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Research on Rapid Construction Technology of Large-diameter Deep Shaft for Highway Tunnels

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Abstract: Based on the large-diameter deep shaft project of Moxunshan tunnel, research on rapid construction technology of large-diameter deep shaft for highway tunnels has been carried out. Reasonably increasing the number of rock drills and adopting the "three small" technology for surrounding holes can improve drilling speed. The combination of different-order millisecond blasting and smooth blasting technology can effectively control the bulkiness of the rock muck after blasting, which not only improves the utilization rate of the borehole and the depth of the trenching footage, but also improves the rock muck loading speed. Through two winches and three buckets picking hooks in the shaft, rock muck loading and lifting are carried out alternately, which greatly improves the speed of rock muck discharging. By optimizing the construction organization form, the excavation speed is improved. The safety and continuity of deep shaft excavation were improved through the maintenance and management of equipment and technical training of umbrella drill operators.

1. Introduction

In recent years, with the further advancement of China's western development, the transportation road network has been continuously extended to the mountainous areas. The construction of deep and long tunnels has been booming[1-4]. To meet the ventilation requirements of long tunnels, shaft construction is also progressing towards greater depths and larger cross-sections. The construction progress of shafts seriously affects the tunnel construction schedule, for this reason, a large number of scholars have conducted a lot of research on the rapid construction technology of shafts. Zhou Baohong[5] relied on the Tianshan Shengli Tunnel 2# shaft project, compared and analyzed the impact of three vertical shaft lining construction schemes on the construction period, and concluded that the overall lifting type molded lining construction is the most efficient. Based on a pumped storage hydropower station project, Zhang Wenhui[6] shortened the construction period of the vertical shaft by using the reverse shaft method for the guide shaft excavation, followed by the positive shaft method to reach the designed excavation section after two reaming. Zhuo Yue[7] proposed the key technology of surface deep hole S-type pregrouting according to the water permeability problem of Gaoligongshan tunnel shaft of Darui Railway. Hu Zhiying[8] employed composite support as temporary support for soil vertical shafts, thereby shortening the construction period of the surge shaft in the hydropower station. Based on the experience gained from coal mine shaft construction, Tang Xie [9] compared and selected various layouts for the Micang Tunnel shaft, ultimately deciding on a single-well layout plan that combined single-layer formwork concrete lining with short-section excavation and masonry mixed operations. This approach yielded significant economic benefits. Liu Xiangyu[10] made a comprehensive discussion on the excavation equipment and advanced geological prediction of the shaft, and concluded that the excavation and detection of integrated equipment is the direction of future development. Xu Shiliang[11] conducted numerical simulation analysis on the stability of the surrounding rock and support structure of the ventilation shaft No.2 of the Qinling Zhongnan Mountain Highway Tunnel, validating the rationality of the high stress flexible support design. Guo Jilin[12] used air submerged hammer instead of traditional backhole drilling rig bit to improve the traditional backhole forward expansion method, effectively control the tilt of the guide hole, and formed a set of small diameter to depth ratio of vertical shaft backhole method of rapid construction methods. Chen Yingjun[13] applied the medium-deep hole blasting construction method to the excavation of ultra-deep vertical shafts with small sections, and improved the excavation efficiency of vertical shafts by optimizing the main processes.

Although the aforementioned research has extensively studied the rapid construction of vertical shafts and yielded numerous beneficial results, it primarily concentrates on the back well methods and lining construction methods for small-section vertical shafts. There are fewer researches on the rapid construction technology of large-section deep vertical shafts with positive shaft method. In this paper, relying on the large-diameter deep shaft project of Moxunshan tunnel, optimization and analysis from four aspects of drilling and blasting design, rock muck bulkiness and rapid rock muck discharging, construction organization and management and comprehensive management measures, to form a kind of rapid construction technology for large-diameter deep shafts, in order to provide certain reference for similar projects.

2. Project Overview

Moxunshan tunnel shaft intersects with the main line at K80+886, located on the right side of the main line. The elevation of the shaft is 3248.148m, the elevation of the bottom is 2800.148m, and the depth is 448m. The topographic features of the Moxunshan tunnel are shown in Figure 1

Topography of the shaft area of the Moxunshan tunnel (Left)
Moxunshan tunnel shaft microfacies (Right)

Figure 1: Topographic features of the Moxunshan tunnel

The level of surrounding rock of the shaft is III~V, which is divided into three surrounding rock sections, and the engineering geological conditions are as follows:

(1) Depth 0~56m: This section is class V surrounding rock, mainly block stone and strong weathering granite. The self-stabilizing ability is poor, and the sidewall is easy to be destabilized without support. In case of concentrated rainfall, the sidewall will be drenched or gush with water.

(2) Depth 56m~195m: This section is class IV surrounding rock, mainly medium-weathering granite, with joints and fissures developed. The rock quality is hard and the rock mass is relatively intact. The self-stabilizing ability is poor, and the sidewalls may drop blocks without support. In the case of concentrated rainfall, the sidewall will be drenched with water or water will come out in the form of drops.

(3) Depth of 195m to the bottom of the well: this section is Class III surrounding rock, mainly medium-weathering - slightly weathered granite, with joints and fissures developed. The rock quality is hard and the rock mass is relatively intact. The self-stabilizing ability is good, and the sidewall is basically stable without support. In case of concentrated rainfall, the sidewalls are wet or dripping with water.

3. Drill and blast design

3.1 Selection of drilling equipments

According to the on-site construction conditions, FJD-6B umbrella drilling frame with YGZ-70 rock drill and five YT-28 high-frequency rock drills was selected for the Moxunshan tunnel shaft project. Selection of diameter Φ25mm hollow hexagonal steel rods, rod length 4.2m, 3.5m, with a straight-shaped drill bit of Φ42mm.

Ventilation shaft excavation diameter up to 10m, the shaft working surface is larger, the working surface layout of more holes. In order to maximize the efficiency of drilling, it was decided to add a YT-28 high-frequency rock drill. This not only greatly shortens the drilling time, but also largely improves the drilling efficiency.

Peripheral holes drilling and blasting using the “three small” technology, that is, a small diameter drill bit, small diameter explosives and small diameter drill pipe as the characteristics of the shaft digging and support technology. The peripheral holes drilling bit from the original Φ42mm straight-shaped drill bit changed to Φ35mm. The diameter of the peripheral holes charge is changed from Φ35mm to Φ32mm, and the charge of other holes is not changed. Straight-shaped drill bit of Φ42mm cutting area of 1384.74mm^2, while Φ35mm bit cutting area of 961.63mm^2, the latter than the former reduced by 423.11mm^2. The smaller the contact area between the drill bit and the rock mass, the greater the pressure on the rock mass, and the easier it is to produce damage to the rock mass. The drilling speed of single hole is greatly improved, and the overall drilling efficiency has obvious improvement.

3.2 Blasting operations

FJD-6B umbrella drill is used in the construction of ventilation shaft excavation, equipped with YGZ-70 rock drill and five YT-28 high-frequency rock drills. Although some achievements have been made in blasting excavation footage, the excavation speed still needs to be improved. There are still problems such as poor digging efficiency, serious over excavation and under excavation, and low utilization rate of boreholes.

(1)Cutting method

Considering the design requirements of the vertical shaft of the Moxunshan tunnel and the actual situation on site, different-order millisecond blasting methods are adopted. The oblique auxiliary holes can not only increase the blasting free surface and reduce the minimum resistance line to provide compensation space for rock fragmentation, but also affect the occurrence and development of cracks in the rock after blasting.

(2)Smooth blasting

The cutting and auxiliary holes are still drilled using a straight-shaped drill bit of Φ42mm, while the explosives used are Φ32mm water-gel explosive rolls approved for tertiary coal mines, ensuring optimal cutting effectiveness and vertical shaft blasting progress. The surrounding boreholes of the vertical shaft are now drilled with Φ35mm drill bits. Small-diameter drill bits and explosive rolls are employed for drilling these surrounding holes, significantly reducing drilling time, enhancing efficiency, and virtually eliminating over- or underexplosion. Through enhancements in borehole diameter and charge structure, the distribution of explosives has been made more scientific and rational, resulting in a notable increase in blasting progress and substantial improvements in blasting effectiveness.

Through on-site practice, it has been proven that the combination of different-order millisecond blasting and smooth blasting techniques can significantly enhance the construction quality of ventilation shafts, thereby achieving rapid excavation. This method significantly increases the effective depth of the cutting advance, ensuring a steady increase in the utilization rate of the blastholes. The resulting vertical shaft cross-section is relatively regular, facilitating better ventilation and reducing the accumulation of harmful gases, thereby significantly improving the working environment for workers. The frequency and amount of over-excavation in vertical shafts have been significantly reduced, which is beneficial for anchor spraying support, greatly reducing the amount of support materials, lowering support costs, and significantly improving work efficiency.

4. Rock fragmentation and rapid slag removal

The size of the rock fragmentation after blasting directly affects the insertion of the grab piece and the filling coefficient of the grab bucket. The increase in the size of the stone blocks will increase the resistance of the grabbing block and reduce the filling coefficient. If the capacity of the grab bucket is large, the block size of the rock can be appropriately increased. The 0.6m^3 grab bucket used on site is suitable for block sizes below 300mm. The optimized blasting parameters are: borehole depth of 3.5m, borehole diameter of 35cm, single borehole charge of 2.4kg, borehole spacing of 800mm, borehole inclination angle of 90°, and minimum resistance line of 550mm. After optimizing the blasting parameters, 80-90% of the blocks are within 300mm in size. At this time, the time required for each bucket to grab rocks is 4-6 seconds, and the time required for the grabbing and unloading cycle of the grab bucket is 20-25 seconds. This is a significant improvement in excavation efficiency compared to before blasting optimization, where the time required for each bucket to grab is reduced by 6-14 seconds and the time required for the grabbing and unloading cycle of the grab bucket is reduced by 20-25 seconds.

The rock excavation on the working face is carried out by combining one Kubota 55 excavator (see Figure 2) with a central rotary rock grabbing machine (see Figure 3). Compared to the traditional single use center rotary rock grabbing machine, it has great advantages in both rock loading efficiency and usage cost. During the entire drilling process, a 4.0m^{3}bucket is selected for the main lift. For secondary lifting, a 3.0m^{3}bucket is selected for depths above 400m, and a 2.0m^3 bucket is selected for depths below 400m. Lift the ground with two winches. When grabbing slag, three buckets are used to remove the hooks underground, and the loading and lifting of slag are alternated, greatly improving the slag removal speed.

Figure 2: 55 type excavator

Figure 3: Central rotary rock grabbing machine

5. Construction organization management

The Moxunshan tunnel vertical shaft construction teams comprises three excavation teams and one shotcrete team. The excavation teams operate using a "3-8 system" for construction, completing a cycle that includes prescribed slag removal, shotcrete, and anchor rod installation. The vertical shaft excavation employs a method of single blasting for shaft completion in one operation, utilizing a construction organization that combines regular cyclic operations with parallel multi-process operations.

The rock section of the ventilation shaft is notably hard, leading to prolonged drilling times. Currently, the only ways to reduce drilling time are by increasing the number of drilling equipments and enhancing the technical proficiency of construction personnel, aiming to fulfill the requirements of scientific and rational cyclic operations. To minimize the time required for anchor spraying support, this process is conducted concurrently with the excavation. By integrating a small excavator with a central rotary rock grab, uninterrupted slag discharge from both the main and auxiliary buckets is achieved. Parallel operations are implemented for key processes like drilling, rock loading, slag transportation, and anchor spraying support, while parallel and intersecting operations are used for other auxiliary and main processes.

Field experience has demonstrated that single-operation well completion offers several advantages, including safer construction practices, faster well completion, material and cost savings, parallel processing of multiple tasks, and overall higher efficiency.

6. Comprehensive management measures

6.1 Management of blasting equipment

The management and use of explosives are of utmost importance in construction safety work and cannot be ignored. To ensure the continuous operation of vertical shaft blasting, it is necessary to establish a scientific and reasonable management system for blasting equipment:

(1) The pyrotechnic devices used for blasting are provided by specialized civilian explosive companies and delivered by dedicated delivery vehicles according to daily demand. No stops are allowed during transportation. There is no explosive magazine at the construction site. After the pyrotechnic devices arrive at the site, the project material administrator will check and accept them, and complete the relevant registration procedures.

(2) When the blasting personnel receive pyrotechnic products from the delivery vehicle, they must present a blasting certificate and a document signed by the supervisor. It is strictly prohibited to distribute explosive detonators to personnel other than the blasting personnel.

(3) Strict inspection shall be carried out before distributing explosives and detonators. Any unqualified, expired or ineffective explosives and detonators shall not be distributed. No one is allowed to handle unqualified, expired, or ineffective explosives and detonators without authorization.

(4) The detonators and explosives used in vertical shaft blasting construction are not allowed to be borrowed or sold without authorization. It is strictly prohibited to use explosives and detonators for any blasting activities other than construction.

(5) Only buckets are allowed to transport explosives underground, and commuting hours must be avoided. It is strictly prohibited to transport explosives during shift handover and personnel entering the well. Explosives and detonators are transported separately in batches and personally managed and used by blasting personnel.

(6) The key to the detonator is kept by the blaster, who must remove it from the detonator after each blast and carry it with him.

6.2 Equipment maintenance and management

The Moxunshan tunnel ventilation shaft project has proposed further refining regulations and systems to address safety hazards and inadequate management of electromechanical equipments in daily maintenance and upkeep.

(1) Complete regulations and operating procedures for various electromechanical equipments should be established. The improved worker operation procedures provide reliable guarantees for the normal operation of electromechanical equipments.

(2) The daily refined management system of electromechanical equipments should be actively promoted and implemented. The management mode of " designated personnel and equipment " should be actively promoted in the use, maintenance, and management of electromechanical equipments. By implementing this management model, the sense of responsibility and enthusiasm of operators can be greatly enhanced, while also improving the utilization rate of electromechanical equipments.

(3) Technical training for operational management personnel should be emphasized and strengthened. Through training, the overall technical level and literacy of operation and management personnel have been enhanced, providing strong support for the normal and safe operation of electromechanical equipments.

6.3 Enhance technical training for umbrella drill operators

In terms of training methods, a combination of on-site training and theoretical assessments is adopted to enhance the comprehensive skills of operators. During construction operations, material rewards are given daily to personnel who drill holes quickly and with high quality, based on on-site records and statistical data.

Through training, the operational proficiency of umbrella drill operators has significantly improved, with an average of 10 seconds saved per drill hole compared to before. The verticality and smoothness of the drilled boreholes fully comply with the specifications, eliminating over excavation and under excavation caused by borehole quality and improving the cycle progress.

7. Conclusion

This article, based on the construction of the Moxunshan highway tunnel vertical shaft project, investigates the rapid construction technology for large-diameter deep vertical shafts in highway tunnels. Through practical experience, the following conclusions have been drawn:

(1) By reasonably increasing the number of rock drills and adopting a vertical shaft excavation and support process featuring small diameter drill bits, small diameter explosives, and small diameter drill rods in the surrounding holes, the overall drilling efficiency has been significantly enhanced.

(2) The integration of different order millisecond blasting and smooth blasting techniques has notably improved the utilization rate of blast holes and the depth of excavation, effectively controlled over- and under-excavation, reduced support costs, and significantly increased work efficiency.

(3) Optimizing the blasting parameters effectively controls the fragmentation of the rock after blasting, thereby enhancing the slag loading speed. By utilizing two winches and three buckets to remove the hooks underground, the slag loading and lifting are alternated, significantly improving the slag removal speed.

(4) The excavation team adopts the "3-8 system" operation method, and the vertical shaft excavation adopts the construction method of one-time blasting and one-time completion. By optimizing the construction organization form, the completion speed of the well has been improved.

(5) By strengthening the maintenance and management of blasting equipment and devices, as well as providing technical training for umbrella drill operators, the safety, continuity, and progress of rapid excavation in deep vertical shafts have been improved.

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