The Study on the Construction Method of Bolting-Grouting Integrated Operation for Unmanned Arch Erection

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Abstract

It is of great significance to improve the mechanization level and construction quality of tunnel construction. At present, large cross-section tunnels are emerging in China. The construction method based on manual work and supplemented by a machinery has long construction period, high labor intensity, and structural quality that cannot be guaranteed. To address those issues, this paper proposes the construction method of bolting-grouting integrated operation for an unmanned arch erection to achieve the rapid and safe construction of large section tunnels and reducing the amount of manual work. This paper mainly introduces the bolting-grouting integrated operation trolley, which can achieve the automatic installation of steel arch, the construction of locking anchor pipe, and shotcrete. Besides, this paper designs a new type of steel arch and an alternative way of longitudinal connecting reinforcement of steel arch. Moreover, with the field test and optimization adjustment of the Xinwushaoling tunnel, it is found that the construction method of bolting-grouting integrated operation for unmanned arch erection can overcome some disadvantages of traditional construction methods.

1. Introduction

Mechanized construction method is an increasingly widespread approach for the direction of tunnel construction. Compared with the most topical of tunnel excavation and lining construction mechanization in China, oppositely, the increasing concern is to develop arch installation mechanization. Therefore, it is urgent to upgrade the mechanical equipment of tunnel arch installation in China to make the arch installation more competitive.

Researchers have achieved significant improvements by plenty of experimentation on the mechanized construction of tunnel arches. Presented SCDZ133 intelligent multi-function operation trolley with independent intellectual property rights through numerous investigations and combined with the research and development experience of tunnel mechanical equipment, which solved the problems of insufficient installation of tunnel steel arch, advanced support, locking anchor rod, high labor intensity and low work efficiency [1]. Utilized the numerical simulation method to determine the step length that meets the mechanized construction based on the actual project, which provides a reference for the size of the mechanized construction platform [2]. Adopted automatic assembly joints and longitudinal positioning connection bars between arch intelligent installation machine and steel arch segment to solve the problems of low construction efficiency and poor safety of large-section tunnel arch installation. Taking Gui-Guang high-speed railway tunnel as an example [3]. Developed a combined trolley for tunnel section construction in response to key issues restricting mechanized construction, which has been widely used in engineering construction. Starting from improving the efficiency of tunnel construction [4]. Analyzes the development status of equipment types and construction technology, and puts forward the supporting principles and safeguard measures of tunnel mechanized construction, which has played a certain innovative role in the management and application of railway construction mechanization. According to the construction technology and installation requirements of tunnel steel arch in China [5]. Proposed the overall scheme of manipulator and basket system, successfully assembled the virtual

prototype model, and carried out the installation test in the tunnel, which provided the basis for the overall optimization of the follow-up work device [6]. Developed XZGMT411 multi-functional steel arch installation machine and introduced its related parameters, construction operation points, and precautions to improve the installation efficiency and accuracy of tunnel steel arch [7]. Proposed the bolt-grouting integrated support method by analyzing the failure status of a deep roadway in the Yima mining area, and conducted a field operation test. The research shows that the anchor-grouting integrated support technology could achieve the expected support effect [8].

In summary, it is of significant engineering value and practical significance to carry out the research on key technologies and equipment of Bolting-Grouting Integrated Operation for unmanned Arch Erection. Based on the integrated construction background of the Xinwushaoling tunnel entrance section, this paper optimizes and improves the installation equipment of steel arch and the connection form of steel arch to achieve the purpose of fast, high-quality, and safe erection of steel arch, combined with the actual construction situation on-site, summarize the key issues about the Bolting-Grouting Integrated Operation for unmanned Arch Erection.

2. Engineering Background

2.1 Engineering overview

The total length of the Xinwushaoling tunnel is 17.125 km, which is located on the east side and upper side of the Wushaoling extra-long tunnel on the second line of the Lanzhou-Wuwei railway [9]. It is a new railway, the dominant engineering on the third and fourth line of Lanzhou-Zhangye railway. The total length of the tunnel entrance under construction by the China Railway Fifteenth Bureau is 8021 m, including 935 m of class III surrounding rock, 4450 m of class IV surrounding rock, and 2636 m of class V surrounding rock. The proportion of class IV and V surrounding rock is 87.6 %. By using the existing slant holes shaft to set up branch holes to increase the working face, there was a total of 7 working faces installed.

2.2 Construction scheme

Considering the structure size of the vertical arch trolley and the height of the upper step, the unmanned arch erected test is scheduled for the upper step construction of the entrance section of the Xinwushaoling tunnel. The elevation of the tunnel entrance is 2800 m, mainly with class III and IV surrounding rocks which are sandstone. The palm surface is stable, with no block falling, no water seepage. Combined with the tunnel section size and excavation method, cause this paper chooses the upper step height is 7.11 m, the lower step height is 3.05 m, and the step length is 35 ~ 50 m. The construction cycle footage is 2 ~ 2.4 meters, two arches what are I-steel 16 and I-steel 18 are erected. On average, three cycles of excavation were conducted in two days.

3. Operation Trolley And Arch Form Of Unmanned Arch Erection

3.1 Bolting-Grouting integrated operation trolley

To process unmanned arch erection construction operations requires advanced operating trolleys and advanced steel arches suitable for construction methods. Based on the original design of the rock drilling rig, the hydraulic arm system is improved to achieve the overall lifting of the steel arch and the purpose of moving omnidirectionally. The trolley used a hybrid-electric drive. After reducing the risk in the palm surface, the trolley moves in a position, and the operator uses the handheld remote control to operate the hydraulic arm system to achieve the unmanned operation under the palm surface. The detailed structure of the arch installation trolley is shown in Figs. 1 and 2.

By changing the connection mode between the steel arch segments to propose a steel arch connection type and installation method suitable for mechanized construction. The connection type of the steel arch is articulated, including a cone-shaped end, a spring buckle matched with the cone-shaped end, and a pre-joining device for the arch.

After the steel arch is erected, as the locking anchor pipe, the bolting-grouting integrated equipment of the arch installation machine is increasingly utilizing. The steel arch is locked by the locking anchor pipe. The locking anchor pipe and the primary steel arch are rigidly fixed with the steel ring through the $\Phi 10$ spiral steel bar, and the length of the spiral steel bar is 25 cm. Figures 3 and 4 are shown.

If the gap between the steel arch and the primary spray coating is large, precast concrete blocks should be inserted every 2 meters along the circumferential direction, and the remaining space is filled with sprayed concrete. Then, to strengthen the rigidity of the locking anchor pipe, the self-contained grouting machine was used to fill the locking anchor pipe with M10 cement mortar. After the steel arch is installed, the concrete should be sprayed immediately to make the steel arch and the shotcrete form a common force.

3.2 New kind arch form

The production of the steel arch are concentrated in the processing plant. The total length of the upper guide arch is 22.5 m, and it has divided into three types, in which one section of type A is 7.5 m, two sections of type B are 6.3 m, and two sections of type C are 1.2 m. The segmental arch can be allowed to next stage manufacturing after assembling to reach the design requirements. The arch combination diagram is shown in Fig. 5.

Before the cool-bend process of steel, the field lofting should accord to the ratio of 1:1 on the hardening and leveling site. Then, a steel arch processing platform needs to be set up and the processing patterns should be manufactured according to the design alignment. In addition, the bending value of the section steel cold-bending machine is tested by the previous section steel. Subsequently, the curvature of the test section steel is repeatedly compared with the mold, and it is not determined until it is fully conformed. To save materials of expenditure and facilitating the cool-bend process, the section steel connection is performed before the cool-bend process. The steel connection should follow the specification, that is, the

embedded welding is adopted, and the weld length and welding plumpness should be ensured, and the welded web is affixed at the connection. After the cold-bending machine jacking-bends the steel into the required curvature radius, the plasma cutter is used to cut the steel according to the section length of the steel arch.

For the production of the connecting plate, to achieve the unmanned installation of the steel arch, the connection method of the steel arch must be switched from bolt connection to hinged connection [10]. The articulated slab implements the locking and anti-detachment function of the arch after the arch is extended through the conical end and spring buckle. The diameter of the pinhole is 40 mm, the diameter of the pinhead is 28 mm, and the scalability amount of the slot is 10 mm. The design thickness of the articulated steel plate is 16 mm. The two steel plates are combined into a 'hinge shape' by a common shaft plug. The diameter of the steel shaft is 20 mm. Details of the connection plate are shown in Figs. 6 and 7.

Description of the snap-fit connection: Clamping structure 2 includes conical end 2.1 which is set on one arch element 1 and elastic chuck buckle 2.2 which is set on another arch element 1. The elastic chuck buckle 2.2 is equipped with a cavity and an elastic chuck buckle 2.2.1 to accommodate the conical end 2.1, and the inner diameter of the cavity of the elastic chuck buckle 2.2 is 1.05–1.1 times that of the conical end 2.1, which can ensure that the conical end 2.1 passes through the cavity of the elastic chuck buckle 2.2 and that the elastic chuck buckle 2.2.1 tightens the conical end 2.1. After the folding arch frame is stretched, the conical end 2.1 is stuck in the elastic chuck buckle 2.2, to obtain the arch frame matching the palm surface of the tunnel, and no additional fixing device is added to the arch frame manually.

The elastic chuck buckle 2.2 in Fig. 7 is equipped with an annular groove installed with elastic collar 2.2.1. The specification of the annular groove is 1.1–1.5 times that of the elastic collar 2.2.1. When the conical end 2.1 passes through the elastic collar 2.2.1, it can provide expansion space for the elastic collar 2.2.1. And the elastic collar 2.2.1 has a gap, which makes the elastic collar 2.2.1 easy to achieve expansion deformation and rehabilitation.

The upper step steel arch has five arch elements, which are folded to form a whole during construction. Otherwise, for the combination of steel arch frame and hinge plate, the fabricated steel section and hinge plate should be welded in the field. Meanwhile, the welding adopts carbon dioxide protection welding, and ensures continuous full-length welding, without leakage welding, or intermittent welding. Eventually, after passing the inspection, it needs numbered and neatly stacked in the semi-finished products area, indicating its inspection test state, to be transported to the tunnel for use. The folding combination of steel arch is shown in Fig. 8.

3.3 Alternative scheme of longitudinal connecting bars and steel mesh

As the traditional connection method cannot realize unmanned construction, when the steel arch is processed, workers are required to bind, overlap and weld. Therefore, the longitudinal connection method is processed into triangular steel bars. The non-top corner ends of the triangular reinforcement are prewelded in the factory with the steel arch. Then, the steel arch is erected by the arch construction trolley, and the top corner ends of the triangular reinforcement between the two arch frames maintain jacking-press contact with the steel arch respectively, which is consistent with the backward extrusion of the soil on the palm surface and can realize the construction with low accuracy requirements for the installation of the steel arch.

The traditional steel arch connection method is shown in Fig. 9. And the longitudinal connection method uses triangular steel bars instead of the connection method as shown in Fig. 10(a) and Fig. 10(b).

4. Construction Method And Key Points Of Unmanned Arch Erection

4.1 Scope of application and characteristics of construction method

The mechanical configuration of this report is determined according to the on-site hydrogeological conditions. Meanwhile, the palm surface excavation method can be selected according to the stability of the surrounding rock. Generally, the surrounding rock has reliable stability, the compressive strength of the rock mass is less than or equal to 60MPa, and the layer thickness is less than or equal to 30 centimeters, and in the absence of water, by using cantilever roadheader for excavation and slag discharge operations. The construction process of the steel arch frame adopts the unmanned arch erection and bolting-grouting integrated operation trolley for operation. Relatively, spraying concrete by large concrete wet spraying trolley.

If the integration of the surrounding rock is appropriate and the surrounding rock is not available for excavation with a cantilever roadheader, the drilling and blasting method should be used for excavation, the loader and dump truck should be applied in the slag discharge operations, before carrying out unmanned arch erection.

To summarize the above two points, this construction method is available for tunnels with a stable surrounding rock and excellent integration, and the excavation method is a two-step tunnel [11]. At present, the construction of weaker broken surrounding rock requires preliminary shotcrete, and it is applicable in the case of tunnel advanced support construction.

4.2 The characteristics of construction method

Improving the efficiency of arch installation. By adopted steel arch installation trolley to replace the work platform. Then, the whole folding steel arch can be lifted from the ground with the telescopic arm of the trolley, and the steel arch is accurately positioned to the design position. Therefore, the construction efficiency of the steel arch lifting and positioning has been significantly improved.

Achieving the unmanned arching operation. To implement the unmanned arch erection of bolting-grouting integrated operation, changing the connection mode between the segments of the steel arch, optimizing replacement scheme of the longitudinal connection bar and the steel mesh. Sequentially, decreasing the labor intensity and the number of workers erecting the steel arch quickly and safely.

Ensuring the safety of support construction. After tunnel excavation, the initial lining construction stage is a period that is a frequent occurrence of safety accidents. This method effectively reduces the number of operation and construction personnel and enhances the safety of support construction.

4.3 Installation procedure and control points of unmanned arch erection

The construction process is shown in Fig. 11.

Steel arch installation Firstly, before the steel arch is installed, check the clearance of the excavation section, and start installation after it is qualified. Secondly, after determining the centerline of the route, elevation could be ensured. Then to measure the lateral position to ensure that the steel arch is not skewed, not twisted, and is located on the same vertical plane. Thirdly, according to the measuring position, the whole steel arch is lifted at once by the arch installation machine. Furthermore, according to the measuring point and using a grab arm of the arch installation machine, the middle A segment of the arch is fixed, then open the unilateral segments B and C through another arm. The locking and anti-detachment function of the articulated slab is used to ensure that the unilateral arch is firmly supported on a stable foundation. Finally, the third grab arm is used to open the B and C segments of the other side in turn and firmly fixed on the foundation. The on-site installation of the steel arch is shown in Figs. 12 and 13.

To ensure that the steel arch is placed on a solid foundation before the whole ring is closed, the slag and debris under the bottom feet of both sides of the steel arch are removed before installation. When the arch foot (arch wall) is overcutted, soil cannot be backfilled, and the concrete cushion block should be used for adjustment.

Key points of quality control for unmanned arch construction In terms of raw materials, the mechanical properties and process performance tests (yield strength, tensile strength, and elongation) must accord to the requirements of the current national standard '*Carbon structural steel (GB/T700)*', which can ensure the types and specifications of steel used to make steel frames to satisfy the requirements. During processing, materials such as steel bars and section steel should be flat and harmless, hence cracks, oil pollution, granular or flake corrosion should not occur on the surface. The sectional length is determined according to the design size and the excavation method adopted, and the drilling position on the web should meet the design requirements. The plane warping should be less than 2 cm, and the joints should be strictly prohibited at the vault of the steel frame. Welding of steel arch processing should not have false welding, weld surface should not have cracks, welding slags. The joint adopts double-sided arc welding and steel plate for auxiliary welding simultaneously. The size of the steel plate is determined

according to the mechanical calculation, and using the four-sided girth welding to machine it which has 12 mm thickness of the weld, and each side is lapped by 50 mm.

When the steel arch is constructed, its footing should be placed on a solid foundation. Timely erection of arches after removal of uncompacted waste residue and miscellany at bottom feet and initial spraying of concrete. If the arch footing (or arch wall) is overcutted, concrete cushion blocks should be used to adjust the tighter so that the allowable longitudinal deviation of the arch foot is controlled at ± 10 cm, the lateral position deviation is ± 2 cm, and the verticality is $\pm 1^\circ$, and not backfilled with soil. Each section of the steel frame should be close to the surrounding rock, along the outer edge of the steel frame every 2 m with concrete precast block wedge.

Safety Measures Before the tunnel support operation, the working surface should be checked to remove loose rocks and concrete blocks. Working face electricity should meet the requirements of temporary electricity. In addition, the illuminance should meet the needs of safe operation, not less than 50lx.

When the surrounding rock is less-fragmentized, concrete should be sprayed immediately after blasting to close the surrounding rock, and when necessary to close the palm surface.

The unmanned archer should be regularly overhauled and maintained following the provisions. Meanwhile, completing the protection facilities.

5. Benefit Analysis Of The Xinwushaoling Tunnel

5.1 Later design optimization

Three tests were carried out on the 'unmanned' arch erection of the upper step of the Xinwushaoling tunnel. In the first outdoor test, the steel processing plant of Lanzhou-Zhangye Railway Project Department of the 15th Bureau of China Railway has carried out multiple tests of articulated connecting footplates and locking anchor pipe + shroud ring. Affected by the processing level and the lack of familiarity of the workers in the first contact, the spring steel bars used for anchor bolts have stuck and cannot be stretched freely. The spring steel bar is stuck as shown in Fig. 14.

The arch erection test of the articulated arch frame with the length of 1:1 on the upper bench was carried out outside the tunnel. According to the size of the upper steps, the steel arch is divided into three sections, A unit is 8 m, B, C unit is about 6 m. It mainly trains the movement of the articulated arch frame, the movement of the two manipulators to change hands over-the-air, and the movement of the locking anchor pipe. The field test erects the arch as shown in Fig. 15.

The second and third tunnel tests mainly solved the problems such as the weak connection of the articulated hinged plate of the steel arch, the disengagement of the articulated joint due to the weight of the arch frame itself after hinged, the insufficient flexibility of manipulators of the arch frame, the long time-consuming grabbing of the arch frame, and inability to stretch the composite articulated arch frame

on the palm surface. Moreover, the type of the upper step steel arch is designed as five sections, the vault length is 7.3 m, the haunch length is 5.7 m, and the arch footing length is 1.6 m. Furthermore, the arch erection is operated remotely by two operators, far away from the palm surface.

The design scheme has been put into tunnel construction at present. In the construction practice, it is difficult to hanging ash in the vault, and the rebound of concrete in the middle of the triangular reinforcement is large, which causes certain construction difficulties. Therefore, optimize the design again on the basis of the design: A transverse reinforcement is set at one-third of the triangular reinforcement on each side to increase the amount of concrete reinforcement in the middle, and it can play a certain effect of hanging ash when spraying concrete. The optimized triangular reinforcement is shown in Fig. 16.

5.2 benefit analysis

The method proposed in this paper improves efficiency and greatly reduces construction time. Compared with the traditional manual construction, the installation time of one arch frame is reduced from 1.5-2h / frame to 1h / frame, according to the average footage of two 1.6 meters per cycle, the time saving per cycle is 1.5h. Besides, for the tunnel with a length of 8000 meters, the total saving time is 7500 h (312 days), and the average saving time is 45 days for each of the seven working surfaces. Moreover, the reduction in construction time resulted in a reduction in the use of personnel, i.e. a reduction in arch personnel from the original 9 to 3 (1 operator and 2 workers), and reduce risk. Meanwhile, reduced personnel leads to lower consumption and lower machine loss. Ultimately, total investment decreased. The number of construction personnel and the labor intensity of workers are greatly reduced by replacing people with machines. According to the worker's monthly wage of 8000 yuan/person, the upper guide hole excavation saves labor costs of 48,000 yuan per month, then 7 working surfaces and 20 months of construction period save labor costs of about 6.72 million yuan. Then, considering the depreciation of mechanical equipment, personnel, electricity, and other inputs, a total of nearly 9.3 million yuan was saved.

6. Conclusion

In a period of the adjustment test of arch erection at the entrance of the Xinwushaoling tunnel, this report established a set of bolting-grouting integrated operation for unmanned arch erection, thereby designing a new type of steel arch, arch connecting plate, and replacement scheme of steel arch longitudinal connection reinforcement. Currently, after trial and error, the construction method has made significant progress and achieved practical construction projects. Compared with the traditional manual-workbench construction method, this construction method has remarkable advantages in respect of safety, construction efficiency, and economic benefits. In the future of promotion and application, it could reduce the total project investment and construction risk.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

1. Liu FX (2019) SCDZ133 Intelligent Multi-function Trolley and its Application in Tunnelling. *Modern Tunnelling Technology*:56(04):1-7, DOI: <https://doi.org/10.13807/j.cnki.mtt.2019.04.001>
2. Zhang N, Zhang GW, Liu RH, Gao HJ, Gong HX (2019) Optimization Analysis of Step Length in Tunnel Construction by Bench Method. *Highway*. 64(10): 299-303 (in Chinese)
3. Sun HB (2019) Study on Stability Bearing Mechanism and Key Technologies of Assembly Confined Concrete Support for Large Section Tunnel. *Shan Dong University*, DOI: <https://doi.org/10.27272/d.cnki.gshdu.2019.000108>
4. Zhang H, Sun JC, Ma H, Chen SG, Huang MY (2019) Development and Application of Mechanized Matching Equipment for High-Speed Railway Tunnel Construction. *Procedia Manufacturing*, 32, DOI: <https://doi.org/10.1016/j.promfg.2019.02.308>
5. Gao J, Lin X (2017) Study on Supporting Technology for Mechanized Construction of High Speed Railway Tunnel. *Jinan Linfeng Culture Media Co., Ltd. : Jinan Linfeng Culture Media Co., Ltd.*4, DOI: <https://doi.org/10.2991/icesem-17.2017.91>
6. Yuan W, Li JC, He X, Chen YW (2018) Design and finite element analysis of two arms and one basket type steel arch installation machine. *Modern Tunnelling Technology*. (02):11-14, DOI: <https://doi.org/10.13667/j.cnki.52-1046/th.2018.02.003>
7. Zhao Y (2020) Technology for Rapid Construction of Multifunctional Steel Arch Erection Machine in Yuelongmen Tunnel. *Railway Construction Technology*. (02): 96-98+132 (in Chinese)
8. Gong SZ (2019) Discussion on Application of Bolt-grouting Integrated Support Technology in Deep Roadway. *Inner Mongolia Coal Econom*. (03):131+140, DOI: <https://doi.org/10.13487/j.cnki.imce.013661>
9. Yang GQ (2018) Study on the construction period of the Wushaoling super-long tunnel on Lanzhang Third and Fourth Line. *Highway* (12): 335-339 (in Chinese)
10. Liu FX, Ji HD, Liao JJ, etc (2020) A steel arch support structure and its installation method. China, CN 112211653: 2020-10-20 (in Chinese)
11. Peng LM (2014) Tunnel engineering. *Hubei: Wuhan University Press* (in Chinese)

Figures

Figure 1

Three-dimensional simulation diagram of the arch installation trolley

Figure 2

Arch installation trolley

Figure 3

Integrated construction of locking foot steel pipe drill installation and injection

Figure 4

Installation schematic of locking steel pipe

Figure 5

Diagram of steel arch combination

Figure 6

Connection diagram of conical end and elastic chuck buckle

Figure 7

Structure diagram of elastic collar

Figure 8

Folding combination diagram of steel arch

Figure 9

Connection diagram of traditional steel arch

Figure 10

Triangular steel bars connection method: (a) Schematic diagram of steel arch connection, (b) A detailed schematic diagram of the local structure of the triangular steel bar

Figure 11

Flow chart of construction process of steel arch

Figure 12

Installation of steel arch on site (a)

Figure 13

Installation of steel arch on site (b)

Figure 14

The spring steel bar Carton

(a)

(b)

Figure 15

Arch erection outside the tunnel: (a)changing hands over-the-air, (b) Locking anchor pipe

Figure 16

The optimized triangular connection reinforcement