The influence of the drilling rate of the raise boring machine on the stability of the surrounding rock of a inclined shaft with large dip angle

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Abstract. The drilling method of counter-well drilling rig has become an important construction method for the construction of large inclination Angle pressure pipeline in pumped storage power station. In order to study the effect of the drilling rate on the stability of the surrounding rock of the inclined well. The method of numerical analysis is used to simulate the drilling rate of backwell drilling machine by changing the drilling depth of certain calculation step, and the drilling depth is along the inclined shaft line. The selection of drilling parameters is optimized and the drilling rate of the reverse well rig is determined. The results show that the tunneling rate has a significant influence on the deformation rate of surrounding rock and the change rate of stress gradient in the process of drilling with reverse-well drill. With the increase of drilling rate, the deformation rate and the change rate of stress gradient increase. The variation amplitude of the surrounding rock deformation and stress value at the monitoring point increases first and then decreases, and finally tends to be stable. Under this formation condition and drilling scheme, the deformation of surrounding rocks in wellbore after drilling at the same depth is small, and the effect of stress disturbance is not significant. The maximum deformation of surrounding rocks in inclined Wells is only 0.27mm, and the strong disturbance zone is about 2.0m. Combined with field drilling test results, the optimal drilling rate of reverse well reaming is determined to be 1.2m/h.

1. Introduction

Large-scale pumped-storage power stations are usually built in mountainous areas with a certain elevation difference. By taking advantage of the elevation difference of the mountain reservoir under the mountain, water flow from the mountain reservoir to the mountain reservoir at the peak of power load to convert the gravitational potential energy of the water into electric energy, and when the power load is low, the water from the mountain reservoir is pumped to the mountain reservoir, thus realizing the role of power frequency modulation, phase modulation and power grid stabilization [1-3]. The inclined wells of large inclination pressure pipelines of pumped-storage power stations are mostly constructed by the pilot well method. First, the small-diameter pilot well is constructed, then the drilling and blasting method is used to expand from top to bottom, and finally the pressure pipeline supporting structure is installed [4]. However, when the pilot shaft is used to construct the inclined shaft in the initial stage, the slag discharge efficiency is low when the drill and blast method expands due to the small diameter of the pilot shaft. To solve this problem, Liu Zhiquiang from Beijing China Coal Mine Engineering Co., Ltd. used the LM-200 raise boring rig to drill the inclined shaft for the first time in the construction of Beijing...
Shisanling Pumped Storage Power Station in 1992, and completed two long distance and large inclination angle pressure pipeline slant wells with a length of 203 m and 236 m, a diameter of 1.4 m and an inclination angle of 50° [5], which has a deflection rate of only 1.41%. Raise boring rig is known as "the construction of the breakthrough technology reform in hydropower system", which fundamentally solves the safety and occupational injury problems of the previous hydraulic system using the can-climbing method to manually excavate inclined well guide well, fills the blank of mechanized construction of large inclined well in China, and leads the development of inclined well construction technology in power station. Subsequently, the raise boring rig was used as an important equipment and technology for drilling the pilot well of the pressure pipeline inclined well, and it has been used in many pumped storage power stations such as Taishan, Yixing, Langyashan, Pushihe, Zhanghewan, Xilongchi, Fengning, etc., which is successfully applied in the construction of vertical shaft/inclined shaft pressure pipeline. Raise rig drilling utilizes the space and production system in the lower tunnel. After the directional drilling guide hole is first drilled, the reaming bit is connected horizontally below, and then the reaming drilling is carried out to form the wellbore, and during the reaming drilling, the rock slag falls on its own weight, realizing the high-efficiency drilling with large volume rock breaking and no repeated crushing [6-11]. The stability of the wellbore surrounding rock of raise drilling has become one of the key influencing factors restricting the success of raise drilling. For pumped storage power stations, the pressure pipeline inclined shaft is arranged inside the mountain. Due to the structural characteristics of the mountain, the stress and pore water pressure of the wellbore surrounding rock are different, and the nonlinear behavior of the surrounding rock medium of the wellbore is more prominent; in addition, raise drilling process is a typical unloading process. During the reaming process of the raise boring rig, the reaming diameter, drilling rate, drilling pressure and other parameters have different degrees of influence on the stability of the surrounding rock structure of the raise. To avoid drilling accidents caused by the instability of the surrounding rock of the wellbore during the reaming process of the raise boring rig, in this paper, the effect of drilling rate of reverse well drilling on the stability of inclined well surrounding rock of pressure pipeline in pumped storage power station is studied on the background of the raise boring drilling engineering.

2. General situation of engineering geology and numerical analysis plan

2.1. General situation of engineering geology

The main buildings of the water delivery system of the pumped-storage power station include the inlet/outlet of the upper reservoir, the main diversion tunnel, including the upper flat section (including the first-level inclined shaft section), the second-level inclined shaft section, the middle flat section, and the third-level inclined shaft section and lower flat section, upstream surge chamber, diversion branch pipe, diversion branch pipe. Among them, the first grade inclined well has a length of 77.5 m and a dip angle of 54.4°. Its geology is the second layer of the second stage of the Upper Cretaceous Jianguan Formation (K<sub>2j</sub>2<sup>2</sup>). The lithology is purple-red thick to the middle and thick layers. Fine-grained sandstone is mainly composed of a small amount of thin mudstone and siltstone; the length of the second-level inclined well is 272.2m, and the dip angle is 54.4°. The geology here is the first layer of the second member of the Jiaguang Formation of the Upper Cretaceous(K<sub>2j</sub>1<sup>4</sup>) and the fourth layer of the first section (K<sub>2j</sub>1<sup>4</sup>), the lithology of K<sub>2j</sub>2<sup>2</sup> is purple-red siltstone interbedded, and the lithology of K<sub>2j</sub>1<sup>4</sup> is mainly purple-red argillaceous siltstone and fine-grained sandstone; the length of grade 3 inclined well is 298.96 m, with an inclination angle of 55°. The existing geology is dominated by the first member of the Upper Cretaceous Jiaguan Formation (K<sub>2j</sub>1<sup>1</sup>, K<sub>2j</sub>1<sup>2</sup>, K<sub>2j</sub>1<sup>3</sup>). The lithology is mainly purplish-red siltstone, medium grained sandstone, and coarse-grained sandstone and conglomerate. The schematic diagram of the project layout is shown in Figure 1.
2.2. Numerical analysis scheme

The existing rock loading rate and unloading rate have a significant impact on the mechanical characteristics of rock mass \cite{11,12}, and show a certain regularity. During raise drilling, the surrounding rock of the wellbore continues to load and unload cycles and stress transfer. During the process, the higher the loading and unloading rate, the stronger the ability of the rock mass to release elastic energy, and the more brittle failure will occur. The drill bit reaming diagram of the raise rig is shown in Figure 2. In this simulation scheme of times value, according to the actual project, the diameter of the raise-drilling 3-level inclined well is 2.5 m, and the interval section with an elevation of 600-662 m is selected for simulation analysis, and the formation is K3. \cite{13,14} According to the design plan of the raise boring rig for drilling a grade 3 inclined well, considering the disturbance range of the surrounding rock of raise drilling, a three-dimensional finite element calculation model is established, as shown in Figure 3, to perform numerical analysis of the stability of the surrounding rock of the raise.

According to the wellbore depth conditions of the numerical analysis section, a vertical uniform load of 2.86 MPa was applied to the top of the model, and a trapezoidal load of 2.86 MPa was applied to the top of the model and 4.35 MPa to the bottom. Raise drilling is a typical unloading process. The speed of unloading is the advancement rate \cite{13,14}. Based on the assumption, the drilling depth is 8.0 m along the axis of the wellbore, and the drilling depth along the axis of the inclined well within a certain calculation step to simulate the drilling rate of the raise boring rig, five numerical simulation schemes were designed to simulate the evolution law of the deformation field and stress field of the raise boring surrounding rock under different driving rates when the drilling scale of every 1000 calculation steps of FLAC3D program was 0.4 m, 0.8 m, 1.6 m and 2.4 m. The plan of reaming drilling and the layout of monitoring points are shown in Figure 4.

According to the on-site engineering geological survey report and preliminary data, the rock integrity factor KV>0.55 of the inclined well in the numerical analysis section accounts for 42.2%–85%, and the average integrity factor is 0.55. Indoor physical and mechanical tests determine the physical and mechanical parameters of numerical calculations. The average compressive strength is 44.3 MPa, the softening coefficient is 0.72, the elastic modulus is 19.2 GPa, the Poisson's ratio is 0.24, the dry density is 2.434 g/cm$^3$, the cohesion is 0.47 MPa, and the tensile stress is 3.13 MPa, the shear stress is 4.0 MPa, and the internal friction angle is 38°.
3. Analysis of numerical calculation results

3.1. Deformation evolution characteristics of wellbore surrounding rock at different drilling rates

According to the numerical simulation calculation results, during the drilling of the inclined well of the same depth, the evolution law of the deformation amount of the monitoring point with the calculation steps at different drilling rates is extracted, and the result is shown in Figure 5.

![Figure 5](image_url)

(a) Vertical deformation
(b) Horizontal deformation

Figure 5 Evolution curve of surrounding rock deformation with different drilling schemes

It can be seen from Figure 5 that with the change of the drilling rate, the deformation of the surrounding rock on the top of the inclined well and the side walls also changes continuously, and shows a certain regularity: with the increase of the drilling rate, the deformation of the surrounding rock increases non-linearly, and every 1,000 steps of drilling from 0.4 m to 0.8 m, the increase in the deformation rate of the surrounding rock of the inclined shaft is the largest; with the increase of the advancing depth, the deformation of the surrounding rock at the monitoring points at different drilling rates will eventually stabilize, and the vertical deformation is 0.173 mm, the horizontal deformation is 0.019 mm, and the vertical deformation is about 9 times of the horizontal deformation. According to the numerical simulation calculation results, after drilling the inclined well of the same depth, the deformation distribution law of the surrounding rock at different depths from the free surface of the wellbore in the monitoring point profile at different drilling rates is extracted, and the results are shown in Figure 6. The total deformation cloud map of the inclined well monitoring profile with different drilling schemes is shown in Figure 7.

It can be seen from Figure 6 and Figure 7 that, without considering the creep of the rock, the amount of deformation and its distribution in the surrounding rock at the top of the inclined well at different drilling rates are basically the same, which can be relatively divided into strong deformation zone, weak deformation zone and extremely weak deformation zone; due to the smaller diameter of the inclined well and the smaller drilling depth, as well as the better drilling conditions of the formation rock, the influence range of the surrounding rock at the top of the inclined well is about 2 m, and the maximum deformation of surrounding rock of inclined shaft is only 0.27 mm.
Figure 6 Deformation distribution curve of surrounding rock at the top of inclined well with different drilling schemes

Figure 7 Cloud diagram of total deformation of monitoring section of inclined well with different drilling schemes

3.2. Stress evolution characteristics of wellbore surrounding rock at different drilling rates

In the process of drilling inclined wells of the same depth, the evolution law of the stress of the monitoring point with the number of calculation steps at different drilling rates is extracted, and the results are shown in Figure 8. It can be seen from Figure 8 that with the change of the drilling rate, the stress of the surrounding rock at the top of the inclined well and the side walls also changes continuously, and shows a certain regularity: with the increase of the drilling rate, the vertical stress of the surrounding rock increases nonlinearly. The horizontal stress decreases non-linearly, and every 1000 steps of drilling is 0.4 m to 0.8 m, the surrounding rock stress change rate of the inclined well is the largest; with the increase of the advancing depth, the surrounding rock stress change range of the monitoring point at different drilling rates increase first and then decrease, and finally stabilize. The vertical stress is 3.89 MPa, the horizontal stress is 1.12 Mpa, and the vertical stress is about 3.5 times of the horizontal stress.

Figure 8 Stress evolution curve of surrounding rock with different drilling schemes

According to the numerical simulation calculation results, after drilling the inclined well of the same depth, the stress distribution law of surrounding rock at different depths from the free surface of the wellbore in the monitoring point profile at different drilling rates is extracted, and the results are shown in Figure 9. The maximum principal stress distribution cloud diagram of the inclined well monitoring section with different drilling schemes is shown in Figure 10. It can be seen from Figure 9 and Figure 10 that, without considering the creep of the rock, the maximum principal stress value and its distribution law in the surrounding rock at the top of the inclined well at different drilling rates are basically the same, which can be relatively divided into strong disturbance region, weak disturbance region and undisturbed region, and that is correspond to the evolution law of surrounding rock deformation;
surrounding rock stress in strong disturbance zone is released. The greater the gradient of maximum principal stress, the higher the risk of instability and failure of surrounding rock in inclined shaft; A stress concentration zone appears in the disturbance zone, and then as the distance from the free surface of the wellbore increases, the surrounding rock stress tends to the original rock stress and belongs to the undisturbed zone.

4. Determination of the optimal drilling rate
The actual raise rig drilling project uses the BMC400 raise rig developed by Beijing Zhongmeishan Engineering Co., Ltd. The main technical parameters of this rig are the pilot hole diameter 270 mm, the drill pipe diameter 228 mm, and the reaming diameter 1.4~3.5 m. The drilling depth is 400 m, the rated thrust is 1650 kN, the rated pulling force is 2450 kN, the rated speed is 0-22 rpm, and the rated torque is 96 kN·m. The applicable rock compressive strength is less than 250 MPa, and the drilling inclination is 45-90°. Using electro-hydraulic drive method [15]. The BMC400 raise drilling rig is fully suitable for the construction of the inclined shaft with a length of 298.96 m, a dip angle of 55°, and a rock compressive strength of 44.3 MPa in the background of this project.

In the initial stage of raise drilling and reaming, an experimental construction was carried out to optimize the drilling parameters. After setting the drill pipe speed to 7~10 rpm, after calculating and subtracting the pulling force occupied by the gravity and friction of the drilling tool when there is no load, it is 490 kN, the actual drilling pressure is 612~1225 kN, and the obtained drilling rate is 0.45~1.41 m/h. The particle size of the slag falling horizontally in the raise shaft is mainly 1~40 mm, and there is no large-sized rock falling. At the same time, considering factors such as the length of the raise shaft, the wear rate of the reaming hob inserts, the efficiency of raising slagging downhole and the optimization of construction organization, the parameters of raise drilling were finally determined as follows: the rotation speed is 10 rpm, the output tension of the reverse well drilling rig is 1592 kN, and the optimal drilling rate is 1.2 m/h under the condition of this formation.

5. Conclusion
In the process of reaming of the deviated well, as the drilling rate increases, the deformation rate and stress gradient change rate of the surrounding rock of the deviated well increase, but after drilling at the same depth, the deformation and stress variation range of the surrounding rock at the monitoring points with different drilling rates increases first and then decreases, and finally tends to be stable; the vertical deformation is about 9 times of the lateral deformation, and the vertical stress is about 3.5 times of the horizontal stress.

At different drilling rates, the deformation of the surrounding rock at the top of the inclined well, the stress value of the surrounding rock and its distribution are basically the same. The top of the inclined
well along the direction perpendicular to the axis of the wellbore, gradually extending from the free surface of the wellbore to the interior can be divided into strong deformation zones, weak deformation zone and extremely weak deformation zone, the corresponding maximum principal stress distribution can be divided into strong disturbance zone, weak disturbance zone and undisturbed zone; due to the smaller diameter of the inclined well and the smaller drilling depth, as well as drilling rock conditions are good, the maximum deformation of the surrounding rock of the inclined shaft is only 0.27 mm, and the strong disturbance zone is about 2.0 m.

After numerical calculation and analysis, under the conditions of the formation and the drilling plan, the excavation rate has a significant impact on the rate of deformation of the surrounding rock and the rate of stress gradient change, but the deformation of the surrounding rock of the wellbore is small after drilling at the same depth, and the stress disturbance effect is not significant. Combined with the actual drilling test on site, considering the impact factors of drilling rig performance, cutter tooth wear, slag discharge efficiency and construction organization, the optimal reaming drilling rate is determined to be 1.2 m/h.

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