Research on Complete Rail-less Construction Technology for Longitudinal Incline Shafts in Extra-long Tunnels

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Abstract. Leveraging the case study of the Daba Mountain Tunnel project within the AL-C20 section of the Anlan Expressway, this paper investigates, selects, and validates various technologies suitable for the construction of longitudinal incline shafts. It assesses the merits and demerits of these technologies across dimensions such as efficiency, duration, safety, and economy. Ultimately, it adopts a comprehensive trackless construction approach utilizing crawler machinery, offering vital guidance for rail-less construction of longitudinal incline shafts in extra-long tunnels.

Keywords: longitudinal incline shafts; rail-less construction technology; comprehensive crawler machinery solution

1 Introduction

With the vigorous development of transportation infrastructure construction, China has become the country with the largest scale of tunnel and underground engineering construction in the world. While the scale and quantity continue to increase, some special long tunnels require the use of inclined shafts for transportation construction with an overall slope greater than 7° (equivalent to 12%) to increase the working face and thereby shorten the construction period [1,2]. However, transportation construction with tracks has disadvantages such as long construction periods, high safety risks, high equipment maintenance costs, significant impacts from cross operations, and high construction costs. Therefore, it is of great significance to research a set of technologies that can replace track transportation construction, thereby improving the construction efficiency of large slope inclined shafts, reducing construction safety risks, and achieving the goal of essential safety and economic efficiency in the construction of large slope inclined shafts.

2 Project Overview

The Daba Mountain Extra-Long Tunnel on the Anlan Expressway is a key project of the national highway Silver Hundred Line (G69) in Shaanxi, extending from Ankang to

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Langao (the boundary between Shaanxi and Chongqing). Located in Tahe Town, Langao County, Ankang City, Shaanxi Province, it traverses the Shaanxi-Chongqing boundary and connects with the Chengkai Expressway in Chongqing. With a total length of 13.593 km, the tunnel is jointly constructed by Shaanxi and Chongqing provinces. The tunnel is divided into three construction sections. The main construction contents of Anlan Section 20 undertaken by China Communications Construction First Highway Engineering Co., Ltd. include the middle section of the main tunnel left and right lines (3.97 km/+1.85%, 3.95 km/+1.85%), the dual-line ventilation inclined shaft 1# with combined track transportation construction inclined shafts on the left and right sides (670m/-33%, 620m/-36%), and inclined shaft 2# for trackless construction (1582m/-9.6%) in Figure 1. This project is a demonstration project of the Ministry of Transport's "Safe Hundred-Year Quality Project" and has significant engineering characteristics such as "great burial depth, abundant water, complex geological conditions, long single-heading advance, challenging construction ventilation, difficult reverse slope drainage, and high construction risks."

The main construction content of the tunnel mainline in this project adopts the newly added inclined shaft 2# for trackless construction. The originally designed inclined shaft 1# for ventilation and track transportation construction has been adjusted to trackless transportation construction, creating favorable conditions for accelerating overall construction progress, reducing safety risks, and lowering comprehensive costs. Within the total project duration, inclined shaft 1# needs to be simultaneously constructed and completed, which will serve as the operational ventilation shaft for the tunnel. Combining the above optimization measures and construction requirements, to avoid the continued use of track transportation construction during inclined shaft construction, the project's research team developed a complete set of crawler-type mechanical trackless construction technology, laying the foundation for reducing construction safety risks, saving construction period, and lowering construction costs for inclined shaft 1#.

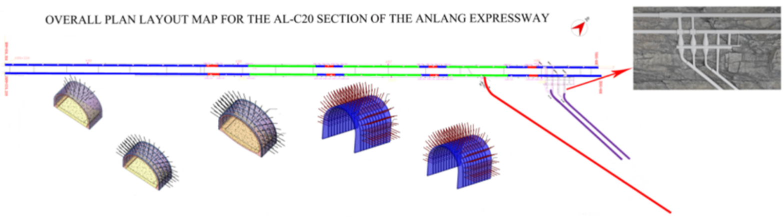

Fig. 1. Layout Plan of 1# Ventilation Shaft and 2# Construction Shaft in Daba Mountain Tunnel.

3 Construction Technology for Steep Inclined Shafts

Considering the significant slope of the left and right sections of inclined shaft 1# in the Daba Mountain Extra-Long Tunnel, and in combination with the abundant water in the surrounding rock of the tunnel site, the perennial flow of multiple drainage ditches passing through the tunnel body surface of inclined shaft 1#, the crossing of multiple fractured zones by the tunnel body, and the fact that both the intersection of inclined shaft 1# with the main tunnel and the tunnel mainline from the intersection to the tunnel entrance have been fully excavated, enabling downhill drainage, the project proposed four feasible construction methods for inclined shaft 1# after thorough research. These methods are forward complete crawler-type mechanical construction, forward track transportation construction, reverse complete crawler-type mechanical construction, and reverse single-track hoisting transportation construction.

3.1 Forward Complete Crawler-Type Mechanical Construction

Forward construction refers to single-directional excavation from the mouth of inclined shaft 1#, progressing until reaching the intersection with the main tunnel. The principle of forward complete crawler-type mechanical construction utilizes the advantages of crawler-type machinery, such as robust and durable walking systems, strong ground adhesion, low ground pressure ratio, strong obstacle-crossing ability, strong climbing ability, and the ability to operate normally within tunnels with a comprehensive slope greater than 7° (i.e., 12%). This method ensures safe and efficient construction operations by providing a working platform, excavation, material transportation, and support using crawler-type machinery.

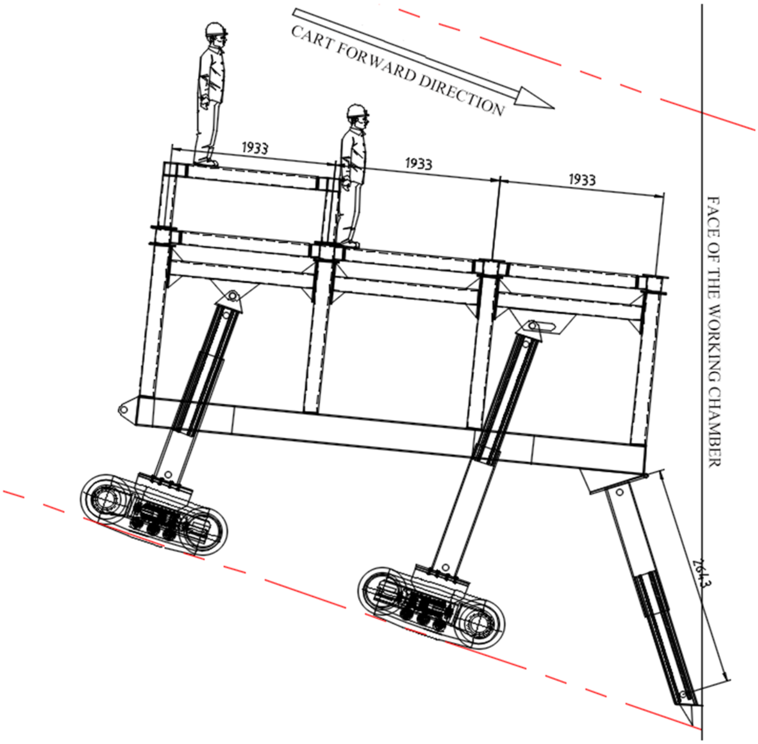

Fig. 2. Schematic Diagram of Fixed Working State of Crawler Excavator.

The main operational procedures include excavation using crawler-type self-propelled platform vehicles in Figure 2, excavation removal using crawler excavators in conjunction with crawler dump trucks in Figure 3, initial support operations using crawler-mounted excavator lifting systems combined with manual erection operations, and initial grouting operations using manual operations with small wet shotcrete machines. Drainage prevention operations are conducted using modified crawler-mounted excavator vehicles, and arch construction is achieved using integral curved formwork casting. Secondary lining construction employs crawler-type hydraulic lining vehicles, with concrete pumped into the formwork. Concrete transport utilizes crawler-type concrete tankers in Figure 4, while other material transport relies on crawler dump trucks. During construction, this method requires the installation of a reverse slope drainage system based on the design water inflow, necessitating the secondary transport of tunnel muck, with a transport distance of approximately 550 meters.

Fig. 3. Dumping Operation of Crawler Dump Truck.

Fig. 4. Transportation of Concrete by Crawler Tanker.

Table 1. Analysis and Statistics of Construction Cost for Forward Set Crawler Mechanical Construction.

Project Name	Unit	Quantity	Unit Price (RMB)	Total (RMB)
C30 secondary lining concrete	m³	6793.1	290	1970002
Backfilling concrete for arch	m³	6279.7	100	627968
Concrete for arch	m³	4099.9	100	409990
Shotcrete	m³	4678.5	280	1309972
Rebars	kg	313793	0.75	235345
Steel mesh	kg	59287	0.8	47430
Rebar anchor	kg	229810	4.5	1034145
Seamless pipe	m	16188	17	275196
Steel section	t	582775	1.2	699330
Excavation	m³	70205.5	120	8424655
Waterproofing materials	m²	39196	3	117588
Secondary disposal of excavated materials	m³	70205.5	1	702055
Track-type dump truck	Set	4	128000	512000
Track-type concrete mixer truck	Set	2	164000	328000
Truck driver for concrete mixer	Person	2	117000	234000
Excavation trolley	Set	1	980000	980000
Track-type vehicle for discharging excavated materials	m³	70205.5	32	2240279
Total (ten thousand yuan)			2014.8	

Considering the resource allocation situation of the forward complete crawler-type mechanical construction method, and based on construction efficiency analysis, each cycle takes approximately 26.5 hours. The total construction period for inclined shaft 1# is estimated at 414 days. Following cost analysis calculations, the total construction cost for inclined shaft 1# amounts to 20.148 million yuan in Table 1.

3.2 Forward Track Transportation Construction

Track transportation construction involves laying tracks inside the tunnel for material transportation operations[3-5]. Equipment used in track transportation construction includes mine cars, wire ropes, hoisting pulleys, hoists, rails, sleepers, excavators, or scraper machines in Figure 5.

The main operational procedures involve excavation using crawler-type self-propelled platform vehicles, muck removal using crawler excavators or scraper machines in conjunction with hoisting systems and mine cars, initial support operations using crawler-mounted excavator lifting systems combined with manual erection operations, and initial grouting operations using manual operations with small wet shotcrete machines. Drainage prevention operations are conducted using modified crawler-mounted excavator vehicles, and arch construction is achieved using integral curved formwork casting. Secondary lining construction employs crawler-type hydraulic lining vehicles, with concrete pumped into the formwork[6]. Concrete and other material transportations utilize hoisting systems and mine cars. Similarly to the previous method, this approach requires the installation of a reverse slope drainage system based on the design water inflow, necessitating the secondary transport of tunnel muck, with a transport distance of approximately 550 meters.

3.3 Selection of Rail Equipment

Mining Vehicle Selection.

In order to meet the demand of slag discharge, the amount of slag discharge is calculated according to the maximum of 2 meters per cycle of surrounding rock and the maximum distance of the well bottom. The excavation footage is 2m, the excavation area is 97.7m2, the false square coefficient is 1.5, and the amount of slag per cycle is 97.7*2*1.5=293.1m3.

Considering the impact of the construction period, the slag discharge time should be controlled within 7-8 hours.

(1) One-lift cycle time T_x

$$Tx = 2(\frac{v}{a}+\frac{L}{v})+u = 2*(\frac{4.8}{0.4}+\frac{4.8}{0.4})+\frac{638-26.3*2}{4.8}*2+510 = 802s = 13.4min \quad (1)$$

Where: a-given acceleration, a=0.4m/s2; lifting speed: v=4.8m/s; u-slag loading and unloading time, u=510s.

(2) One increase amount is V

$$V = \frac{V_t T_x}{60} = \frac{36.6*13.4}{60} = 8.174m^3 \quad (2)$$

In formula:

Vt-increase per hour, 293.1/8=36.6m3

Tx-One lift cycle time

Lift container: considering the reasons of unloading truck, single curved rail side unloading truck is adopted, whose parameters are: volume 8m3, external size: length, width and height = 6.38m×1.5m×1.66m, gauge 900mm, rated load 20t, dead weight of the whole machine is 5.6t.

Lift the Steel Wire Rope Type Selection.

The single cylinder winding lifting winch and 8m3 side unloading truck are 620m long and the slope is 18.59°. The loose bulk weight of ore is 2.0t / m3, the load of ore vehicle Q =8*2=16t, and the weight of 8m3 is 5.6t.

(1) The approximate quality Pk calculation per unit length of the wire rope

$$P_k \geq \frac{Q_d(\sin\alpha + f_1\cos\alpha)}{K_z\frac{R_0}{m_a} - L_c(\sin\alpha + f_2\cos\alpha)} = 2.70kg/m \tag{3}$$

In formula:

Q_d-rope end load, $Q_d = Q_k + Q$=16000 + 5600=21600kg

R_0-nominal tensile strength of wire rope, R_0=1770MPa

K_z -comprehensive coefficient of wire rope, $K_z = 100\ K_2\ K_3\ /(K_1 g)$=11.0075

f_1-running resistance coefficient of mine vehicle, $f_1 = 0.015$

f_2-resistance coefficient of wire rope, $f_2 = 0.2$

L_c- -the overhanging length of the wire rope, L_c = 620 m + 9m + 9m + 12m=650m

m_a-wire rope safety factor, m_a=6.5 (specially for lifting material)

Select 6*7 + FC natural fiber core wire rope, the relevant parameters of the wire rope are as follows:

Nominal diameter: d=32mm

The nominal tensile strength: R_0=1770MPa

Minimum breaking tension of steel wire rope: F_0=602kN

Mass per meter:P_k=3.59kg/m.

(2) Calculation of the safety factor of the wire rope n

The diameter of the wire rope isφ32(3.59kg/m)

Minimum breaking force of φ32 wire rope: F_0=602kN

$$\text{n} = \frac{Fz}{F_{\max}} = \frac{602}{83.2} = 7.24 \tag{4}$$

Coal safety regulations provide for the safety factor n≥6.5, when lifting materials, to meet the requirements.

Lift Machine Promotion Capacity Calculation.

$$F_{\max} = 9.8 \times \left[n_1 \times Q \times (\sin\alpha + f_1 \times \cos\alpha) + P_c \times L_c \times (\sin\alpha + f_2 \times \cos\alpha)\right] = 83.2kN \tag{5}$$

In formula:

n1- Increase the number of containers; n1=1;

Q- The sum of lifting vessel's dead weight Q1 and load Q2, according to 8m3 mine car's dead weight Q1=5.6t, Q2=8*2=16t (the weight of virtual slag is considered according to 2t/m3);

Lc - Rope maximum overhang length, 650m;

Pc - unit weight of wire rope, 3.59kg/m;
f1 - Raise the resistance coefficient of container movement to 0.015
f2 - steel wire rope moving resistance coefficient, 0.2 ~ 0.40; Take 0.25
α - Inclined hole inclination, 18.59°

Coal safety regulations stipulate that the maximum static tension of steel wire rope of JK-2.5x2.0P type hoist is 90kN, so JK-2.5x2.0p type single-barrel single-rope winding mine hoist is selected to meet the requirements.

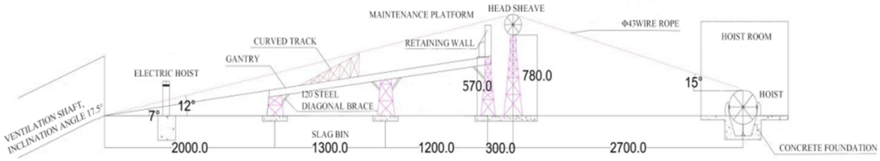

Fig. 5. Longitudinal Section Layout of On-track Construction System at Tunnel Entrance.

Taking into account the resource allocation situation of the forward track transportation construction method, and based on construction efficiency analysis, each cycle takes approximately 31.13 hours. The total construction period for inclined shaft 1# is estimated at 474 days. Following cost analysis calculations, the total construction cost for inclined shaft 1# amounts to 21.8954 million yuan in Table 2.

Table 2. Analysis and Statistics of Construction Cost for Forward Tracked Transport Construction.

Project Name	Unit	Quantity	Unit Price (RMB)	Total (RMB)
C30 Secondary Lining Concrete	m^3	6793.11	330	2241726
Backfill Concrete for Inverted Arch	m^3	6279.68	130	816358
Inverted Arch Concrete	m^3	4099.9	130	532987
Shotcrete	m^3	4678.47	300	1403541
Rebar	kg	313793	0.75	235345
Rebar Mesh	kg	59287	0.8	47430
Rebar Anchor Rod	kg	229810	4.5	1034145
Seamless Pipe	m	16188	17	275196
Steel Section	t	582775	1.2	699330
Excavation	m^3	70205.46	120	8424655
Waterproofing Materials	m^2	39196	3	117588
Secondary Re-transportation of Spoil	m^3	70205.46	1	702055

Project Name	Unit	Quantity	Unit Price (RMB)	Total (RMB)
Winch Rental Cost	Year	1.3	385000	500000
Winch Operators' Wages	Person	4	409750	1639000
Winch Electricity Expenses	Year	1.3	461538	600000
Excavation Platform Trolley	Unit	1	980000	980000
Gantry Crane	Unit	1	120000	120000
Track and Installation	Set	1	364500	364500
Wire Rope, Rail Sleepers, etc.	Set	1	361500	361500
Winch Site and Workshop	Set	1	800000	800000
Total (ten thousand yuan)			2189.54	

3.4 Reverse Set of Caterpillar Machinery Construction

Reverse construction refers to the single-directional excavation starting from the intersection of inclined shaft 1# and the main tunnel, and progressing until reaching the entrance of inclined shaft 1# to achieve breakthrough. The principle of reverse set of caterpillar machinery construction is essentially similar to that of forward set of caterpillar machinery construction, with the main difference lying in the reverse slope construction instead of the forward slope construction. Similarly, it utilizes the advantages of the robust and durable walking system of caterpillar machinery, strong ground adhesion, low ground pressure, strong obstacle-crossing ability, strong climbing ability, and the capability to operate normally in tunnels with a comprehensive longitudinal slope greater than 7° (or 12%), thereby achieving safe and efficient operations of caterpillar machinery in providing work platforms, discharging debris, transporting materials, and supporting construction activities.

The main operational processes include excavation operations using self-propelled crawler platform vehicles in Figure 6; debris removal operations using crawler excavators in conjunction with self-dumping trucks; initial support operations using crawler-type excavation platform vehicles and manual erection operations, along with manual spraying operations using small-scale wet spraying machines; drainage prevention operations using modified excavation platform vehicles; construction of the arch using integral arc-shaped formwork casting; secondary lining using crawler-type hydraulic lining trolley, with concrete pumped into the formwork; concrete transportation utilizing crawler-type concrete tanker trucks, and transportation of other materials using crawler-type dump trucks. This method can achieve downhill drainage during construction, but still requires secondary transportation of tunnel debris, with a secondary transportation distance of approximately 3530 meters in Figure 7.

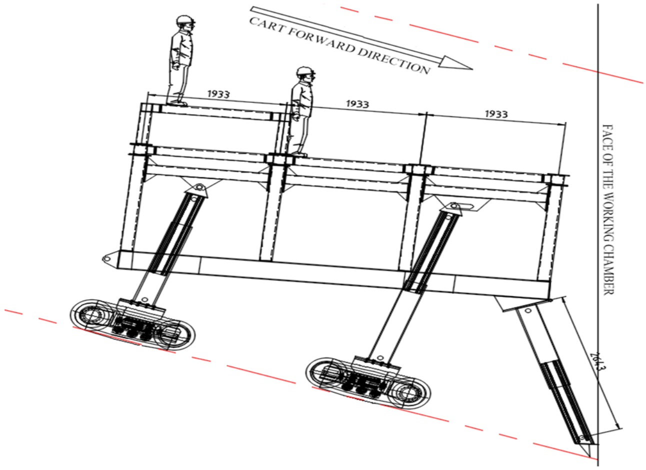

Fig. 6. Schematic Diagram of Fixed Working State of Traveling Excavator.

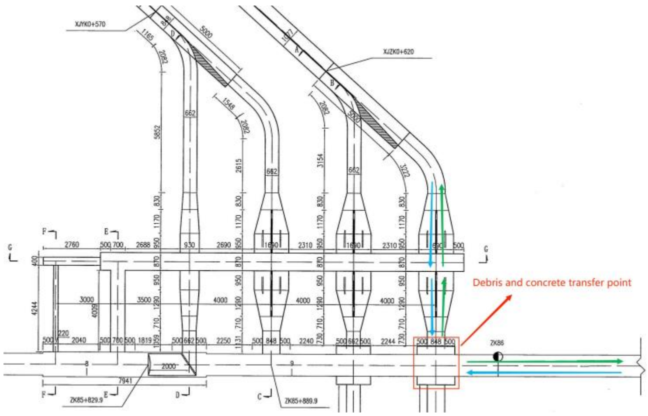

Fig. 7. Schematic Diagram of Material Transfer Points.

Considering the resource allocation situation of the reverse set of caterpillar machinery construction method, through construction efficiency analysis and calculation, the time required per cycle is approximately 26.95 hours, with a total construction period of 422 days for inclined shaft 1#. Through cost analysis and calculation, the total construction cost of inclined shaft 1# amounts to 21,872.29 million yuan in Table 3.

Table 3. Cost Analysis Summary Table for Reverse Set of Tracked Mechanical Construction Units.

Item	Unit	Quantity	Unit Price (RMB)	Total (RMB)
C30 Secondary Lining Concrete	m^3	6793.11	290	1970002
Arch Backfilling Concrete	m^3	6279.68	100	627968

Item	Unit	Quantity	Unit Price (RMB)	Total (RMB)
Arch Concrete	m³	4099.9	100	409990
Shotcrete	m³	4678.47	280	1309972
Rebar	kg	313793	0.75	235345
Rebar Mesh	kg	59287	0.8	47430
Rebar Anchor Rod	kg	229810	4.5	1034145
Seamless Pipe	m	16188	17	275196
Steel Section	t	582775	1.2	699330
Excavation	m³	70205.46	140	9828764
Waterproofing Material	m²	39196	3	117588
Secondary Slag Discharge	m³	70205.46	1	982876
Tracked Dump Truck	Unit	4	128000	512000
Tracked Concrete Tanker	Unit	2	164000	328000
Tanker Driver	Person	2	117000	260000
Excavation Cart	Unit	1	980000	980000
Tracked Vehicle for Slag Discharge	m³	70205.46	32	1903280
Ventilation Costs	Set	1	351027	351027
Total (ten thousand yuan)			2187.29	

3.5 Reverse Monorail Crane Transport Construction

The principle of reverse monorail crane transport construction mainly involves installing a track on the initial support section of the tunnel arch, and using locomotives and hoist boxes for material transport. The monorail crane system consists of locomotives, hoists, and tracks in Figure 8. The locomotive adopts a turbocharged diesel engine or an electric motor monorail crane. The maximum traction and braking force are determined according to the construction requirements such as slag removal and material transport. It is equipped with a lifting beam and hoist box, and the track adopts a V-shaped rail. The hanging method of the track chooses four thin-threaded high-strength anchor rods with double hanging plates, one end of the anchor rod is processed into an "L" shape, reserved during each initial support construction process, and welded or bolted to the initial support steel arch, while the other end passes through a special hanging plate, and special pads and nuts are installed to fix the special hanging plate. Considering the large slope of the inclined shaft, each track is inclined with a tensioned chain.

The main operational processes include excavation using a crawler self-propelled trolley; slag removal using a crawler excavator combined with the monorail crane system to transport the slag to the end point of the shaft, then using a wheeled transport vehicle to reverse it to the slag dumping site; initial support using a crawler excavator with a lifting system for erecting operations, combined with manual spraying using a small wet spray machine; anti-drainage operations using a modified crawler excavator; arching using integral curved formwork pouring; secondary lining using a crawler hydraulic lining trolley, with concrete pumped into the mold; concrete and other materials transported using wheeled concrete tankers or loaders to the transfer point at the intersection of the tunnel mainline and the inclined shaft, and then transported to the operation point using the monorail crane system. This method can achieve downhill drainage during construction, but still requires secondary reverse transportation of tunnel spoil, with a secondary reverse transportation distance of approximately 3530 meters.

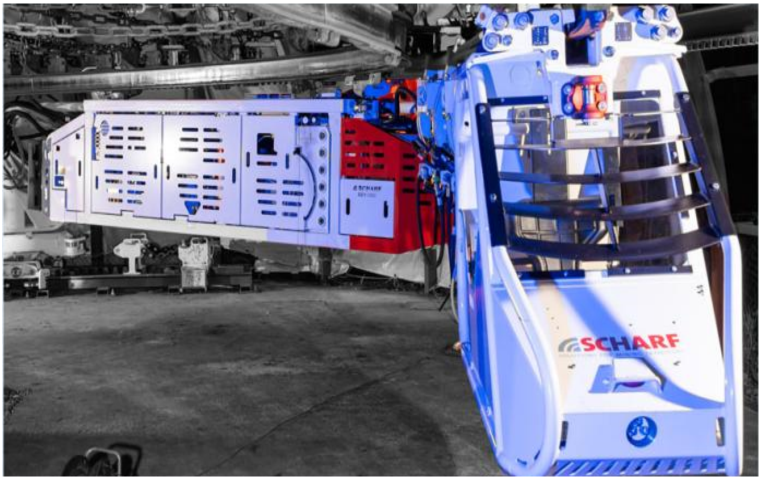

Fig. 8. Application Example of Single Rail Crane System in the Tunnel.

Based on the resource allocation of the reverse monorail crane transport construction method, the construction efficiency analysis calculates that each cycle takes approximately 32.79 hours. The total construction period for the 1# ventilation inclined shaft is 470 days. According to the cost analysis, the total construction cost for the 1# ventilation inclined shaft is calculated to be 23,549,700 yuan in Table 4.

Table 4. Cost Analysis Summary for Reverse Single-Rail Hoisting Transportation Construction.

Project Name	Unit	Quantity	Unit Price (RMB)	Total (RMB)
C30 Secondary Lining Concrete	m^3	6793.11	290	1970002
Arch Backfill Concrete	m^3	6279.68	100	627968
Arch Concrete	m^3	4099.9	100	409990
Shotcrete	m^3	4678.47	280	1309972
Rebar	kg	313793	0.75	235345
Rebar Mesh	kg	59287	0.8	47430
Rebar Anchors	kg	229810	4.5	1034145
Seamless Pipe	m	16188	17	275196
Steel Sections	t	582775	1.2	699330

Project Name	Unit	Quantity	Unit Price (RMB)	Total (RMB)
Excavation	m^3	70205.46	140	9828764
Waterproofing Materials	m^2	39196	3	117588
Secondary Slag Transport	m^3	70205.46	1	982876
Monorail Crane System	Unit	1	2586500	2586500
Monorail Crane Operator	Person	4	226400	905600
Track-Mounted Concrete Tanker	Set	2	164000	328000
Tanker Driver	Person	2	117000	260000
Excavation Platform	Set	1	980000	980000
Ventilation Costs	Unit	1	351027	351027
Total (ten thousand yuan)			2354.97	

4 Analysis and Comparison of Construction Technologies for Steep Inclined Shafts

Combining the four construction methods for steep inclined shafts mentioned above, we will now conduct a comparative analysis in terms of efficiency, construction period, safety, and economy.

4.1 Forward Integrated Caterpillar Mechanical Construction

Advantages.

(1) Safety: Compared to reverse construction, forward construction reduces the safety risks associated with rock collapse at the tunnel face, thus ensuring higher safety.

(2) Occupational Health: Forward construction provides better ventilation compared to reverse construction, leading to shorter ventilation periods and improved occupational health conditions.

(3) Efficiency and Duration: With this method, each cycle takes approximately 26.5 hours, achieving the highest construction efficiency. The construction period is 414 days, which is the shortest among the methods analyzed.

(4) Economy: Forward construction involves shorter distances for waste transportation, resulting in lower waste removal costs. The estimated construction cost for the 1# ventilation inclined shaft is about 20.148 million yuan, making it the most cost-effective option.

Disadvantages.

(1) Forward construction faces unpredictability due to geological complexities such as rich water content in the surrounding rocks, requiring additional investment in drainage equipment or advance drilling to achieve downhill drainage. This may increase construction costs by approximately 480,000 yuan.

(2) There are relatively few cases of integrated caterpillar mechanical construction for similar large-gradient inclined shafts, making the technology less mature.

(3) The large size of the construction site at the tunnel entrance significantly affects surrounding access roads, explosives depots, and other facilities, leading to higher upfront costs compared to reverse construction.

4.2 Forward Tracked Transport Construction

Advantages.

(1) Construction: There are abundant resources of tracked equipment in the market, which can be leased or purchased. There are also more teams with qualifications for tracked transport construction and experienced operators. The technology for tracked transport construction is relatively mature, with many referenceable and adaptable technical resources, requiring fewer technical obstacles to overcome.

(2) Occupational Health: Forward construction has better ventilation effects compared to reverse construction, and requires shorter ventilation time.

Disadvantages.

(1) Efficiency and Construction Period: With this method, each cycle takes approximately 31.13 hours, resulting in the lowest construction efficiency and the longest construction period of 474 days. Progress is significantly affected by factors such as power outages or equipment failures, as debris removal from the shaft is only possible via mine cars.

(2) Economy: Maintenance and repair costs for tracked equipment are high, and the planning area for the shaft entrance is large, resulting in high setup costs. Overall, the investment cost is high, with the construction cost of the 1# ventilation shaft being approximately 21.8954 million RMB, which is higher compared to the complete tracked machinery method.

(3) Safety: Tracked transport construction poses high safety risks, with stringent safety management requirements. Equipment management, operation, and maintenance require high levels of expertise. Additionally, emergency response capabilities are limited in case of adverse geological disasters like mud and water influxes.

4.3 Reverse Complete Tracked Machinery Construction

Advantages.

(1) Efficiency and Construction Period: With this method, each cycle takes approximately 26.95 hours, resulting in the lowest construction efficiency and a shorter construction period of 422 days compared to forward tracked transport construction.

(2) Economy: Adopting reverse construction allows for downhill drainage, saving about 480,000 RMB in drainage costs. Additionally, existing equipment in the main tunnel, such as air compressors and transformers, can be utilized, reducing setup costs at the shaft entrance.

Disadvantages.

(1) Safety: Compared to forward construction, reverse construction poses a higher risk of rock collapse at the tunnel face. In case of sudden geological risks like mud and water influxes, the emergency response time is shorter, leading to higher construction safety risks.

(2) Occupational Health: Reverse construction has poorer ventilation effects compared to forward construction, and requires longer ventilation times.

(3) Technology Maturity: There are fewer examples of reverse complete tracked machinery construction for similar steep inclined shafts, making the technology relatively less mature. Consequently, there are more safety and quality issues to address during construction.

4.4 Reverse Single Rail Crane Transport Construction

Advantages.

(1) Reverse construction can utilize existing equipment in the main tunnel, such as air compressors and transformers, saving costs for shaft entrance layout. It can also achieve downhill drainage, saving drainage costs.

(2) Using single rail crane transport construction makes material transportation more convenient.

(3) The debris removal process involves heavy-duty track downhill, which has low traction requirements for motor vehicles.

Disadvantages.

(1) Safety: Compared to forward construction, reverse construction poses a higher risk of rock collapse at the tunnel face. In case of sudden geological risks like mud and water influxes, the emergency response time is shorter, leading to higher construction safety risks. Single rail cranes need to rely on the stability of the initial support structure of the tunnel entrance, which significantly affects the stability of the initial support section, increasing construction safety risks.

(2) Occupational Health: Reverse construction has poorer ventilation effects compared to forward construction, and requires longer ventilation times.

(3) Technology Maturity: There are fewer examples of reverse single rail crane transport construction for similar steep inclined shafts, making the technology relatively less mature. Consequently, there are more safety and quality issues to address during construction.

(4) Efficiency and Construction Period: With this method, each cycle takes approximately 32.79 hours, resulting in the lowest construction efficiency and a longer construction period of 470 days compared to complete tracked machinery construction.

(5) Economy: Maintenance and upkeep costs for single rail crane transport equipment are high. When using this method, the construction cost of the 1# ventilation shaft is approximately 23.5497 million RMB, making it the most expensive construction option.

5 Key Points and Conclusion of Forward Tracked Machinery Construction

5.1 Key Points of Forward Tracked Machinery Construction.

The key points of construction for the large inclined shafts of the tunnel using forward tracked machinery construction are as follows:

Excavation Operation.

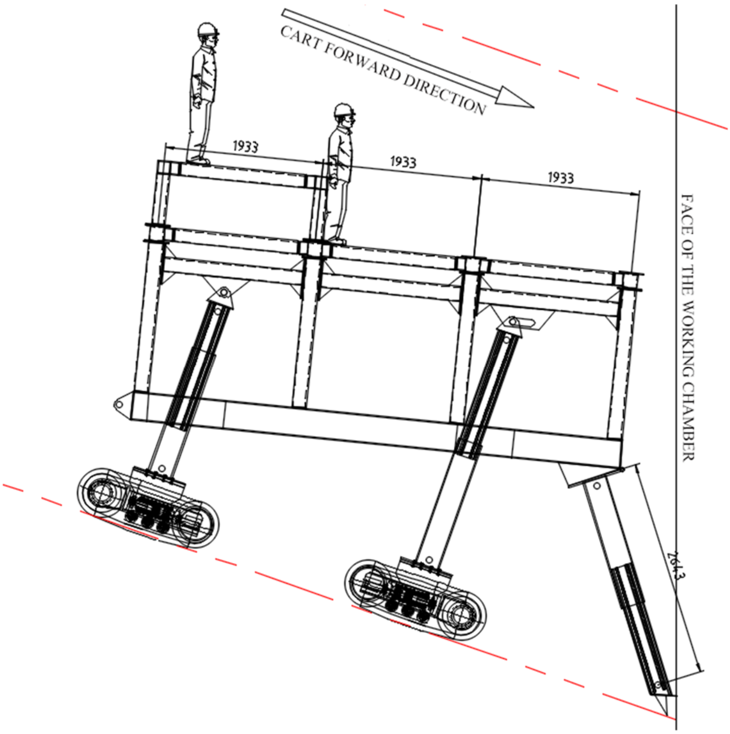

Fig. 9. Schematic Diagram of the Fixed Working State of the Walking Excavator.

In the excavation operation, an operational platform for drilling and blasting personnel—excavation trolleys—are used, which are self-propelled tracked trolleys. The dimensions of the trolleys need to be determined based on the comprehensive longitudinal slope and cross-section dimensions of the inclined shaft. For example, in this project, the longitudinal slope of the tunnel shaft is -33%, and the cross-section adopts a single circular section with a radius of 5.57 meters, a net width of 10.77 meters, and a net height of 7.0 meters. Through simulation analysis and calculation, the length of the trolley used in the construction of the tunnel shaft in this project is determined to be 6 meters, with a width of 10.5 meters, a height of 4.5 meters, a weight of 20 tons, and a maximum climbing ability of 19.3° (or 35%), meeting the requirements for uphill and downhill traction. The net clearance width of the trolley for passing through is 4.19 meters, and the height is 3.91 meters, meeting the conditions for the passage of fully loaded dump trucks and excavators. Hydraulic support devices are installed at the front and rear of the trolley, and when walking, the trolley is parallel to the slope of the shaft. When fixed, the hydraulic devices at the front and rear of the trolley are raised to provide workers with a relatively horizontal working platform in Figure 9, and auxiliary limit-fixing is provided by the ground screw limit device to ensure its safety performance during use. The trolley frame is equipped with a 6-meter retractable working platform, which can simultaneously meet full-section and step-by-step construction methods. The trolley comes with a lifting and telescopic arm for hoisting arches and assisting workers in erecting supports. During blasting, the trolley retreats to a safe area and is fixed.

Residue Removal Operation.

The residue removal operation on the face is carried out using a tracked excavator in conjunction with a 7.3m^3 tracked transport vehicle to transport the face stone residue to the discharge pit at the shaft mouth. Periodically, a wheeled side dump loader and wheeled dump truck are used to transfer the residue to the waste disposal site. The tracked dump truck has a maximum climbing ability of 25° (or 46.6%) and a maximum load capacity of 15 tons in Figure 10. The cargo box dimensions are length × width × height (3.8m × 2.4m × 0.8m), and the average speed when fully loaded is 10 km/h (or 167m/min).

Fig. 10. Operation of the Tracked Dump Truck for Slag Discharge.

Initial Support Operation.

As the residue removal process approaches completion, scaffolding and supporting materials are transported from the rebar plant to the face using tracked transport vehicles. Manual assistance is provided for scaffolding and other operations using the lifting system of the excavator. The initial support concrete spraying is centralized at the mixing station, and $3m^3$ tracked concrete tank trucks are used to transport the concrete to the face. Manual assistance is provided with a small wet spraying machine for the initial support concrete spraying operation.

Arching and Arching Backfilling Construction.

After the completion of the shaft boring, the stone residue for backfilling the tunnel bottom is excavated in reverse, and tracked dump trucks are used for residue removal. For arching and arching backfilling, $9m^3$ concrete tank trucks are used to transport the concrete to the intersection of the shaft and the main tunnel. Concrete is then pumped to the arching and backfilling areas using concrete conveying pumps. During the arching and arching backfilling process, standardized templates are used to ensure stable and firm formwork and to conform to the slope of the shaft. Arching and arching backfilling are carried out section by section, with each section's length not exceeding 3m.

Drainage and Secondary Lining Operations.

The drainage operation vehicle is modified from the excavation vehicle. The secondary lining is constructed in reverse after the completion of shaft boring. A 6m-long tracked hydraulic lining vehicle is used for secondary lining, with concrete pumped into the mold. Concrete is transported to the intersection of the shaft and the main tunnel using $9m^3$ concrete tank trucks and pumped into the secondary lining area using concrete conveying pumps.

Other Operations.

Refuge chambers are established every 200m in the ventilation shafts, serving as vehicle turning points and water storage tanks for drainage within the tunnel. Buffer platforms are determined based on the location of the refuge chambers, ensuring they are not excessively long and have appropriate slopes for easy construction. Construction workers move along pedestrian pathways built on both sides of the shaft, with fences and warning signs installed along the pathways, following a left-up, right-down sequence.

5.2 Comparison Conclusion

Based on the comprehensive consideration of the safety, economy, and other advantages and disadvantages of various construction methods for large longitudinal slope shafts, and through on-site practical verification, the project ultimately adopts the forward complete set of crawler-type mechanical construction method, which has the following significant advantages:

It provides a new construction method for the construction of large longitudinal slope shafts in tunnels, which can replace the conventional track transportation construction method. This helps to avoid the safety risks and high maintenance costs associated with equipment such as winches, mine cars, tracks, and wire ropes in track transportation construction, thereby reducing construction risks. It significantly reduces the interference between residue removal and the transportation of materials such as concrete, steel frames, and rebars. Particularly, it greatly improves emergency response capabilities when facing adverse geological disasters such as mud and water inflow in tunnels.

The construction efficiency of using the complete set of crawler-type mechanical construction for large longitudinal slope shafts in tunnels is higher compared to conventional track transportation construction. The construction period is shorter. Taking the example of the No. 1 ventilation shaft in this project, the efficiency per cycle is increased by approximately 4.6 hours, saving about 60 days in total construction period.

The cost of using the complete set of crawler-type mechanical construction is lower compared to traditional track transportation construction. Taking the example of the No. 1 ventilation shaft in this project, the construction cost is reduced by 1.7474 million yuan.

The forward complete set of crawler-type mechanical construction technology provides important guidance and reference for similar construction of long tunnels with large longitudinal slope shafts.

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