Case Study on Synchronous Construction Technology for Secondary Lining of Large-diameter Single-track Shield-bored Tunnel

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Abstract: The synchronous construction of the secondary lining during the boring of large-diameter shield faces challenges such as the design of the lining jumbo, the high requirements on the performance for the lining jumbo, the organization of the construction activities in the small and confined area, the horizontal transportation for shield boring and high safety management requirements. A super-long invert lining construction jumbo, as well as the matching California switch, is developed, which provides solution for the confliction between the invert lining construction and the horizontal transportation. The procedure and method for the synchronous operation of the shield boring and the secondary lining are developed by referring to the synchronous construction of the secondary lining during the boring of the TBMs in hard rocks. Due to the adoption of the synchronous operation of the shield boring and the secondary lining, the construction period is shortened and the construction cost is reduced. The paper can provide reference for the synchronous construction of the secondary lining in similar projects in the future.

Keywords: large-diameter shield-bored tunnel; synchronous construction of secondary lining; super-long invert lining construction jumbo; California switch; “arch + side wall" lining jumbo

(This paper is selected from *China Railway*)

1 Introduction

With the improvement of the science and technology and the growth of the social demand, the construction technologies for tunnels and underground works are developing rapidly[1]. Due to the high requirements on the safe operation of railway tunnels (including shield-bored railway tunnels), as well as on the fire resistance, collision resistance, explosion resistance and durability thereof, there are more and more shield-bored railway tunnels with composite secondary lining. The secondary lining is installed for shield-bored railway tunnels in order to reduce the impact of fire, derailment, explosion and other disasters on the tunnel structure. The invert part of the railway tunnel is filled with reinforced concrete, which is used as a longitudinal concrete beam to reduce the impact of differential settlement on the railway operation and to increase the rigidity of the tunnel. Such innovative design of the secondary lining of shield-bored tunnels imposes high requirements for the synchronous construction of the shield boring and the secondary lining, which requires an urgent solution in the industry[2-8].

2 Project Overview

2.1 Project description

Wusongkou Yangtze River Crossing Tunnel of Phase II Project of Shanghai-Nantong HSR, located in Baoshan District and Pudong District of Shanghai, runs under the Yangtze River Estuary and Huangpu River. The tunnel is one of the control works of the whole railway line. The total length of Wusongkou Yangtze River Crossing Tunnel is 11 515.32 m. The on-shore section of the tunnel, i.e., the tunnel discussed in the paper, is 2 905.3 m long, including 608 m-long open-cut and buried section, 20 m-long working shaft and 2 277 m-long shield-bored section. The tunnel consists of twin single-track tubes. The lining of the tunnel is of composite lining structure consisting of reinforced concrete segment lining and cast-in-situ concrete lining. The tunnel is constructed by an EPB shield, with the outer diameter of the segment ring being 10.3 m and the inner diameter of the segment ring being 9.3 m. The segment is made of C50 P12 concrete. The thickness of the secondary cast-in-situ concrete lining is 0.25 m. The secondary cast-in-situ concrete lining is made of C40 micro-expansion reinforced concrete, with P12 impermeability. The plan of the route of the on-shore section of Wusongkou Tunnel (the tunnel discussed in the paper) is shown in Figure 1, and the design of the lining of the tunnel is shown in Figure 2.

Figure 1 Plan of on-shore section of Wusongkou Tunnel

2.2 Analysis of difficulties

The synchronous construction of shield boring and secondary lining involves shield boring, segment erection, invert construction, lining construction above the invert, ditch/trough construction etc. Furthermore, the horizontal transportation of the construction materials such as mortar, segment, mucks, steel bars and concrete has to be ensured. Therefore, the synchronous construction of shield boring and secondary lining has high requirements on the structural design and performance of the super-long invert lining construction jumbo and the "arch + side wall" lining jumbo, as well as on the construction organization, horizontal transportation and safety management in this area.

3 Equipment

According to the characteristics and difficulties of the project, the lining jumbo is researched and designed. The super-long invert lining construction jumbo should meet the requirements of horizontal transportation, vehicle meeting and concrete casting above the jumbo, and should also

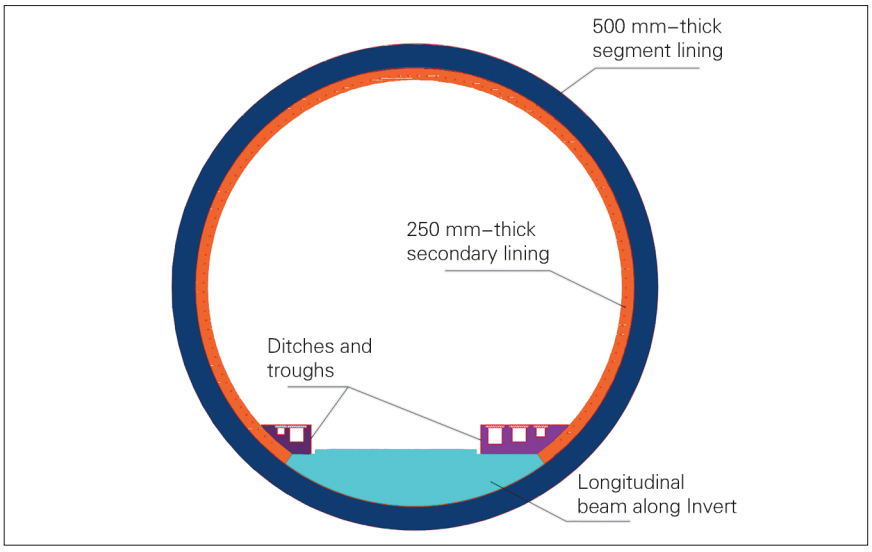

Figure 2 Sketch of secondary lining of tunnel

meet the requirements of safe working below the jumbo. Furthermore, the length of the jumbo should match the progress and curing of the invert construction[5-6]. The "arch + side wall" lining jumbo and the integral "ditch + trough" construction jumbo are of gantry structure, which can meet the requirements of horizontal transportation and vehicle meeting.

3.1 Super-long invert lining construction jumbo

In order to ensure the normal working above and below the super-long invert lining construction jumbo and to meet the construction requirements of these working areas, the super-long invert lining construction jumbo is designed to consist of "front slope section + front symmetrical switch section + four-rail double-track standard section + rear switch section + rear slope section". The longitudinal gradient of the front slope section and the rear slope section is 3%. The super-long invert lining construction jumbo has one 61 m-long front slope section, one 41 m-long rear slope section, one 4 m-long rear switch section and 11 working areas with 12 m-length each, with a total length of 238 m. Under the condition that the elevation of the track remains unchanged, multiple sets of telescopic hydraulic legs are designed to support the track during transportation. Moving support, which is driven by the cylinders, is design to move the jumbo. The jumbo is equipped with necessary machines, tools and devices to facilitate the construction.

11 working areas, with 12 m-length each, are designed below the super-long invert lining construction jumbo (see Table 1). Due to the long time needed for the binding of the rebars for the invert structure, 2 working areas are arranged to bind the rebars, which matches the concrete casting progress and maximizes the working efficiency of the jumbo. Due to the long curing time of the concrete, the jumbo cannot move forward and the tracks of the horizontal transportation system cannot be extended during the curing period, therefore the length of the jumbo is extended so that 3 curing zones are arranged. In this way, the parallel construction time is extended, the curing time is ensured and the strength of the invert concrete is guaranteed.

Table 1 Working areas of super-long invert lining construction jumbo

Serial Number	Working areas	Quantity	Remarks
1	Track and sleeper dismantling area	1	To dismantle the π-shaped sleepers and tracks that have been installed for the horizontal transportation for shield boring
2	Mud clearing area	2	To clear the mud on the bottom of the tunnel
3	Invert rebar binding area	2	To bind the reinforcement bars for the invert
4	Invert concrete casting area	2	To cast the concrete for the invert
5	Invert concrete curing area	3	To cure the concrete for the invert
6	Rear track mounting area	1	To mount the tracks for the traveling of the jumbos

The super-long invert lining construction jumbo consists of several sections, which are connected by the articulation system and are equipped with anti-tilting devices. The lining system has movable structures, with independent functions such as positioning, formwork removing and longitudinal moving. A pair of crossing switches is designed on the jumbo to provide enough tracks on the jumbo so as to meet the requirements of vehicle meeting on the jumbo.

3.2 "Arch + side wall" lining jumbo

The operation platform is used to bind rebars for the secondary lining. The rebars of the secondary lining are connected to the circumferential rebars of the invert by welding, and are connected to the rebars of the segment lining by means of the connectors embedded in the segments. 12 m-long multifunctional lining jumbo[7-8]

is used for the secondary lining of the tunnel. The concrete for the secondary lining is pumped by the concrete conveying pump. The concrete is cast symmetrically from the bottom to the crown and layer by layer. The concrete for the side walls is cast before that for the arch. Mechanical vibration is performed for the concrete. The construction by means of the concrete lining jumbo and the rebar binding jumbo is shown in Figure 3.

Figure 3 Secondary lining jumbo and rebar bar binding jumbo

The theoretical length of the lining cycle of the lining jumbo is 12 150 mm. The width of the individual formwork of the lining jumbo is 1 500 mm, and the thickness of the surface board of the formwork is 10 mm. The maximum length of an individual part of the lining jumbo is 13 800 mm. The dimension of the working window of the lining jumbo is 500 mm×500 mm, and the inner diameter of the grouting hole thereof is 125 mm. The lining jumbo is equipped with pressurized concrete mixture distribution system. The formwork for the side wall has 3 levels. On each side, there is 1 concrete casting window on the formwork of the second level and the third level respectively, and there are 2 concrete casting windows on the formwork of the first level. In this way, there are totally 8 concrete casting windows on the formworks for both side walls. Furthermore, there are 3 concrete casting windows on the formwork for the crown. Therefore, totally there are 11 concrete casting windows on the formwork of the lining jumbo. The lining jumbo is equipped with 5 backfill grouting holes, with the inner diameter of the backfill grouting holes being 40 mm. Furthermore, the lining jumbo is equipped with void detection system and position limiting devices.

The stroke of the lifting/lowering cylinders of the lining jumbo is 300 mm, and that of the transverse-moving cylinders is ±150 mm. The stroke of the cylinders of the side formwork and the bottom formwork is 300 mm. The traveling speed of the lining jumbo is 6.7 m/min. The lining jumbo is applicable to tunnels with the longitudinal slope being not more than 1%.

3.3 Integral "ditch + trough" construction jumbo

When the strength of the secondary lining concrete of the shield-bored tunnel reaches the design value, the ditches/troughs on the left side and the right side should be constructed synchronously. The ditches/troughs are constructed by means of the integral "ditch + trough" construction jumbo[9-10]. The key points of the construction of the ditches/troughs include the control of the centerline and the horizontal line of the formwork, the firm supporting of the formwork and preventing the displacement and floating of the formwork during concrete casting. The design of the integral "ditch + trough" construction jumbo is shown in Figure 4.

The integral "ditch + trough" construction jumbo is mainly composed of the formwork, the supporting and hoisting system, the hydraulic system and the traveling system. The formwork of the integral "ditch + trough" construction jumbo is mainly composed of the box-shaped formwork for the ditches/troughs, the formwork for the outer side wall, the end formwork, the formwork positioning block and other components. The cyclic length of the integral "ditch + trough" construction jumbo is 12 m. The thickness of the formwork is 8 mm.

The hydraulic system of the integral "ditch + trough" construction jumbo mainly consists of the lifting/lowering cylinders for the portal structure, the lifting/lowering cylinders for the ditch/trough formwork, the cylinders for the horizontal movement of the cantilever beam and the cylinders for the horizontal movement of the outer side wall formwork. The integral "ditch + trough" construction jumbo has 2 sets of independent hydraulic systems and 18 sets of cylinders. The longitudinal movement of the integral "ditch + trough" construction jumbo is driven by the electrical motors. The movement speed of the integral "ditch + trough" construction jumbo is 6.7 m/min. The rail used for the movement of the integral "ditch + trough" construction jumbo is 38 kg/m rails.

The lateral adjustment of the position of the formwork is achieved by the lateral-moving cylinders, the adjustment of the vertical position of the

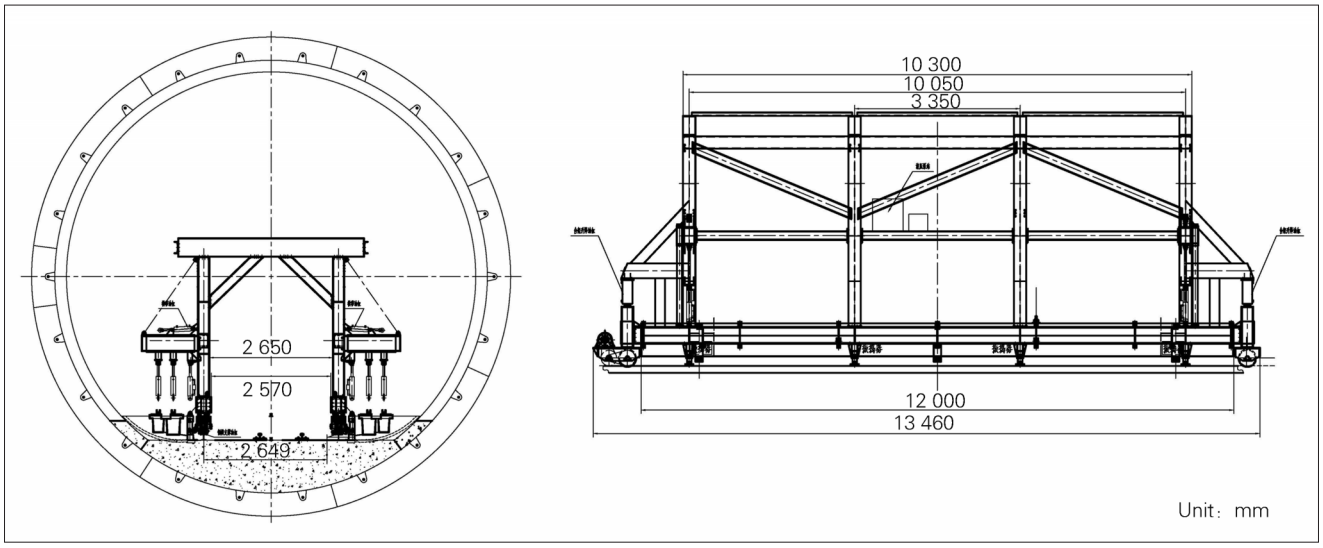

Figure 4 Design of integral "ditch + trough" construction jumbo

formwork is achieved by the lifting cylinders of the formwork, thus the accurate position of the formwork is realized.

4 "Shield Boring + Secondary Lining" Synchronous Construction Technology

Due to factors that the trailer of the shield machine is 110 m long and the invert lining construction jumbo is 238 m long and considering the horizontal transportation and the tunnel settlement, the construction of the tunnel invert structure (12 m/ section) is organized 500m after shield boring. The 238 m-long invert lining construction jumbo is used to ensure the horizontal transportation and vehicle meeting in the invert construction area. When the shield boring reaches the appropriate position, the super-long invert lining construction jumbo is installed, and the π-shaped temporary sleepers used for horizontal transportation (see Figure 5) is removed. A total of eleven 12 m-long working areas are designed below the super-long invert lining construction jumbo, including 1 track and sleeper dismantling area, 2 mud clearing areas, 2 invert rebar binding areas, 2 invert concrete casting areas, 3 invert concrete curing areas and 1 rear track mounting area.

The construction of the "arch + side wall" lining (12 m/section) is carried out after the construction of the invert structure. 2 lining jumbos are used for the construction of the "arch + side wall" lining. The lining jumbos are of gantry structure to ensure the horizontal transportation and vehicle-meeting. Reinforcement bar binding platform is used for the binding of the reinforcement bar, as well as for removing the ventilation duct fixing hooks and for the replacing of the water pipes. The construction of the "arch + side wall" lining is carried out by means of the 2 lining jumbos in alternative manner, i.e., No. 1 lining jumbo is used for the "arch + side wall" lining with serial numbers 1→2→3... 7→8→9..., while No. 2 lining jumbo is used for the "arch + side wall" lining with serial numbers 4→5→6... 10→11→12.... The automatic concrete curing jumbo, which is kept 12 m after No. 2 lining jumbo, is used for concrete curing, as well as for backfill grouting and ventilation duct fixing-hook installing.

The ditches and troughs on both sides in the tunnel are constructed 100 m after No. 2 lining jumbo, synchronously with the shield boring.

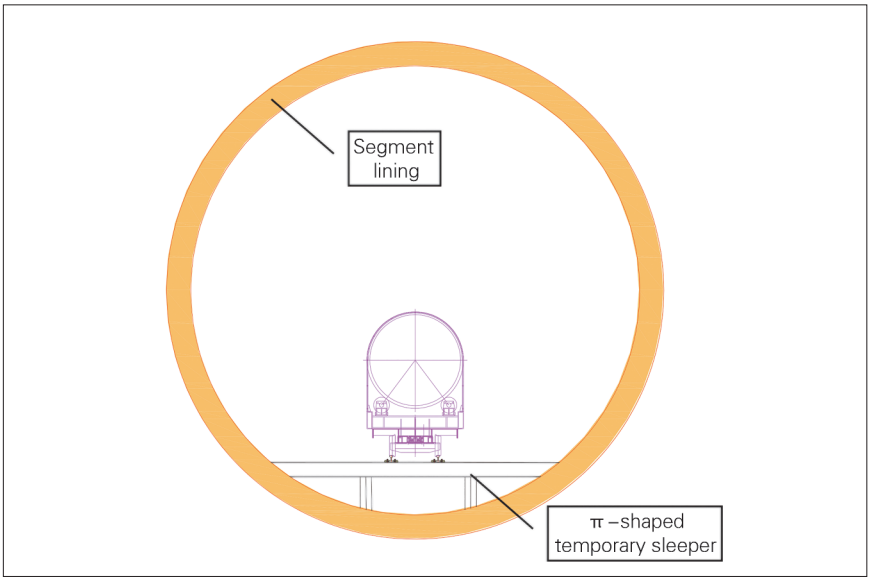

Figure 5 π-shaped temporary sleepers used for horizontal transportation during shield boring

The flowchart of "shield boring + secondary lining" synchronous construction is shown in Figure 6.

5 Conclusion

The synchronous construction of the shield boring and the secondary lining not only saves time and cost, but also promotes the improvement of the tunnel construction technology, therefore has remarkable social and economic benefits. However, the construction organization for the synchronous construction of the shield boring and the secondary lining is complicated, and the safety management of multiple working points and long working areas is difficult. Many vehicles are running in the tunnel to deliver mortars, segments, mucks, reinforcement bars and concrete, which imposes high requirements on the scheduling of these vehicles. Due to the reasonable arrangement of the construction activities and development of specific equipment, the synchronous construction of the shield boring and the secondary lining is realized, which effectively reduces the cost, shortens the construction period and avoid "rush construction" of the secondary lining after the tunnel is broken through. The application of the specific equipment effectively saves the human resources and ensures the construction accuracy and the construction quality.

However, the in-situ-casting of the invert structure has high requirements on the design and performance of the super-long invert lining construction jumbo. Therefore, it is recommended that the mode of "prefabricated member + post-cast concrete strip" should be adopted for the invert structure, so as to improve the overall efficiency of synchronous construction of the shield boring and the secondary lining and to reduce the risks in the in-situ-casting of the invert structure.

(Translated by ZHAI Jinying)

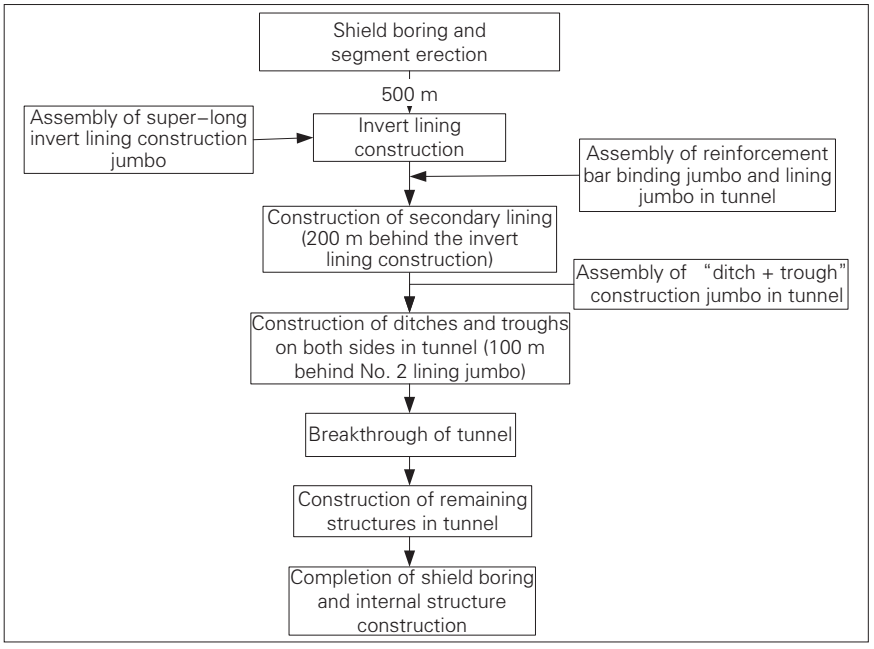

Figure 6 Flowchart of "shield boring + secondary lining" synchronous construction

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