installation system, hydraulic system and other structural components are balanced. Drilling action, speed adjustment, braking, lifting and other actions of rig can be precisely controlled through hydraulic system. The overall system design of drill is reasonable, which meets the technical requirements of engineering construction.

(b) The special drill for inclined guide hole can adapt to the complex construction environment of underground space such as roadway or chamber, without the requirement of on-site assembly or integral crane. By using its own walking device, it can realize rapid emplacement and migration, which greatly reduces the use of auxiliary equipment such as crane, transport vehicle, slide and improves the comprehensive efficiency of drilling engineering construction.

(c) The special drill for inclined guide hole is equipped with an adjustment system of rig dip angle, which can meet the requirements for drilling construction of arbitrary 0 ~ 90 ° inclined borehole. At the same time, it can adapt to the technical requirements of the directional drilling tool combination of screw power drill, non-magnetic drill collar and wireless random drill instrument, and monitor the real-time change of track during the long-distance inclined drilling process. By analysing the data, the trend of borehole is predicted, and the deviation of borehole trajectory is corrected in time, so that the actual borehole trajectory is basically consistent with the design value.

(d) The special drill for inclined guide hole is equipped with a 1600N•m power head, which meets the technical requirements for rapid drilling in hard rock formations. At the same time, the lifting force of the inclined hole drill is up to 500kN, which can timely solve the hole accidents in the unstable stratum stuck, and realize the fast and safe drilling of the long-distance inclined hole.

(e) Industrial field test of special drill of inclined guide hold was carried out. The slope length of borehole under actual construction is 289.5m, and the deviation slope of the borehole is controlled within 2.86‰. The drilling task of the reverse shaft hole of the lower inclined section of 1# high-pressure pipeline of water diversion system of pumped storage power station in Changlongshan of Zhejiang was completed, which has created good conditions for the countershaft hole-expanding construction.
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