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Excavation and Construction Technology of Diversion Tunnel under Complex Geological Conditions

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Abstract: During the construction of a diversion tunnel, geological problems often include faults, fragile strata, hard rock formations, karst landforms, etc., which may have adverse effects on the excavation and construction of the diversion tunnel. Based on the analysis of the engineering overview, this study designed a new construction technology for the excavation of water diversion tunnels in hard rock layers and high-karst areas. Based on tunnel seismic prediction (TSP) technology to achieve advanced geological prediction, combined with actual geological conditions, construction difficulties are analyzed. Then, detection technology is used to collect two-way travel time, amplitude, and waveform data. By processing and analyzing the detection image, the spatial orientation and length of the main tunnel during the construction of the diversion tunnel are calculated. After completing the construction ventilation and wind, water, and electricity layout, the excavation construction procedure is designed. In the specific excavation design, the tunnel curtain excavation technology, tunnel body excavation and support technology, excavation grouting technology, important unfavorable geological tunnel section excavation technology, upper/lower flat section excavation technology, upper/lower curved section excavation technology, and vertical shaft section excavation technology were elaborated. Finally, a plan was made for the reuse process of slag material and a construction quality control system was established. During the testing process, it was found that the antidamage coefficient of the side wall was above 0.9 after using the technology described in this article. Therefore, it indicates that the excavation construction technology designed in this article can ensure the support capacity of the side wall of the diversion tunnel, which is suitable for the excavation of the main tunnel during the construction of the diversion tunnel.

Keywords: diversion tunnel; excavation construction; complex geological conditions; TSP technology; detection technology; support design; excavation grouting; construction quality control

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1. Introduction

With the rapid development of China's economy and the acceleration of urbanization, water conservation and hydropower engineering construction have become important means to promote economic development, improve people's livelihoods, and ensure energy security [1]. As an important component of hydropower engineering construction, the excavation and construction technology of diversion tunnels has also received widespread attention and research. The progressiveness and practicability of the diversion tunnel excavation construction technology directly affect the efficiency and safety of the project construction, which is of great significance [2].

The construction technology of diversion tunnel excavation is a complex engineering system that requires the comprehensive application of multidisciplinary knowledge such as geology, mechanics, hydrology, etc. Reasonable construction plans and technical routes for different geological conditions and engineering requirements need to be developed, with the aim of improving the quality of engineering construction [3,4].

Yu et al. [5] comprehensively consider the impact of random changes in construction activity time, construction machinery failures, and risks such as landslides and water inrush on the construction of diversion tunnels and propose a method for selecting construction plans for diversion tunnels that considers the impact of risk factors. This method first establishes an optimization model for tunnel construction plans that considers the impact of risk factors, and then uses the Levy Flight Adaptive Chaos Particle Swarm Optimization (LFACPSO) algorithm to solve the model to obtain a set of construction plans. The LFACPSO algorithm introduces Levy flight to improve the ability of particles to jump out of local optima, while using a chaos algorithm to initialize particles and adaptively adjust particle inertia weight coefficients. Finally, the Intuitive Fuzzy Entropy Weighted Power Average (IFEWPA) method is used to select the final excavation construction plan from the set of options, taking into account expert evaluation hesitation. Jing et al. [6] elaborated on key technologies such as precise blasting vibration control, treatment measures for special geological conditions of tunnel sections, rapid lining of needle beam trolleys, and information construction for personnel tracking and positioning for the diversion tunnel at the head of the North South Main Canal of the Xiangjiaba Irrigation Area Project, which stabilized the deformation of the surrounding rock after excavation and ensured the safety of the lining structure.

Due to different geological conditions, there are many difficulties and challenges in the actual excavation construction process [7]. For example, complex tectonics, uneven geological body properties, and poor hydrogeological conditions have brought great risks and challenges to the excavation and construction of diversion tunnels.

In order to overcome these difficulties and challenges and improve the efficiency and safety of diversion tunnel excavation construction, this study designs new construction techniques for diversion tunnel excavation construction projects under complex geological conditions. This technology innovatively combines TSP technology for advanced geological prediction, uses detection technology to calculate the spatial orientation and length of the main tunnel, and designs multiple excavation construction techniques and quality control systems, improving the efficiency and safety of excavation of the diversion tunnel under complex geological conditions.

2. Project Overview and Construction Difficulties Analysis

2.1. Project Overview

The project is located in G City, with a total length of 11.4 km and a total of 1–4 diversion tunnels. It is a key and difficult project along the entire project line and a key node project. The construction length accounts for 82.6% of the total project length, with characteristics such as hard rock layers, large burial depth, long distance, and high pressure. Among them:

No.1 headrace tunnel: Located in the first section of the G City headrace tunnel project, the tunnel is 2.24 km long and has a geological condition of hard rock layers, which may have high karstification. It is necessary to pay attention to handling karst problems that may occur during the excavation process. The buried depth of the tunnel is 121.55 m. Tunnel 1 belongs to the starting section of the entire diversion tunnel and is relatively short in length. This section of the tunnel has a high water pressure, and it is necessary to consider the impact of water pressure on construction safety.

Headrace tunnels 2–4 are similar to tunnel 1, with lengths of 3.17 km, 3.06 km, and 2.93 km, respectively. Compared to the starting section of tunnel 1, the length is longer. The geological conditions of tunnels 2–4 are also hard rock layers, among which tunnel 2 may have high karst, and attention should be paid to the treatment of karst problems. Diversion tunnels 2–4 also have high water pressure, and it is necessary to design reasonable support and drainage measures to ensure construction safety.

The design and construction of this diversion tunnel aims to improve the utilization rate of local river water resources, strengthen the safety guarantee of regional drinking water, improve the regional water ecological environment, and optimize the allocation of regional water resources. The construction system layout is shown in Figure 1.

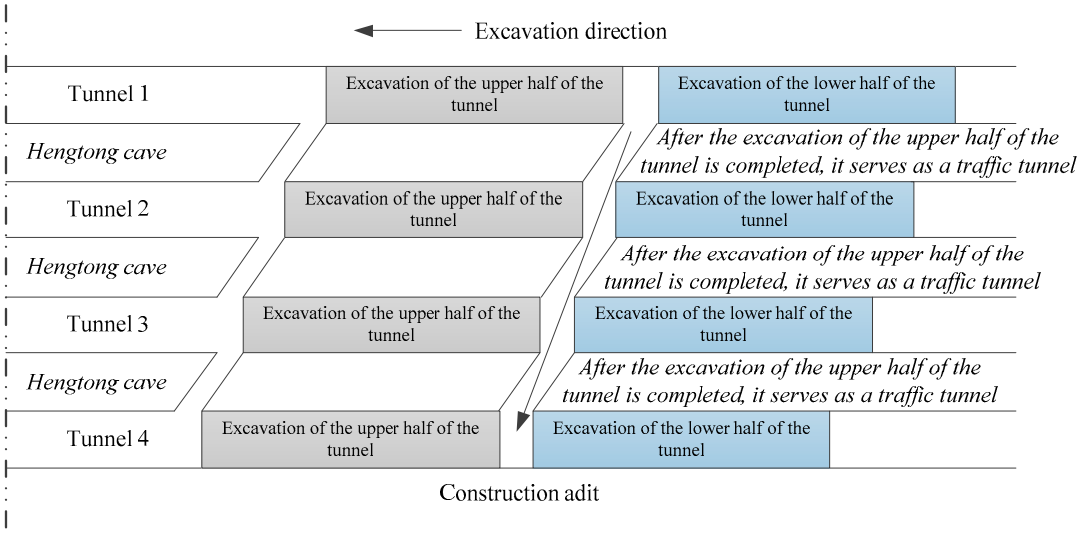


Figure 1. Construction system layout.

The total length of the diversion project is 11.4 km, with a total of four diversion tunnels. The upper part of the tunnel is excavated first, and after completion, it serves as a transportation tunnel, allowing the lower part to be excavated first. There is a construction adit left between the upper and lower parts.

2.2. Implementing Advanced Geological Prediction Based on TSP Technology

Step 1: TSP data collection and parameter settings.

TSP technology is a technique for predicting tunnel geological conditions using seismic methods. TSP technology is based on the principles of seismic wave propagation and reflection. By deploying seismic detectors on the ground or underground, they monitor and analyze the propagation and reflection of seismic waves in underground rocks in order to obtain geological information about underground rock formations in front of tunnels or potential work areas.

The prediction mileage range selected by TSP technology in the excavation project of the diversion tunnel is 44 + 700~16 + 632.357. On the basis of determining the relationship between the location and direction of the unfavorable geological body and the tunnel axis, the seismic source point is selected to arrange the measurement wall. This measurement wall is selected at the left wall position of the tunnel entrance. In addition, based on the actual geological conditions on site, the mileage of the receiver is determined, and the offset distance between the blast holes and the detector is reasonably set. A total of 24 blast holes are set on the same horizontal plane as the sensor, with a spacing of 1.5 m between each blast hole. The detector is placed in the casing according to the standard, directional calibration work is performed, and an anchoring agent is used to tightly connect the casing with the surrounding rock, ensuring that there is no gap between the casing and the surrounding rock, which is conducive to signal reception.

After connecting the entire instrument according to the operation process, the collection phase begins in preparation to collect data [8]. Finally, the finished explosive package is placed at a depth of 1.5 m in the blast hole, the blast hole is filled with water until it is saturated, then the muzzle is sealed for detonation. The propagation form of vibration waves excited by explosions is spherical waves, which propagate in the opposite direction to the sensor. When encountering unfavorable geological bodies such as karst and faults, some seismic wave signals will generate reflected waves and be received by sensors, while the remaining part will continue to propagate until it is completely consumed [9,10]. After completing the data reception of 24 shots, the on-site data collection work is completed.

The principle of TSP observation is shown in Figure 2.

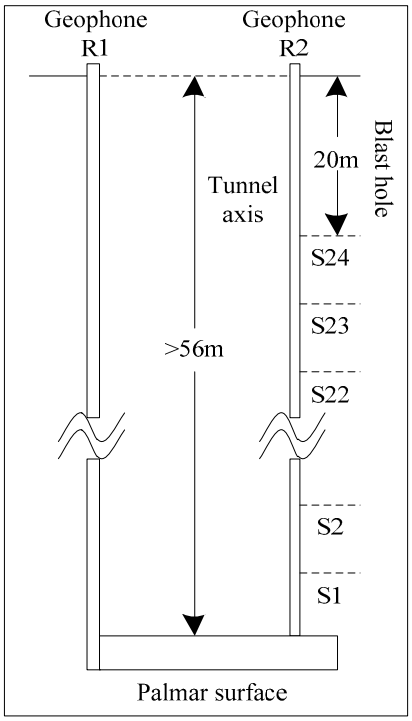


Figure 2. TSP observation principle.

The parameters for setting blast holes and receiving holes are shown in Table 1.

Table 1. Parameters of blast holes and receiving holes.

	Receiving Hole	Blast Hole
Quantity	One on each side wall	24
Diameter	Φ42–45 mm	Φ32–38 mm
Depth	2 m	1.5 m
Direction	Vertical tunnel axis. Tilt up 5~10°	Vertical tunnel axis. Tilt down 10~20°
Height	1.0–1.5 m from the bottom of the tunnel	1.0–1.5 m from the bottom of the tunnel
Position	Above 60 m from the palm surface	The first shot point is 55 m away from the same side detector, and the spacing between the shot holes is 1.5 m

Using SeisSpace/ProMAX3D software to process the collected data, the specific processing steps include: data adjustment, bandpass filtering, head wave pickup, pickup processing, gun energy balance, loss coefficient estimation, reflection wave extraction, transverse and longitudinal wave separation, velocity analysis, depth migration, and reflection surface extraction. The processing parameters are set to default. In order to ensure the processing accuracy of TSP data, it is necessary to select the appropriate maximum gain and loss coefficient in the reflection wave extraction, otherwise information will be lost. By setting appropriate parameters, this problem can be effectively improved, restoring some high-frequency information and improving the quality of ground detection.

To improve the service effectiveness of TSP prediction results in practice, it is necessary to use indicators such as wave velocity, density, Poisson's ratio, and mechanical modulus to depict the rock mass quality in front of the diversion tunnel face through TSP [11]. The higher the Poisson's ratio, the higher the water content of the rock mass, while the smaller the values of other indicators, the poorer the quality of the rock mass [12].

Step 2: Calculate TSP data.

Using the TSP data collected and processed to obtain the wave line time, and combining it with the distance between it and the blasting position, the longitudinal wave velocity V_p of the rock mass is obtained as follows:

$$V_p = \frac{X_s - R_{cv}}{T} \tag{1}$$

In Formula (1), $X_s - R_{cv}$ represents the distance between the detector and the blasting hole. Based on this, the shear wave velocity V_s and other physical coefficients of the rock mass can be obtained, and the water content of the rock mass can be obtained based on practical foundations.

Combining velocity analysis, the propagation world of reflected signals is transformed into distance, and the dynamic elastic modulus and dynamic Poisson's ratio are respectively expressed as:

$$E_d = \rho V_s^2 \left(3V_p^2 - 4V_s X_s^2\right) / \left(V_p^2 - V_s\right)^2 \tag{2}$$

$$v_d = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)} \tag{3}$$

In the formula, ρ represents the density of the rock mass.

If the dynamic elastic modulus of a rock mass is higher than the static elastic modulus, the $\frac{E_d}{E_s}$ value of hard rock is lower, while the $\frac{E_d}{E_s}$ value of weak rock is higher [13], then:

$$E_s = \frac{E_d}{A_1 \exp\left(A_2 \times V_p / V_s\right)} \tag{4}$$

In the formula, A_1 and A_2 both represent the rock mass coefficient.

By using TSP technology to obtain parameters such as rock wave velocity, V_p/V_s, and density, comprehensive prediction of surrounding rock information in front of the diversion tunnel can be achieved.

Step 3: Determine the classification of rock surrounding tunnel.

Based on the "Code for Engineering Geological Survey" and the underground seepage situation, stress magnitude, and surrounding environment of the surrounding rock, combined with the value of V_p, the classification standards for the surrounding rock of the diversion tunnel are comprehensively analyzed, and the results are shown in Table 2.

Table 2. Basic classification table for railway tunnels.

Surrounding Rock Level	Longitudinal Wave Velocity of Rock Mass (km/s)
I	>4.5
II	3.5–4.5
III	2.5–4.0
IV	1.5–3.0
V	1.0–2.0
VI	<1.0

Step 4: Interpretation of forecast results.

After processing the collected TSP data, in order to predict the geological conditions of the rock surrounding the tunnel, it is necessary to combine tunnel design data, geological exploration data, and the actual geological conditions of the excavated section to interpret the predicted data. In general, the interpretation of data should follow the following principles:

① Interpretation is based on reflection amplitude, which is positively correlated with the difference between reflection coefficient and wave impedance. If the reflection

amplitude is larger, the difference between the two is greater, and vice versa; the reflection amplitude can also reflect the rock mass, with positive and negative reflection amplitudes corresponding to rigid and weak rock masses, respectively.

② When interpreting based on V_p, when the rock mass is harder and more complete, V_p is relatively higher, and vice versa.

③ Based on the ratio of longitudinal to transverse wave velocity and Poisson's ratio, if the data of the two suddenly increase, it is considered that it is due to the presence of fluid. At this point, the properties of the fluid can be determined based on the magnitude of the change.

④ Based on V_s as the basis for interpretation, V_s largely reflects the water content of the rock mass. If the reflection of transverse waves is stronger than that of longitudinal waves, it indicates that the rock mass has a high water content.

⑤ Finally, when predicting unfavorable geological conditions in the surrounding rock, it is necessary to combine the surrounding rock conditions of the excavated section behind the face, exploration geological data, and accumulated experience in the early stage to make a judgment, and comprehensively provide the unfavorable geological and hydrogeological conditions ahead, in order to improve the accuracy of the judgment.

Based on the above steps, the engineering geology of this diversion tunnel is obtained as follows:

The burial depth of the rock mass at the entrance section of the diversion tunnel gradually increases, and the direction of the tunnel is nearly parallel to the direction of the rock layer. The lithology is mainly layered sandstone and slate, and the rock mass is weakly weathered and generally not unloaded, with good integrity. Affected by lateral horizontal weathering and unloading, some rock masses are broken. Especially, the surrounding rock at the top of the tunnel is poor, with two slightly better walls classified as Class IV 1 surrounding rock.

The burial depth of the tunnel from the entrance section of the diversion tunnel to the inclined shaft section is relatively large, and the angle between the tunnel direction and the rock layer trend gradually changes from nearly parallel to about 45°. The lithology is mainly composed of slightly weathered sand and argillaceous slate mixed with metamorphic sandstone, which is hard and has good rock integrity. It belongs to Class III 2 surrounding rock, with good overall tunnel formation conditions and poor stability in local structural development areas.

The inclination of the tunnel from the inclined shaft to the powerhouse section is about 45° from the rock layer, and the burial depth of the tunnel is relatively deep. The lithology is mainly sandy slate and muddy slate, mostly hard rock, with underdeveloped structure and good rock integrity. It is classified as Class III 2 surrounding rock. The stability of the tunnel is good, and local side walls may be cut by structures or gently inclined cracks, which may cause small-scale collapse and require strengthened support.

The local development of the entrance and body sections of the headrace tunnel is classified as Class IV 1, accounting for approximately 15.1% of the tunnel length. The upper, vertical, and lower flat sections are mainly classified as Class III 2 (accounting for approximately four fifths of the tunnel length), followed by Class III 1.

2.3. Analysis of Construction Difficulties

Based on the geological conditions of the project, the difficulties in construction are analyzed, and the results are as follows:

① Due to insufficient geological exploration during the feasibility study phase of the project, the potential risks during the construction phase are high.

② The excavation volume of the sedimentation tank and water inlet is large, with high strength and poor geological conditions. Local rock mass is broken, especially at the top of the tunnel, which belongs to Class IV 1 surrounding rock. Moreover, the tunnel body is cut by large geological faults, which can easily cause rock mass detachment

and falling off during blasting construction and disturbance, affecting the quality of tunnel cross-section formation. In addition, the slope is steep after excavation, and the problem of slope stability is prominent.

③ The excavation section of the diversion tunnel by a conventional drilling and blasting method is characterized by complex geological conditions, small tunnel excavation section, high crustal stress, long line, large quantities, tight construction period, etc. The underground water seepage (gushing), rockburst, surrounding rock stability, etc. in the tunnel are extremely harmful to safety during the construction period.

④ The TBM excavation section of the headrace tunnel is characterized by large burial depth, high crustal stress, complex geological conditions, long route, and tight construction period. Underground water seepage, rockburst, and surrounding rock convergence deformation in the tunnel are unfavorable to TBM construction.

⑤ The single head excavation of the diversion tunnel has a long distance, making ventilation and smoke exhaust extremely difficult. At the same time, due to the problem of high ground temperature, it has a significant impact on work efficiency.

⑥ The water diversion and pressure-regulating shaft is deep, has a large diameter, and has poor geological conditions. During the excavation process, it is easy to cause of the shaft, which poses a high safety risk during the construction period. Therefore, high requirements are placed on the excavation accuracy of the guide shaft and the performance of the excavation support equipment.

3. Calculating the Construction Length of Diversion Tunnel Based on Detection Technology

Detection technology is the process of using the transmitting antenna of the transmitter to transmit electromagnetic waves with a frequency of (1~n) × 100 MHz. The propagation path, electromagnetic field strength, and waveform will reflect with changes in the construction medium parameters of the water diversion tunnel, and be recovered by the reflected waves from the receiving end to the host.

Therefore, using the received two-way travel time, amplitude, and waveform data, after processing and analyzing the detection image, the spatial orientation and length of the main cave can be inferred.

Based on the electromagnetic wave velocity v_i of the underground medium in the water diversion tunnel and the two-way travel time t_i of the transmitter receiving the reflected wave, the length of the water diversion tunnel is calculated using Formula (5):

$$H_i = \frac{1}{2}\sqrt{v_i^2 t_i^2 - d^2} \tag{5}$$

In Formula (5), H_i represents the construction length of the water diversion tunnel; d represents the distance between the transmitter antenna and the receiving antenna.

The detection technology is based on the premise that there is a significant difference between the detection object and other objects [14]. Therefore, the close relationship between the propagation speed v_i of the transmitter radar wave and the electromagnetic parameters is as follows:

$$v_i \approx \frac{c}{\gamma_x / \phi_x} \tag{6}$$

In Formula (6), c represents the velocity of the transmitter in vacuum, with a value of 3×10^8 m/s; γ_x is the propagation medium coefficient; and ϕ_x is the emissivity of the propagation medium.

In practical work, antennas with different center frequencies should be selected based on the different depths of the water diversion tunnel that need to be detected, and more suitable observation points should be replaced.

4. Construction Ventilation and Wind, Water, and Electricity Layout

The air and water supply pipelines inside the tunnel adopt Φ150 mm steel pipe and Φ80 mm PVC pipe, arranged at a height of 1.2 m from the bottom plate along the right side of the entrance, using Φ Fix with 25 dowels.

Two SDA112B-2F75 axial flow fans are used to ventilate the two headrace tunnels through the construction adit, and a 150 cm high-strength composite fiber cloth ventilation duct is used to pressure the air inward. According to the height of the tunnel, an approximately 1.5 cm expansion bolt is set every 3.5 m at the arch angle to hang the inner air bucket with a stay wire.

A DN80 welded steel pipe is laid in the water supply system at the construction adit, with each section of the pipeline being 5 m long and connected by flanges. The distance from the working face is 60 cm, and it is arranged on the right side of the tunnel.

Two 630 kVA transformers are used to connect the construction adit to supply power to the headrace tunnel. Additionally, a 10 kV high-voltage line is erected from the 10 kV switch post near the inlet and outlet of the upper reservoir to the entrance section of the headrace tunnel. One S9 type 500 kVA transformer is installed to supply power to the axial flow fan and other fans at the excavation construction entrance of the headrace tunnel entrance section. Three-phase four-wire BLXT 120 mm^2 insulated wire is installed inside the tunnel, with a lighting voltage of 36 V. A 250 W high-voltage mercury lamp is installed every 25 m, and the lighting wire is installed along the tunnel wall.

5. Excavation Construction Program Design

(A) According to regulatory requirements, in order to ensure the stability of surrounding rock during the excavation process of the tunnel, the principle of "interval excavation and timely support" should be followed, and the front and rear excavation working surfaces should be staggered by more than 30 m. The adjacent tunnel should be excavated after the initial support of the first excavated tunnel is completed. The project consists of tunnels 1 and 3 as a group and tunnels 2 and 4 as a group and is excavated in two groups at intervals.

(B) The construction of the diversion tunnel is divided into two working faces: upper and lower. The construction of the lower part starts from the 4th construction adit and connecting tunnel. Firstly, the construction of the 4th and 2nd diversion tunnels is carried out. After the support reaches 30 m, the construction of the 3rd and 1st diversion tunnels is started; the upper construction will enter from the Y2 construction adit, and the construction of the 4th and 2nd diversion tunnels will also begin. After the support reaches 30 m, the construction of the 3rd and 1st diversion tunnels will begin.

(C) The construction of a single diversion tunnel is divided into two layers, and the excavation of the vertical shaft is expanded in two stages. The process proceeds in the following order: after excavating the upper layer of the lower adit, excavate the upper layer of the upper adit → excavate the slag chute in the vertical shaft section → expand the vertical shaft twice → excavate the upper and lower flat sections and the lower layer of the curved section area.

6. Design of Excavation Construction Methods

6.1. Tunnel Curtain Excavation

Before the excavation of the main tunnel curtain during the construction of the diversion tunnel, the layout of the drainage ditch at the top of the slope should be drawn according to the actual terrain, and the construction site of the drainage ditch should be pre-set during the construction [15,16]. During peak floods, daily maintenance of the tunnel should be carried out to prevent rainwater from converging into the tunnel or wall collapse caused by poor drainage.

During tunnel construction, the excavation of the main tunnel curtain earth is carried out by a 1 m^3 excavator, which is used to excavate and unload materials, and manual construction is carried out. The top-down segmented construction method is used. During

the excavation process, the first step is to excavate the water channel to ensure that the excavation surface is in a continuously dry state and avoid collapse and landslide disasters caused by improper excavation methods.

6.2. Tunnel Excavation and Support Construction

The excavation and support of the tunnel body are completed by three working groups: the drilling and blasting group, the slag removal working group, and the support group. Without affecting the construction, the slag removal working group and the initial support group can work in parallel to minimize the construction period. The excavation and support process of the tunnel body is shown in Figure 3.

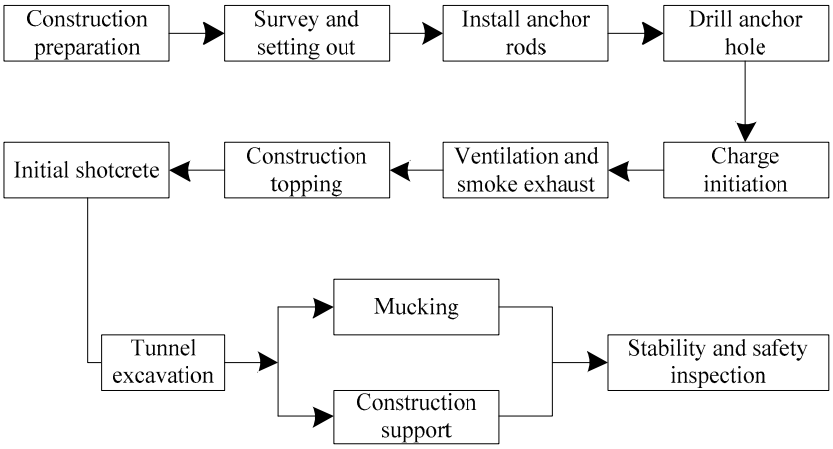


Figure 3. Tunnel excavation and support process flow.

In the support construction of this study, the excavation method is mainly used for construction. During construction, it is necessary to directly adopt the operation mode of underground excavation in the tunnel in order to achieve a close combination of initial support and secondary lining for the weak surrounding rock at the tunnel entrance. The main construction process of trapezoidal cutting is shown in Figure 4.

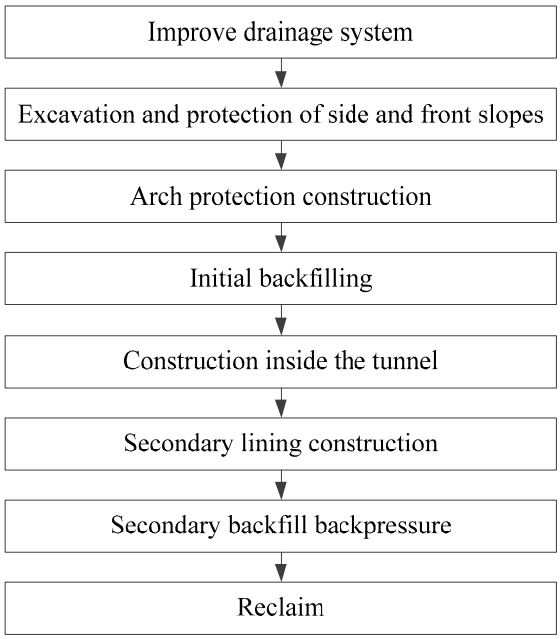


Figure 4. Main construction process diagram of trapezoidal cutting.

In Figure 4, the main construction of trapezoidal cutting is completed in the order of improving temporary drainage, excavation and protection of side and front slopes, and arch protection construction. Among them, the inner mold of the arch protection is reshaped. The installation of arch protection formwork, pouring of arch protection concrete, backfilling construction, and other steps are all within the scope of arch protection construction.

① Improve temporary drainage. Firstly, construct a temporary drainage ditch to divert the right tunnel gully water system to the portal drainage system. After backfilling is completed, construct a circular intercepting ditch outside the tunnel to introduce the natural water system.

② Excavation and protection of side and front slopes. Open excavation construction will be carried out on the muddy soil and silty clay at the top of the tunnel arch. The excavation range is 120° from the center, the longitudinal length of the excavation is 30 m, the excavation height is 5.18 m below the arch top, and the permanent slope rate is 1:075. Anchor rod frame beams will be used for protection, and the temporary side and front slopes will be protected with anchor rods (C25 sprayed concrete+) Φ20 roll anchor rods+ Φ8 steel mesh.
Before excavation, the excavation contour line of the side and front slopes should be set out, with one excavation point set out every 3 m to ensure that the excavation contour line of the side and front slopes is linear, smooth, and beautiful. And monitoring and measuring points should be set up at the top of the slope, with a longitudinal spacing of 5 m. Each monitoring and measuring point should be buried with a steel head of no less than 50 cm and firmly fixed with concrete and pasted with reflective stickers.

③ Arch protection construction.
Step 1: Testing the bearing capacity of the foundation of the arch protection. Before the construction of the arch protection, the bearing capacity of the foundation should be tested. When the bearing capacity is less than 200 kPa, steel flower pipe grouting reinforcement should be carried out at the platform, and the steel pipe should be Φ105 × 5 mm hot-rolled seamless steel pipe (section length 6.2 m), with a horizontal spacing of 80 cm and a vertical spacing of 80 cm, arranged in two rows in a plum blossom shape.
Step 2: Temporary drainage. A ditch of 60 cm × 20 cm shall be constructed outside the platform on both sides of the arch guard, and the water system shall be discharged to the drainage system of the entrance.
Step 3: Shape the inner mold of the arch protection. Preliminary trimming of the inner formwork of the arch protection is carried out through measurement, setting out, and mechanical coordination. After the preliminary trimming is completed, Φ42 steel pipes are used as longitudinal positioning measures. After pouring the protective arch cushion layer, a ring arch frame is assembled at a distance of 5 m for horizontal positioning. After the longitudinal horizontal positioning is completed, the inner arc is manually trimmed and formed, and the mortar is plastered.
Step 4: Install the arch protection frame. After the completion of internal formwork repair, install the arch protection frame using a 22b I-beam as the reinforcement measure, with a longitudinal spacing of 0.5 m. The arch frame is connected longitudinally using Φ20 deformed steel bars with a circumferential spacing of 0.1 m, and the steel bar joints must be arranged in a staggered manner, as shown in Figure 5.



Figure 5. Arch installation.

Step 5: Install the arch protection template. The end mold adopts 18 mm bamboo plywood, and the outer mold is 0.2 m × 0.05 m wooden board. Install the formwork on both sides and at the end according to the design thickness of 0.8 m, fix the formwork with square wood to ensure the structural size, and use steel pipes and steel bars to provide diagonal support and reinforce the outer formwork. When installing the template for the first time, only a 2 m high template needs to be installed on both sides, leaving enough space to use a vibrating rod to vibrate the arch protection concrete. During the pouring process, gradually lengthen the top template until it is completely sealed. To prevent the collapse of the arch protection, steel pipes are used on both sides of the arch protection with diagonal support to ensure the overall stability of the arch protection.

Step 6: Pour concrete for arch protection. Before pouring concrete, the formwork needs to be inspected again. The centerline, level, and size of the template must meet the design requirements, the template must be firm and tight, and the arch protection should be covered with concrete [17,18]. During the construction process, it is necessary to strictly control the quality of raw materials and strengthen the quality control of various links such as concrete mixing, transportation, and pouring.

The concrete is uniformly supplied by the mixing station, transported by concrete pouring trucks, manually combined with mechanical pouring and compacted by vibration. The pouring sequence is symmetrical on both sides of the arch protection until the arch crown. Due to the length of the arch protection being 30 m, segmented pouring is adopted, with a one-time pouring length of 10 m.

After the pouring of arch protection concrete is completed, monitoring and measuring points are set up on the arch crown and both sides, with a longitudinal spacing of 10 m. Steel reinforcement heads are embedded and reflective stickers are affixed.

Step 7: Initial backfilling. After the concrete pouring is completed, it needs to be cured in a timely manner, and the curing period should not be less than 7 days. After the strength of the arch protection reaches 80%, the initial backfilling is carried out to backfill the arch feet on both sides of the arch protection to form the foot protection.

Step 8: Construction inside the tunnel. The original design adopted the excavation method of double-sided walls for the entrance section, which resulted in complex construction processes and low work efficiency. After using the trapezoidal cutting method to form the arch protection cutting section, three steps are used to enter the tunnel inside the cutting section, reducing the difficulty of hidden excavation construction at the tunnel entrance and greatly reducing the safety risks of tunnel entrance construction.

Step 9: Secondary backfilling. After the completion of the secondary lining and portal wall construction, proceed with the secondary backfilling construction of the tunnel top. Before backfilling construction, debris should be cleaned up and there should be

no accumulated water. The backfilling soil and rock should be symmetrically layered and filled, with a thickness of 0.3 m for each layer. The height difference between the soil surfaces backfilled on both sides should not exceed 0.5 m. After backfilling to the level of the arch crown, it should be immediately layered and fully filled to the required height. After backfilling is completed, the drainage system should continue to be improved.

6.3. Excavation Grouting Technology

The grouting of the excavation section of the main tunnel during the construction of the diversion tunnel is set at the T65 fault fracture zone. In order to prevent geological disasters such as collapse during the excavation process of the main tunnel, the grouting starting section is set at 0 + 306, with 0 + 306 as the center, and the grouting area is determined by

$$\Omega = \chi \cdot \frac{\beta + \alpha}{\xi} \times K_a \tag{7}$$

In Formula (7), χ represents the permeability coefficient during the grouting process; β represents the excavation angle of the main tunnel; ξ represents the soil parameters of the main tunnel; K_a represents the compressive value of the side wall of the main tunnel; α represents the numerical value of the grouting angle [19].

In order to ensure construction safety on the workbench, a 1.0 m thick flocculant main mudguard is poured first, and then segmented grouting is carried out at intervals of 15 m, with 10 m of excavation every 10 m. In order to ensure the quality of the main tunnel excavation grouting, a push type segmented grouting process was adopted, as shown in Figure 6.

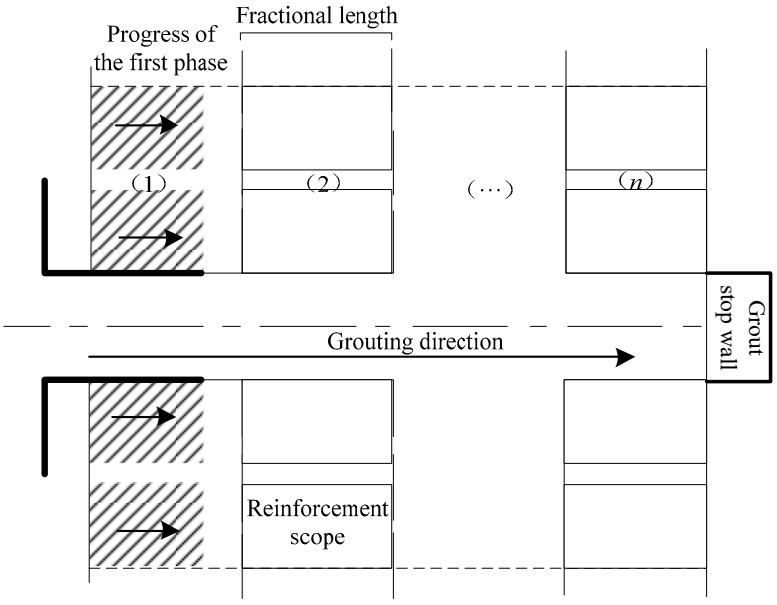


Figure 6. Segmental drilling and grouting construction mode.

According to the segmented drilling and grouting construction mode, the grouting equation for the excavation of the main tunnel of the diversion tunnel is:

$$f = \lambda \frac{|\mho \cdot L|}{\phi + \sigma} - Z \tag{8}$$

In Formula (8), λ represents the grouting parameters for the excavation of the main tunnel; $\mho$ represents the area of the grouting operation during the excavation process of the main tunnel; L_s represents the excavation parameters of the main tunnel during the

construction of the diversion tunnel; ϕ represents the height of the main tunnel; σ represents the depth of the main tunnel; Z_j represents the amount of grouting [20].

According to the grouting equation for the excavation of the main tunnel of the water conservancy diversion tunnel, the grouting technology for the excavation of the main tunnel of the water conservancy diversion tunnel has been designed. The specific steps are as follows:

Step 1: Set up the structure and antislurry board of the antislurry wall. T65 fracture is a type of strata with high pressure. To prevent groundwater from entering the working face or erosion during the grouting process in the nongrouting area, C20 cement mortar is poured once before each pregrouting, with a thickness of 100 m. After each grouting is completed, leave a 5 m space for the next grouting step.

Step 2: Calculate the grouting pressure and diffusion radius. In the fracture zone, the grouting pressure is mainly split grouting, and the grouting pressure should not be too high to avoid causing too much disturbance to the formation and exceeding the bearing capacity of the grout stop wall and grout stop plate. Therefore, it is recommended to have a grouting pressure of 2–6 MPa at the fracture zone and control the grouting radius at 2 m.

Step 3: Install grouting holes for the main tunnel of the diversion tunnel. In the headrace tunnel, there are 86 preinjected mud holes in each cycle, with a depth of 10 m for boreholes 1–23, 12 m for boreholes 24–43, and 16.5 m for boreholes 44–86. As shown in Figure 7, 89 are installed at the front end of the grouting hole × 4 mm orifice tube with a length of 3.5 m.

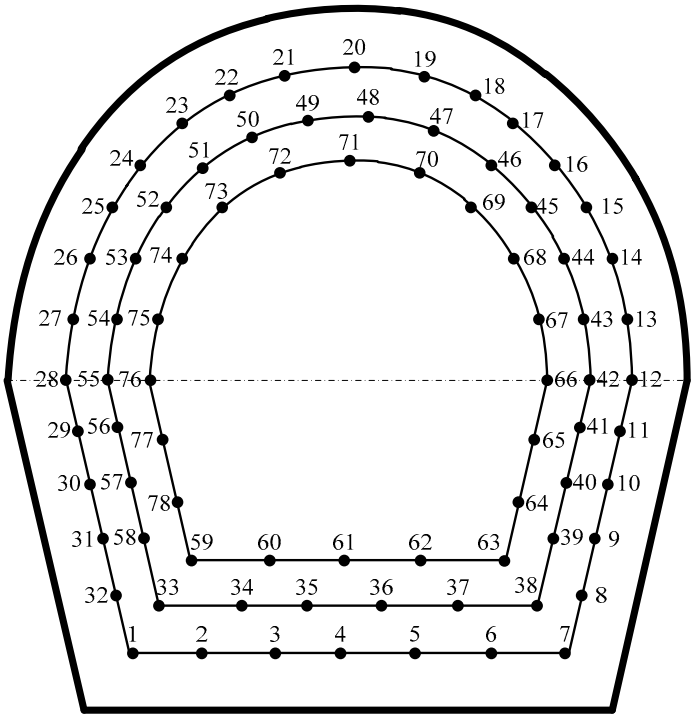


Figure 7. Layout of pregrouting holes in the excavation section of the main tunnel during the construction of the diversion tunnel.

The grouting problem in the excavation of the main tunnel of the diversion tunnel construction is analyzed. If the grouting pressure and expansion radius cannot meet the requirements of the main tunnel construction, mud should be injected first, and the grouting operation can only be completed when the mud is injected to twice or more of the level of the original grouting. By conducting periodic inspections and construction judgments on the grouting effect, the grouting range is determined, the grouting position is determined to be within the specified range, and the grouting pressure and flow rate are tracked in a timely manner to ensure that the grouting process indicators are within a good range.

After the grouting quality meets the requirements, the excavation of the main tunnel of the diversion tunnel can be carried out.

6.4. Excavation of Unfavorable Geological Tunnel Section at the Entrance

The entrance section of the diversion tunnel is a single-track tunnel with a length of 150.62 m, with a horseshoe shaped cross-section and an excavation diameter of 15 m. The surrounding rock is mainly composed of sand and gravel, with a small number of boulders. The excavation of the section adopts a two-layer excavation method, with an upper excavation height of 7.5 m and a lower excavation height of 4.5 m. The excavation is carried out from the tunnel to the entrance, and the slope support of the tunnel face and double row of 60 mm @ 500 mm, L = 10 m pipe shed support are completed at a distance of 15 m near the entrance. Then, the excavation is carried out from the outside to the inside.

(a) Upper excavation support. First, within the 140° range of the top arch Φ32 self-propelled anchor rods are used for advanced support, and then a hydraulic hammer is used for short footage (L $\leq$ 1 m) excavation. For sections where the surrounding rock cannot self-stabilize, the top arch and side walls are excavated first, and a buttress is reserved in the middle of the face. After the completion of steel grating and shotcrete support, the excavation is carried out, and the strong support is followed up every cycle. The strong support method is anchor rod + hanging net + spraying steel fiber concrete + steel grating.
(b) Lower excavation support. Use a backhoe to directly excavate and then support and follow up.
(c) Key points of construction technology. It is necessary to strictly control the upper circulating footage to not exceed 1.0 m, and excavation and support should be carried out alternately and gradually; in the upper support, 3–4 anchor rods are used to lock the feet on both sides of the steel grating; the exposed part of the self-propelled anchor rod or advanced anchor rod should be connected to the steel grid and subjected to joint forces; the sprayed concrete is relatively thick and needs to be sprayed multiple times, with each spraying thickness not exceeding 0.1 m.

6.5. Excavation of Upper and Lower Flat Sections of the Diversion Tunnel

The excavation of the upper and lower flat sections of the headrace tunnel is carried out in two layers, with an excavation height of 7.62–9.15 m for the upper layer and 2.75–3.45 m for the lower layer. The excavation of the upper flat section begins from the water inlet, and the hole is filled with slag to the upper drilling and blasting elevation; the lower flat section is constructed from the 4th construction adit, and the upper layer on the downstream side is excavated first. The triangular body at the top of the intersection is reserved for processing during reverse excavation.

The upper excavation adopts a drilling and blasting trolley combined with an air leg drill to create holes, forming the entire section in one go, cutting the middle wedge, and blasting the surrounding smooth surface, with support and follow-up; after the completion of the upper layer support, the excavation construction of the lower layer can be carried out. Air leg drilling is used to create holes in the lower layer, and the full-width construction is completed in one excavation. The bottom hole smooth blasting is carried out, and the support is followed up. After the excavation of the lower layer, a 1.0–1.5 m thick slag material is reserved as the construction channel. After the excavation is completed, the remaining slag is removed section by section according to the support progress.

According to the engineering analogy method and on-site tests, the main blasting design parameters of the adit section are determined: a slotted charge blasting method, with a footage of 3.0 m per cycle, a spacing of 0.5 m between surrounding holes, a minimum resistance line of 0.6 cm, and a charging density of 125 g/m. To ensure the quality and half-porosity of the peripheral holes, it is required to strictly use a bamboo sheet charging method for the peripheral holes.

6.6. Excavation of the Upper and Lower Bend Sections of the Diversion Tunnel

(a) Design excavation. The upper curved section above the elevation of the upper flat section bottom plate and the lower curved section below the elevation of the lower flat section top plate are excavated together with the adit. The design surface of the curved section is a curved surface. During the construction process, the blasting effect and the size of the over- and underexcavation must be strictly controlled. The drilling direction is required to be the tangent direction of the designed curved section, and an appropriate overexcavation is allowed for a single footage, but the drilling depth should not exceed 2.5 m.

(b) Technical overbreak. In order to meet the construction space required for the mucking shaft and its expansion excavation and ensure the transportation channels for supporting materials, equipment lifting, etc., it is necessary to perform technical overexcavation on the upper and lower bending sections of the diversion tunnel and later use the same grade of lining concrete for backfilling.

The excavated and exposed surrounding rock indicates that the lithology of the overexcavation area is poor, with faults and developed fractures. The angle between the rock strata and the tunnel direction is relatively small (only about 8°). Technical overexcavation should be smoothly connected with the designed body shape to avoid the formation of unstable inverted suspension. By comparing and optimizing various schemes, it is clear that the technical overbreak width of the curved section is consistent with the design width of the tunnel. The overbreak is carried out straight forward along the side wall, and random anchor rods are used in the overbreak area (φ28. L = 6 m, 2 × 2 m), shotcrete (0.1 m thick) and other methods are used for random support, and the palm surface is sealed with C20 plain concrete with a thickness of 5 cm.

6.7. Excavation of the Vertical Shaft Section of the Diversion Tunnel

The excavation area of the vertical shaft section is from the elevation of the upper flat section bottom plate to the elevation of the lower flat section top plate, including the curved section of the section. Due to the lack of conditions for the arrangement of reverse drilling rigs and considering factors such as construction progress, economy, and reliability, it was ultimately decided to use the manual reverse drilling method for construction. The manual reverse drilling well excavation was carried out from bottom to top, then expanded into a slag chute, and finally excavated from top to bottom to the design section. Among them, the diameter of the excavation section for the guide shaft is 2 m, the diameter of the excavation section for the slag chute is 4 m, the angle between the central axis and the horizontal is 98.5°, and the length is 65.8 m. Before the construction of the guide shaft, the technical overbreak construction of the lower bend section must be completed, and before the first expansion excavation, the technical overbreak construction of the upper bend section must be completed.

(a) Artificial antimissile. To ensure construction safety, before excavation, the excavation support trolley must be used to lock and support the surrounding area of the guide shaft opening. At the same time, the exposed face and surrounding walls should be sealed with plain shotcrete to prevent the collapse of surrounding rock around the opening. Support measures and parameters: 0.2 m away from the contour line, with a circumferential spacing of 0.55 m, Φ25. L = 3 m anchor rod, with a shotcrete sealing thickness of 5 cm. When drilling and blasting at the entrance of the pilot shaft, secondary blasting operation is adopted. The first blasting will be carried out by cutting the small pilot hole at the entrance of the tunnel, with the blasting footage controlled at 1–2 m. The second blasting will be carried out by surrounding hole smooth blasting, and the bedrock surface after the entrance blasting should be promptly sprayed and supported to ensure the safety and stability of the tunnel entrance. After the formation of the tunnel gate, manual excavation of a 2 m diameter pilot shaft will be carried out from bottom to top. The pilot shaft blasting will be

carried out using a "half second detonator, smooth blasting" method, with a distance of 40 cm between the smooth blasting holes and a footage of 2 m per cycle.

(b) Expansion excavation of slag chute. To ensure the smooth excavation of the vertical shaft section and the smooth mucking, after the construction of the guide shaft is completed, the first expansion excavation is carried out using a hanging basket and lifting equipment to drill radially from bottom to top. The expansion excavation is carried out in a mucking shaft with a diameter of 4 m.

(c) Secondary expansion excavation. After the expansion of the slag chute is formed, the second expansion of the vertical shaft section is carried out to the design structural line. After each row of shots, safety measures must be taken seriously, and then the measuring personnel should retest the section to clarify the underexcavation situation and promptly handle it. The final depth of each layer of blasting holes is controlled by a slightly inclined slope towards the direction of the slag chute to facilitate manual slag removal. In the second excavation process, to ensure the quality of the upper and lower bend forming, the drilling direction is the tangent direction of the arc section, the drilling depth does not exceed 2.5 m, and the technical overbreak is controlled within 16 cm. To ensure the flatness of the excavation of the upper and lower bends and vertical sections, as well as to control overexcavation and underexcavation, smooth blasting is used around the perimeter, and the single-cycle footage is controlled at around 2.5 m. The stone slag is manually scraped into the slag chute and slid into the lower slag discharge area.

7. Reuse of Slag Material

The slag material formed by the excavation of the diversion tunnel is a good building material that can be used to make concrete aggregates, cushion materials, etc. Therefore, it is necessary to make full use of the tunnel excavation slag material as much as possible, which can greatly reduce the construction cost of the project.

The particle size and quality of the tunnel slag formed by tunnel excavation are some of the most important factors to consider in the selection of construction methods. The tunnel-boring machine (TBM) method is used to excavate tunnels, and the smaller the slag material block, the more suitable the slag equipment is. To use the slag material extracted by the TBM as concrete aggregate, it is necessary to adjust the TBM tool, but it will increase the engineering cost. In addition, compared to the drilling and blasting method, the coarse particle size of TBM slag material is relatively small, and the particle shape is mostly flat. The quality of the finished aggregate is poor, the content of artificial sand and stone powder exceeds the standard, and the moisture content of the raw material is too high. If used to make concrete aggregates, it will increase the amount of concrete cement used, and even the aggregates will struggle to meet the specification requirements. Therefore, from the perspective of reusing the slag material, the TBM method produces a small block size of the hole slag material during the construction process, and the content of artificial sand and stone powder exceeds the standard. The quality of the processed finished aggregate is not as good as that of the drilling and blasting method, which does not meet the requirements for reusing the slag aggregate. On the other hand, the hole slag generated by drilling and blasting construction has been used for making building materials such as concrete aggregates and filter materials.

8. Construction Quality Control

8.1. Establishing a Quality Assurance System for Diversion Tunnel Excavation

A quality assurance system network should be established, from the project department to the work area to the excavation operation team and each construction team. Full-time and part-time quality inspectors should be appointed, and their responsibilities and authorities should be determined. Each team should be a unit, and each person should be assigned a specific responsibility. During the construction process, the quality requirements

of each process should be followed with caution, and the occurrence of quality accidents or problems should be avoided as much as possible from a systemic perspective.

8.2. Develop Quality Assurance Measures for Excavation Construction

The following quality assurance measures are formulated to standardize each construction process and avoid human factors affecting the construction quality, in response to potential quality issues that may arise during the construction process and the special nature of the diversion tunnel construction.

① Excavation must be carried out strictly in accordance with the measurement points, drilling layout, and blasting parameters in order to prevent excessive overexcavation and avoid underexcavation.

② After each round of blasting and prying is completed (including safety treatment and no accumulated slag on the face), the tunnel work area should promptly notify the measuring personnel to conduct overexcavation and underexcavation inspection before supporting, set out the next cycle, and provide overexcavation and underexcavation detection data. The measurement work should include:

   a. Regularly calibrate measuring instruments;
   b. Clear underexcavation thickness markings should be left on the excavation contour surface;
   c. The contour on the palm surface should be clearly marked (with paint markings);
   d. After the underexcavation treatment, the measurement should be notified in a timely manner for retesting until the design requirements are met, and the measurement data after retesting is qualified should be provided;
   e. Set up a pile number sign on the tunnel wall every 10 m. Add pile numbers and indicate the positions at the starting and ending points of the cross-section changes and upper and lower bending sections.

③ All spray protection surfaces must ensure that there is no underexcavation on the excavation surface and the overexcavation must be controlled within 20 cm before spray protection (except for geological reasons).

④ According to the design requirements, the system anchor rod shall be installed, and random anchor rods shall be added to the locally fractured parts. Random anchor rods shall not replace the system anchor rod. The anchor rod hole must be blown clean, and the anchor rod mortar should be mixed according to the designed mix ratio and injected fully.

⑤ The installation of the mesh should be 3–5 cm away from the rock surface, and the overlapping parts should meet at a lap length of 30 cm and be firmly welded with the anchor rod.

⑥ The arch frame (if required for installation) should meet the requirements of the design drawings and welding specifications. The arch frame entering the construction site should be properly stored and not damaged. The installation of the arch frame should be in accordance with the design requirements and welded firmly with the system anchor rod.

The quality department focuses on meeting the above control requirements in the daily inspection and acceptance process. Factors that do not meet the requirements will not be accepted and rectification will be carried out within a specified period of time. In order to ensure the smooth progress of the acceptance work, each construction team and tunnel work area must organize and execute the “first inspection” and “second inspection” work of on-site construction, especially the control of over- and underexcavation and the remeasurement work of underexcavation treatment. Timely inspection and handling should be carried out to ensure the smooth progress of excavation acceptance work and pouring.

9. Test and Analysis

Due to the fact that the groundwater in this project is mainly infiltrated by gravity, when there is heavy rainfall in the engineering area, there will be seasonal abundant water inside the tunnel, which is affected by climate and leads to unstable water levels in the diversion tunnel. Therefore, in order to analyze the performance of the excavation and construction technology of the diversion tunnel under the complex geological conditions above in terms of wall resistance, the following tests were conducted using detection technology.

Point measurement is combined with line measurement and multiple measurement lines and points are simultaneously arranged on the palm and sidewall of the hand, as shown in Figure 8.

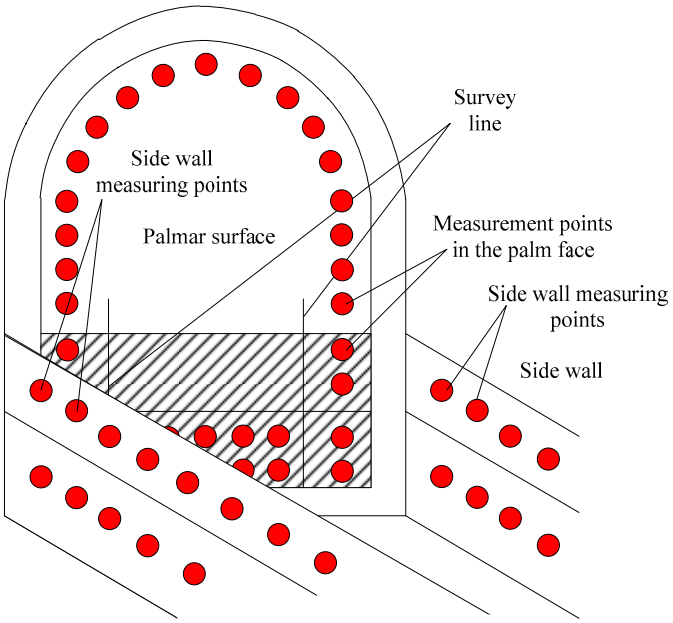


Figure 8. Layout of measuring lines and points.

In the diversion tunnel project, shielded dual body antennas with detection frequencies of 100 MHz and 300 MHz are used to identify adverse geological bodies such as hard rock layers and high-karst geology at the location of the side walls.

The detection parameters during the testing process are shown in Table 3.

Table 3. Detection parameters during the testing process.

	Parameter	Numerical Value
When measuring lines and points are arranged inside the face of the water diversion tunnel	The movement speed of the detection antenna	10 cm/s
	Sampling points	1000
	The spacing between measuring points	30 cm
	Detection scanning rate	40/s
	Time window	500 ns
When measuring lines and points are arranged on the side walls of the diversion tunnel	Sampling points	500
	Distance between measuring points	30 cm
	Detection scanning rate	40 scans/s
	Time window	500 ns

On the basis of ensuring the stability of detecting unfavorable geological bodies near the tunnel face and side walls, it is also necessary to ensure that the tunnel side walls have greater resistance to damage. The antidamage coefficient of the side wall during the construction of the diversion tunnel is shown in Figure 9.

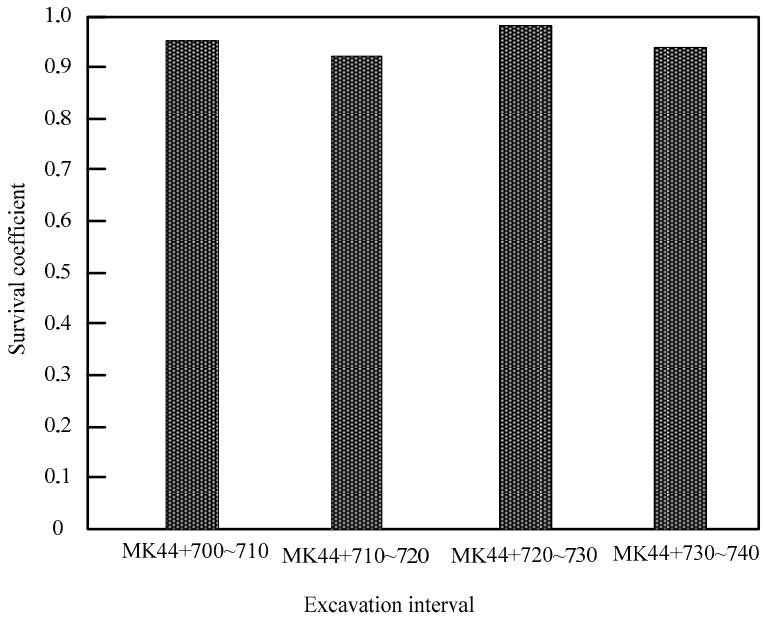


Figure 9. The resistance coefficient of side walls in the construction of water diversion tunnel.

The results in Figure 9 show that after using the technology proposed in this paper, the resistance coefficient of the side wall is above 0.9. Therefore, it indicates that the excavation construction technology designed in this paper can ensure the support capacity of the side wall of the diversion tunnel, which is suitable for the excavation of the main tunnel in the construction of the diversion tunnel. The reason for this result is that in order to address the differences in geological conditions and tunnel sections in terms of geological structure, stress state, excavation sequence, and other aspects, this study specifically designed various excavation and support technologies. Especially through the design of excavation grouting technology, the bearing capacity and stability of the surrounding soil around the tunnel can be enhanced, thereby improving the antidestructive ability of the side wall.

10. Discussion and Summary

Based on the above analysis, it can be concluded that the diversion tunnel excavation construction technology designed in this article has achieved good application results. Combined with specific technical content and experimental results, the innovative breakthroughs of this technology are summarized as follows:

① Introducing TSP technology to achieve advanced geological prediction. By using TSP technology, advanced geological prediction can be made for excavation projects of diversion tunnels under complex geological conditions, identifying potential geological problems and difficulties in advance and providing a basis for decision making during the construction process.

② Combining detection technology for data collection utilizing detection technology to collect two-way travel time, amplitude, and waveform data. By processing and analyzing the detection image, the spatial orientation and length of the main tunnel during the construction of the diversion tunnel are calculated, providing support for the accuracy and accuracy of construction.

③ Designing multiple excavation and support technologies in a targeted manner. Due to the differences in geological conditions and tunnel sections in terms of geological structure, stress state, excavation sequence, etc., targeted designs have been made for tunnel curtain excavation technology, tunnel body excavation and support technology, excavation grouting technology, excavation technology for unfavorable geological tunnel sections at the entrance, upper/lower flat section excavation technology, upper/lower curved section excavation technology, vertical shaft section excavation

technology, etc. to adapt to the complex and ever-changing underground environment and ensure the safety of diversion tunnel construction as well as stability and quality. The excavation grouting technology can enhance the bearing capacity and stability of the soil around the tunnel body, further improving the antidamage ability of the side wall.

④ Establishing a construction quality control system. During the tunnel construction process, a construction quality control system is established to monitor and manage all aspects of the construction, ensuring that the construction quality meets the requirements.

⑤ Planning for the reuse of slag materials. The reuse process of slag materials is planned to minimize resource waste and improve the sustainability and economic benefits of the project.

These innovative points enable the excavation technology of the diversion tunnel to have better geological prediction ability, accurate data support, diversified construction technology selection, construction quality control, and reasonable utilization of resources under complex geological conditions, thereby improving the efficiency and safety of excavation construction.

11. Conclusions

The diversion tunnel excavation technology designed in this study can improve the safety, construction efficiency, and quality of a project, reduce engineering risks, and provide reliable technical support for the successful implementation of a diversion tunnel excavation project. The application prospects of this technology in the field of engineering are broad. It helps to improve the safety, efficiency, and quality of engineering, reduce costs, and promote technological innovation in the field of engineering.

The excavation and construction technology of water diversion tunnels under complex geological conditions is a complex engineering system. For example, in hard rock geological conditions, it is necessary to fully consider various factors such as geology, hydrology, and engineering and formulate reasonable construction plans and technical routes to ensure the smooth progress of engineering construction and the guarantee of engineering quality. In this process, we need to constantly explore and study new technologies and methods, actively respond to existing problems and challenges, and improve the progressiveness and practicability of the diversion tunnel excavation and construction technology.

At the same time, we also need to fully leverage the role of technological innovation, strengthen scientific research and technological innovation, and promote the continuous development and improvement of construction technology for diversion tunnel excavation. Only in this way can we better meet the requirements of China's economic development and social needs, promote the sustainable development of hydropower engineering construction, and provide more high-quality services and guarantees for the people.

In future development, we believe that with the joint efforts of all parties, the excavation and construction technology of diversion tunnels under complex geological conditions will continue to innovate and improve, making more important contributions to the development of hydropower engineering construction in China.

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