TBM Tunnelling in Karst Regions : Wanjiazhai Project

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ABSTRACT: The project is located in the northern region of the People's Republic of China and was awarded to Wan Long Joint Venture, in September1997. The project consists of four tunnels for a total length of 88,700 m, with an excavation diameter of about 5.96 m. The lining is made of honeycomb pre-cast segments, connected by PVC dowels and the joints are sealed with elastomeric gaskets. The geology is mainly Limestone, Dolomite and Sandstone. Karst cavities are abundant and are often in-filled with plastic red clay. This has adversely affected the TBM's progress. Four double shield telescopic TBMs were mobilized to cope with the very tight construction schedule and, at the after only 36 months, more than 80% of the tunnel has been bored. The article analyses the project conditions and the results of different technical solutions adopted to the project.

1 INTRODUCTION

The Shanxi Wanjiazhai Yellow River Diversion Project is an all-encompassing project to alleviate the water shortages in three of China's industrial areas - Taiyuan, Pingsuo and Datong. The country's rapid economic growth is fuelling water demand beyond the capacity of the existing infrastructure.

The contracts were awarded in 1997. In November 2001 the first major step was inaugurated when water from the Yellow River ran to the Fenhe reservoir. By the end of 2002, it should have been extended eastward 100km to the Taiyuan. The cost of the entire enterprise is estimated at $1.5 billion, $400 million of which will come from the World Bank.

The project is located in the north west region of Shanxi Province. The diversion project has three major waterways, the General Main, South Main and North Main.

The General Main waterway is 44km in length. It is designed to take $48m^3/s$ of water from the Wanjiazhai reservoir to a diversion sluice located at Xiatuzhai village. The reservoir was created by the Yellow River Commission by the building of the Xiaolangdi dam. This was one of the largest World Bank-funded projects at $1.6 billion. To speed the water on its way, there are three pumping stations on the General Main.

The South Main travels from the diversion sluice at Xiatuzhai for approximately 100km southward. It is intended to supply $640m^3$ x 106 of water per annum at a rate of $20.5m^3/s$.

The North Main travels from the diversion sluice at Xiatuzhai for approximately 167km in a northward direction. It has a flow rate of $22.2m^3/s$.

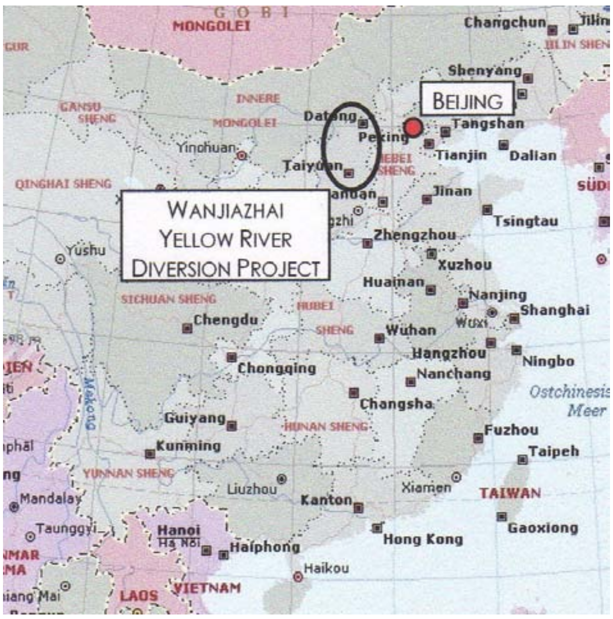

Figure 1. Location of the project on the PR China map.

Contracts WYRPD-C2 and WYRPD-C3 make up the chief part, though not all of the civil works for the South Main. These contracts were won by the 'Wan Long Joint Venture', a formation of IMPREGLIO S.p.A. from Italy (the leader of the joint venture with a participating share of 45%), C.M.C. of Ravenna S.a.r.l. of Italy, China Water Conservancy & Hydropower and Engineering Bureau No. 4 of China.

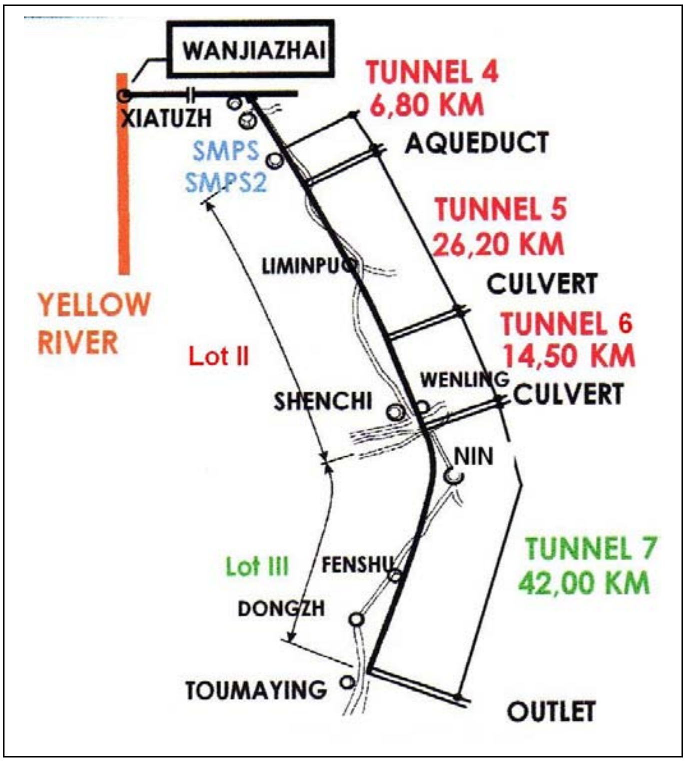

Figure 2. Project sections for TBM drive.

The WYRPD-C2 contract consists of the following work:

- Tunnel four will be 6.9km long, excavated by a tunnel boring machine (TBM), with a diameter of approximately 5m, and lined with pre-cast concrete segments
- Bridge canal three is to be 370m long and approximately 20m high
- Tunnel number five will be 25.8km long, excavated by TBM, with a diameter of approximately 5m, and lined with pre-cast concrete segments
- Culvert one is to be 530m long and to have a diameter of 5m
- Culvert two will be 730m long and have a diameter of 4.2m
- Tunnel six will be 14.6km in length, possibly excavated by TBM, with a diameter of approximately 5m, and lined with pre-cast concrete segments

The WYRPD-C3 contract consists of the following work:

- TBM with a diameter of approximately 5m and lined with pre-cast concrete segments
- Flood control sluice
- Open channel section approximately 460m long, built of stone

2 GEOLOGICAL CONDITIONS

The entire project area is located in the influence region of Northchinese fault zone. All underground structures of Lot II and Lot III of the WYRDP are situated in layers of Cambrian limestone and dolomite stone layers. The stone layers are placed in packages and layers that are almost horizontal.

Due to the mostly limestone formations very often karst phenomena have been found along the project route. Karst cavities have been mostly filled with clay, sometimes with some smaller amount of water and that have had direct influence on the reduction of TBM advance rates.

3 TBM CONCEPT

The entire drive of more than 80 km of tunneling have been performed with 4 hard rock double-shielded telescopic TBMs from 4 different advance points. 3 of them have been produced by Robbins, USA and one of them from NFM producer from Lyon, France.
One double-shield TBM (DS-TBM) has actually two separated steel shields that are connected over main press-cylinder.The boring head is at the head of the machine and a gripper device with plates aside.

Figure 3. View to the boring head of one of DS-TBMs.

Further the machine has another supplemental press cylinder, erector device for the mounting of segmental lining and the conveyor belt device for the transport of excavated material.

The front shield is carrying the boring head connected to the main bearing and entire excavation unit. In the back shield (gripper-shield) is the gripper unit located that presses on a tunnel rock wall aside and enables further TBM advance, supplemental press-cylinder and the erector unit. The rear part of the back shield is usually called shield tail where the erection of the segmental lining takes place.

The supplemental press-cylinder takes over three mayor roles :

- it secures the placing of the last installed lining ring
- additional support against the installed lining ring during excavation in swelling rock
- main advance support against lining during excavation in soft material (the gripper is out of use)

The back (gripper) shield stays fixed during one step of the machine advance and acts as the support for the pressure of the main press-cylinder that presses the rotating boring head against the rock face. Due to the rotation of the boring head and rolling of concentrically placed cutting discs on the boring head the rock will be cutted. The pressure of the head against the rock face is with the force of approximately 20-30 tonns per each disc. Excavated rock material falls down and is collected by showels on the perimeter of the boring head and transported back to the conveyor belt and further out of the tunnel. After the end of the one step of excavation the pressure of the gripper will be losen, the main pressure-cylinder moved in and therefore the back shield replaced ahead. At the same time supplemental pressure-cylinder will be stretched to press and stabilize the last installed segmental lining elements. The gripper press shoes will be pressed against the rock aside again and a new excavation step can start. The main advantages of the DS-TBM are :

- lining installation during the excavation process
- flexibility (as it could be used in hard rock as open hard rock shield)
- could be used in soft ground without gripper using as advance force the pressure of supplemental pressure cylinder on installed lining rings
- better steering possibility in mixed and soft ground formations

4 SEGMENTAL LINING

The segmental lining has been designed as a single pass lining consisting of 4 hexagonal (honeycomb) segments. The lining watertightness has been provided by neopren EPDM gasket (fig.4). Different tunnels have different diameters (D_{in} = 4.64-5.46m) and segment thickness of 25 cm and segment width of 1.40 m. Segmental lining has been using plastic dowels as connectors in the ring joint and plastic guiding rods in longitudinal joints that had 28 mm diameter and rod length of about 80 cm.

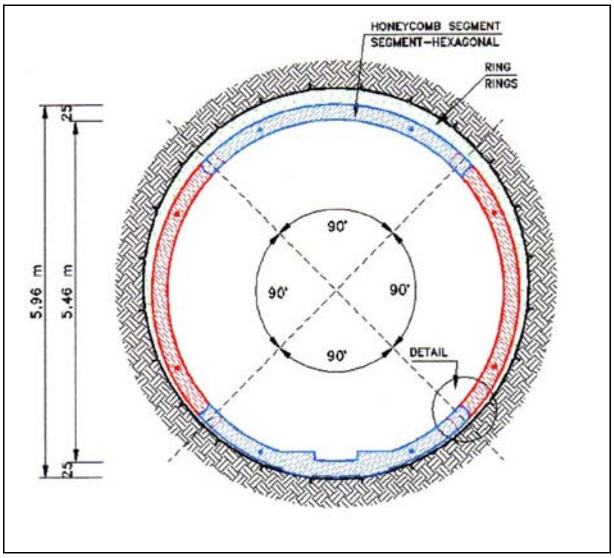

Figure 4. Typical cross section for TBM tunnels 6, 7 and 8.

The lining concept has been defined with the eccentric location of the longitudinal tunnel axis regarding lining axis (fig.4). This eccentricity has resulted with the gap of about 130 mm in the tunnel top that enables free rock deformation, redistribution of stresses and forming of a supporting vault within the rock mass (near to a NATM principles).

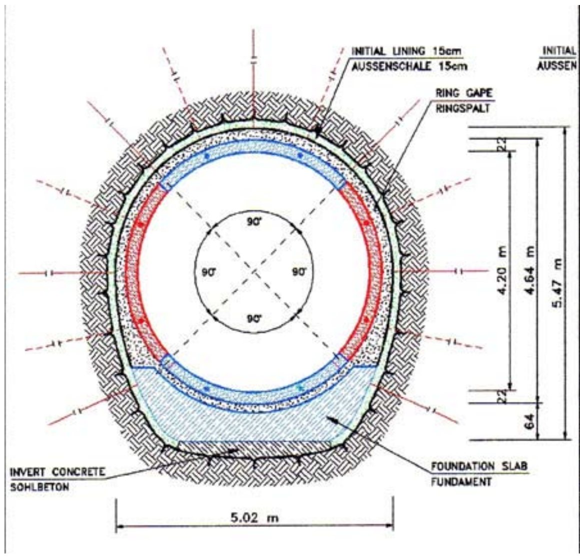

Figure 5. Conventional chamber with segmental lining.

The lining installation is preformed after about 2D length after the boring head where the stress redistribution and rock mass loosening is already finished. The ring gap has been filled out with the pea-gravel (size 8-12 mm) about 25-30 m after the tunnel face by blowing in through 50 mm diameter nozzles in order to stabilize the statically optimal circle lining form. The pea-gravel material has not been compacted in any way beside its self weight. About 4 weeks after the filling the gap the pea-gravel material has been injected with the cement emulsion (contact – injection).

The segmental lining has also been used in conventional tunnel parts as at starting chambers or tunnel junctions to other underground structures (fig.5). In this parts lining elements have been installed manually, the ring was closed and the gap between lining and the rock mass filled out with the pea gravel as well.

5 PREFABRICATION OF THE LINING

The prefabrication of all segmental linings has happened in one central casting yard that was located in the vicinity of the main site camp and approximately in the middle of the project length.

Figure 6. Concreting of segments in the hall of casting yard.

Production facilities have been placed in one hall with units for the preparation of reinforcement cages, carousel production lines with movable segment moulds, concreting chamber and steam chamber. The segment production has been performed with a lot of domestic manual work power and using other lifting devices as cranes (fig.6).

The production facilities have enough capacity to provide enough segments for all 4 advance directions having working tempo of 2 working shifts of 10 hours each a day. After the segment concreting moulds have been transported into the steam, chamber in a 6 hours working cycles and afterwards taken out for cooling in the hall. After reaching planned temperature segments have been taken out of the moulds, rotated 180 degrees and prepared for the installation of neoprene gasket frames that were glued in the gasket chamfer on the segment.

After several production cycles it came out that the segmental lining in the tunnel suffers from often eccentricies or gaps in the joints. That was the reason to intensify the quality control measures during the segment production including often calibration of steel moulds (fig.7).

Figure 7. Calibration of steel mould by steel calibration device..

The investigation has shown that the quality of the lining has been reduced due to the several mould deformation that has happened because of the multiple casting of segments. The quality of the moulds have not been good enough to withstand with the intensive segment production and with the quality requirements that were placed at the beginning of the production. Finally improvements in the production process have been applied and deformed mould have been replaced with new ones. During further production period quality assurance control has been intensified to provide required level of segments quality.

Figure 8. Segments on the storage near to production hall.

When the segments have been finalized in the production hall they have been further transported toward storage area located out of the production hall in its vicinity (fig.8). They have been placed on wooden shims, ring by ring, and prepared for the transport toward tunnel site by train. Some of segments have been placed on the storage yard for longer time as preproduction of the lining should be far advance of the tunnel installation. Therefore they have been influence by big temperature changes (up to +45 degree C in summer and down to -25 degree C in winter) and other weather influences (sand storms, heavy rains and snow). However, rings have been checked once again before the tunnel portal and brought toward the tunnel face only in case they have fulfilled required quality level.

6 TUNNEL DRIVE AND INSTALLATION

6.1 *TBM Drive*

The TBM drive trough limestone formations have been performed reaching high peaks of about 100 m/ working day of advance including installed final lining. These results were possible within sound limestone and dolomite formations. Such advance rates are within the range of world records and have been rarely possible on other similar projects.

Figure 9. Supply train bringing segments toward tunnel face.

Special karst conditions have otherwise reduced advance rates. Karst cavities that have been reached along the project route have been usually filled with the clay, sometimes with some water in addition. The clay was quite sticky and has always blocked the boring head after just few head revenges. Therefore a special supplemental equipment has been ordered and installed on the TBM providing possibility of using foam injections into the clay body.

Foam injection s have penetrated the clay body and hardened and made therefore the clay body more stiff and able to be cutted with existing discs on the boring head. This way problematic area of clay cavern could be passed but always with serious advance rate reductions.

6.2 *Installation of the Lining*

From the temporary segment storage in front of the tunnel portal (fig.9) segments have been placed on the supply train unit and brought to the tunnel face. Here the erector unit at the TBM shield tail has brought each segment to the required installed position (fig.10).

Figure 10. Segment installation within the shield tail.

The installation of the lining have been reached and handled very fast. Anyhow it was always faster than the time required for the excavation at the tunnel face and was therefore not on the critical construction path. The steering of the lining along vertical and horizontal alignment curves have been performed by hard wood plates that have been stick on the radial ring joints. Some more work have been required when installing segments in prepared conventionally driven chambers but the procedure have been also very fast due to the bigger segment lengths and smaller number of segments forming one ring.

6.3 *Filling the Lining Gap*

At least 20-30 m after the lining has been installed the gap between the lining and the excavated rock mass has been filled with a fine corn pea-gravel. The filling started always from bottom up on both sides.

Figure 11. Filling the lining gap with the pea-gravel.

The pea-gravel have been blown into the gap through two holes in the third of the segment length over flexible ducts with 50 mm diameter nozzles. The segmental lining between the shield tail and the place of gap filling has been stabilized through connectors : plastic dowels in ring joints and guiding rods in longitudinal joints.

6.4 *Quality of Installed Segmental Lining*

Fast tunnel advance and lining installation and fast production of numerous segments had as a result different types of imperfections that were obvious on sections of installed lining (fig.12). Honeycomb segments are usually used as 4 pieces in one ring for tunnel diameters in the range 4.0-8.0 m. Because of small number of segments in one ring they are very sensitive on each geometrical imperfections whether they are coming from improper segment dimensions or are happening due to the improper installation. This project met both types of imperfections and when the one with the production of segments could be improved by mould replacing the other one caused by improper segment installation could be improved by filling gaps in joint wit cement mortar (fig.12).

Figure 12. Imperfections in radial and longitudinal joints.

7 CONCLUSION

The Wanjiazhai Yellow River Diversion Project Lot II and III was a mega tunnel project wit h its 88 km of TBM tunneling over 4 advance faces and with 4 TBM units. It has shown that a huge project organisation could be successfully performed even in a very difficult location and whether conditions. TBM tunneling through limestone and dolomite formations have been performed with high advance rates within sound rock conditions but at the same time karst phenomena had reduced these results each time. In this case foam injection units have been successful solution to pass difficult clay filled caverns.

However this project and the production of segmental lining has also shown that measures of quality assurance have to be applied even more intensive and considering imperfections caused by the size of a project and the huge number of pieces that are prefabricated within the project.

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