TBM Case Histories

Chairmen
L.W. deStwolinski
Kiewit Construction Co.
Omaha, NE

B. Mariucci
Kiewit Construction Co.
Omaha, NE
Chapter 24

YINDARUQIN IRRIGATION PROJECT:
HIGH SPEED TUNNELLING IN CHINA

by Ivano Andreis
Giovanni Valent

Technical Director Yndaruqin Project CMC Ravenna
European Sale Manager - Robbins, Tunnel Division

ABSTRACT

The Yindaruqin Irrigation Project is designed to irrigate 57,000 ha of land in the central part of Gansu Province of People's Republic of China.

Water for the Project will be diverted through an 87 Km long feeder canal which will convey 36 cubic meters per second from an intake on the Datong River. (Fig. 1)

The feeder canal consists of approximately 10 Km of open channels, 75 Km of tunnels and 2 Km of siphons and aqueducts.

This is the biggest self-flowing irrigation water control project in the Northwest of China and it is among the most interesting projects in China for the geological and environmental conditions.

Nearly half of the investment in the Project is a World Bank Loan and contractors were chosen by means of international bidding.

The Italian Company, CMC Ravenna, succeeded in answering the bidding for the construction of tunnels 30A and 38, perhaps the most difficult in the Project, submitting a TBM alternative to the conforming drill and blast contract recommendation.
This paper is a description of the concepts for tunnel support and TBM selection, the achieved advance rate and the behavior of the machine and equipment during the driving in different geological conditions.

INTRODUCTION

Tunnel 30A and tunnel 38 was designed with a boring diameter of 5.54 m and a finished diameter of 4.80 m. Tunnels slope is about 1/1350. Tunnel 30A length is 11,649 m and the tunnel 38 length is 5052 m (of which 4880 m to be bored and 172 m at the inlet already excavated where TBM had to pass through).

Being the area of moderate relief, overburden is from 200 to 430 m with a minimum of 70 m in tunnel 38.

According to the Geological Report, tunnel 30A is located mainly
in tertiary sediments with pre-cambian crystalline limestone with slate at the inlet and with quaternary sediments at the outlet. The tertiary rocks consist of gently dipping conglomerate with drift block and sandy conglomerate.

The second, tunnel 38, is in moderately dipping beds of Cretaceous sedimentary rocks, mainly sandstone.

The geological survey carried out during driving has shown the above to be quite accurate.

In tunnel 30A from outlet to inlet we encountered in sequence:
- 40 m of loess and argilaceous sand;
- 54 m of sandstone;
- 167 m of silty conglomerate;
- 33 m of loess;
- 1791 m of sandy and silty conglomerate;
- 1160 m of sand-gravel;
- 2762 m of sandy conglomerate;
- 1352 m of sandy and silty conglomerate interbedded with blocks of sandstone;
- 1360 m of argillaceous conglomerate;
- 1072 m of fractured gray and black limestone interbedded with slate;
- 654 m of argillaceous conglomerate;
- 279 m of breccia and block of crushed limestone filled with sand;
- 925 m of gray crystalline limestone.

The compressive strengths range from 5.2 MPa, sandstone, to 80.9 MPa, crystalline limestone.

In the limestone 23 main faults, of broad joints, have been encountered as well as some big karst caves.

Ground water was not anticipated, but extensive tunnel sections in tunnel 30A, were excavated in saturated conglomerate; in the fractured limestone a high water inflow of 3000 lt/min with a peak (for several days) of 15,000 lt/min has been met, the progress was affected seriously.

In tunnel 38 we met in sequence from outlet to inlet:
- 606 m of fractured red sandstone with calcareous cement;
- 488 m of clayly sandstone interbedded with siltstone;
- 1328 m of red sandstone;
- 762 m of sandstone interbedded with breccia and gravel;
- 1786 m of clayey sandstone.

The compressive strengths range from 11.8 MPa, argillaceous sandstone to 56.9 MPa, sandstone.

In the clayey sandstone a short section of rock with important convergence was met where TBM got trapped by the quick squeezing ground.

TUNNEL SUPPORT AND TBM EQUIPMENT SELECTION

The total tunnel length of 16.7 km, the extremely variable geology, the tight contractual period of only 54 months which is affected moreover by the very low winter temperatures, together with the consideration that, for entering in the Chinese construction market, the bidding did not leave any margin, led the contractor to adopt a tunnelling concept which had to give priority to the advance speed of the heading.

In fact, as suggested by the experience, the key to lower tunnelling cost is in the increase of the advance rate. High average advance rate can be achieved by combining a good penetration rate, in the different geological formations, with many hours per day of actual excavation time.

The decision was made in favour of a telescopic double shield machine for the following main reasons:
- A double shield or telescopic shield with grippers in the second shield allows the front shield to bore forward under the thrust of the main cylinders while the rear shield remains in a fixed position. This permits the installation of tunnel lining, precast concrete segments, within the protection of the rear shield while the machine is boring ahead. The experience also showed that a gripper system with shoes having wide rock contact area and therefore reducing the specific ground pressure, has good efficiency both in weakened rock and in soft rock.
For the condition of very soft rock where the gripper is no longer effective it can find adequate thrust reaction on the precast lining as in a single shield machine, using the auxiliary thrust cylinders.
Changing the original proposal in the tender, it was decided to use a precast segment lining everywhere. The segments were also designed with the unusual exagonal shape with a width of 1.60 m in order to reduce the number of rings to be installed and consequently left more time for excavation. There are four 300 mm thick segments per ring which fit together in a mosaic pattern (Fig. 2). The segments are not bolted together nor are they expanded out, against the rock with a wedging key. Segments fit together by a self locking design where the rounded lip of one curved segment edge overlaps that of the neighboring segments. This allows to overcome the disadvantage of the excavation in the single shield mode, where with conventional cylindrical ring type segmental lining system, boring must stop while a new ring of segment is installed.

FIG. 2 – TYPICAL SECTION AND LINING ASSEMBLY
This is a big problem if an high average advance rate is required, because it slows the overall advance rate in case there are many parts of tunnel with very soft rock.

The adopted segmental lining system, which reminds of a honeycomb pattern, allows continuous boring and simultaneous lining even in this condition of soft rock. After advancing 800 mm (half a segment width) the lateral two segments or the crown and invert segments are erected in alternative pairs. In this way there are always 4 auxiliary cylinders thrusting on the lining.

PHOTO 1 – PRECAST CONCRETE SEGMENTS

TUNNELLING EQUIPMENT

Double shield TBM Robbins 1811-256, with a boring diameter of 5.54 m was specifically designed for the Yindaruqin Irrigation Project, implementing the last technical features conceived and developed by the manufacturer Robbins Co. and Seli acting as CMC consultant.

The concept of the TBM is shown in Fig. 3.

Substantially it is composed of a front section which incorporates the cutterhead and cutterhead support structure and a
YINDARUQIN IRRIGATION PROJECT: HIGH SPEED TUNNELLING

rear section incorporating the grippers and 8 auxiliary thrust cylinders. The cutterhead is fitted with 37 disc cutters 17 inches diameter.

Model 1811-256
Specifications:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>Double Shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIAMETER</td>
<td>5.5 m (18 ft.)</td>
</tr>
<tr>
<td>POWER</td>
<td>960 kW (1287 hp)</td>
</tr>
<tr>
<td>THRUST</td>
<td>797,733 kg (1,755,000 lbs.)</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>332 metric tons (365 tons)</td>
</tr>
<tr>
<td>CUTTERS</td>
<td>33 x 432 mm (17 in.) disc cutters</td>
</tr>
</tbody>
</table>

Between these two sections there is a telescoping section and an articulating joint with 16 articulation cylinders.

The cylinders are installed at alternating angles between the
gripper shield and the forward shield. This angular arrangement allows the cylinders to react to cutterhead torque and transfer this reaction to the gripper shield, thereby providing roll control without the need for additional torque cylinders. The arrangement of the cylinders, to provide lateral and vertical steering of the forward shield and cutterhead.

In this double shield TBM the steering in the gripping mode is very effective as the rear section is gripped tightly during the boring and remains good when in incompetent rock, because it is possible to use the auxiliary thrust cylinders in the rear section of the machine to thrust against the lining using the main cylinders for helping the steering.

TBM was also chosen with:
- cutterhead power and thrust equivalent to a conventional hardrock TBM, for the same diameter, for maximum penetration in competent rock;
- two speed cutterhead drives to be selected according to ground requirement;
- fully mechanized, designed segment erector capable of erecting the 5 ton segment with 6 movements (3 principal movements and 3 articulations to pivot the segment around its center axis). Two hydraulic lifting pins engage in each of the two grout holes to lift the segment into final position.
- Operation of the segment handling equipment is performed from a remote pendant station. The station is radio-controlled allowing the operator to control the erector from safe positions while still being able to observe the operation.
- laser guidance system ZED to ensure accuracy in the control of the machine attitude;
- hydraulic clutches to permit cutterhead starting under unstable face conditions without excessive stress to the gear box and power overloading;
- removable grillwork the muck bucket to further control the extraction of excavated material in wet poor ground;
- stand by hydraulic pumps and oil filters to perform routine maintenance and repairs without stop TBM operation.

All the TBM support services are carried on 146 m of trailing platform.

The backup system was designed by CMC and Seli. The challenge was
to organize the work so that the muck could be loaded and hauled out without interfering with movement and erection of tunnel lining, laying of track, extension of ventilation, backfilling and grouting behind segments.

It was also decided that, being most of tunnel in soft rock, therefore with expected high penetration rate, the backup system behind the machine should be designed to load the muck efficiently into muck cars for haulage and bringing in segment and materials with no delay in the best advance rate predictable according to the penetration rate in soft rock and the time for the sequence of segment installation and train exchange on back-up.

We fixed this advance rate: one ring every 30 minutes.

After comparison of different advantages we decided to use a single track trailing gantry followed by a movable "California" crossing and a series of fix crossing station located along the tunnel at intervals of about 3500 m according to the average speed of empty and loaded trains.

A special lattice structure was designed as interacing between the trailed platforms and the TBM to allow the transferring, inside a steel tunnel, of segments from the flatbeds to the erector located in the tail shield of the machine and at the same time the safe installation of rails under the structure itself.

This structure also supports the secondary conveyor for mucking. Backfill between precast lining and rock surface was routinely performed immediately behind the tail shield using pea-gravel pumped through the lifting holes of segments by a dry shotcrete machine installed along the backup. A hopper fed by mixer provided enough storage for facing unexpected consumption.

Grouting operations, originally to be performed daily, during the maintenance shift by a special grouting train, showed very soon to progress more slowly than heading, and forced us to install a grouting pump system and cement storage on the back-up last platform. In this way grouting time could be extended it is required to follow the daily advance of the machine.

Air compressors are installed on the back-up to avoid the laying of the air line along the tunnel.
Ventilation up to 24 m$^3$/sec. of fresh air is conveyed to the working area through a 1400 mm diameter ventilation duct, with dust-laden air extracted through the 4.5 m$^3$/sec. capacity air scrubber.

Cable drum with 300 m of 10 KV power cable, hose reels for 50 meter of water supply line and ventilation duct cassette type accumulator for 100 m of vent line were adopted to minimize all tunnel extension downtime.

Installation of water steel pipes and tunnel power line were as much as possible concentrated during the maintenance period.

Muck is transferred from the cutting head via 6 m$^3$/min capacity belt conveyors back to the awaiting 10 m$^3$ muck cars. These muck cars designed by Seli were manufactured in China as well the back-up platform. The muck trains are hauled by 24 ton Brookville diesel locomotive to the dumping site near the portal.

ADVANCE RATE

The system performed even better than expected.

The tunnel heading including lining and grouting was advanced 1500 m in a 30 days period, which is one of the highest performance for a tunnel in soft rock.

Table 1 shows the best performance obtained in tunnel 30 A.

In tunnel 38 best monthly performance is 1401.60 m, best weekly is 348.80 m, and best daily performance is 75.20 m.

But, more than this peaks, what made the success of the Project was the average daily progress.

The 11,649 m of tunnel 30A have been driven in 339 working days, with an average daily progress of 34.29 m.

Launch took place in December 1990 with full boring routine established by January 1991, and the breakthrough took place in January 1992, totally 13 months.

Throughout seven consecutive months, the monthly progress rate exceeded 1 km.
TABLE 1 - BEST PERFORMANCE OBTAINED IN TUNNEL 30/A

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>ROCK TYPE</th>
<th>AVERAGE DISTANCE FROM ADIT m</th>
<th>ADVANCE m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best working month</td>
<td>Conglomerate</td>
<td>6140</td>
<td>1301</td>
</tr>
<tr>
<td>Best 30 working days</td>
<td>Conglomerate</td>
<td>5820</td>
<td>1491,20</td>
</tr>
<tr>
<td>Best working week</td>
<td>Sand conglomerate</td>
<td>7560</td>
<td>312</td>
</tr>
<tr>
<td>Best working days</td>
<td>Sand gravel with loam</td>
<td>2170</td>
<td>65,6</td>
</tr>
<tr>
<td>Working</td>
<td>Conglomerate with</td>
<td>7465</td>
<td>62,4</td>
</tr>
<tr>
<td></td>
<td>a layer of gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conglomerate (weathered)</td>
<td>9950</td>
<td>64,0</td>
</tr>
</tbody>
</table>

In tunnel 38, the machine performed even better, boring the 4880 m in 120 working days, with an average daily advance of 40.7 m (see table 2).

TABLE 2 - SUMMARY OF THE FULL-FACE EXCAVATION IN TUNNEL 38

<table>
<thead>
<tr>
<th>MONTH</th>
<th>Working days</th>
<th>Excavat. progress m</th>
<th>Average daily advance m</th>
<th>TBM hours</th>
<th>Penetr. Cutter rate m/h</th>
<th>Penetr. Cutter bings replaced N.</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>22</td>
<td>605,6</td>
<td>27,5</td>
<td>177,5</td>
<td>3,41</td>
<td>18</td>
</tr>
<tr>
<td>May</td>
<td>24</td>
<td>1.270,4</td>
<td>52,9</td>
<td>314,3</td>
<td>4,04</td>
<td>68</td>
</tr>
<tr>
<td>June</td>
<td>26</td>
<td>1.401,6</td>
<td>53,9</td>
<td>341,3</td>
<td>4,11</td>
<td>75</td>
</tr>
<tr>
<td>July</td>
<td>28</td>
<td>735,2</td>
<td>26,2</td>
<td>177,0</td>
<td>4,15</td>
<td>30</td>
</tr>
<tr>
<td>August</td>
<td>20</td>
<td>867,2</td>
<td>43,3</td>
<td>208,3</td>
<td>4,17</td>
<td>37</td>
</tr>
<tr>
<td>TOTALS</td>
<td>120</td>
<td>4.881</td>
<td>40,6</td>
<td>4,01</td>
<td>228</td>
<td></td>
</tr>
</tbody>
</table>
Penetration rates were as follows:
- in conglomerate, from 4.3 to 6.3 m/hour with an average 5.5 m/hour;
- in crystalline limestone, from 2.7 to 4.2 m/hour with an average 3.15 m/hour;
- in sandstone, from 2.8 to 5.0 m/hour with an average 4 m/hour.

OPERATING STATISTICS

In order to control the performance of the TBM equipment the time spent on each activity was recorded in daily excavation and maintenance reports.

The results of the two tunnels are shown in table 3.

**TABLE 3 - YINDARUQIN PROJECT - TUNNEL 30A & 38**

MONTHLY PRODUCTION

![Bar chart showing monthly production for Tunnel 30A and Tunnel 38 for Gen.91, June, and Gen.92, June, and Aug.92.]

For a better understanding of these statistics, we have to clarify the scope of the main activities:
- SEGMENT INSTALLATION: It is the time required to complete the installation of the two last segments of the ring, which cannot be done simultaneously with the excavation.
- MAINTENANCE: It is the time required for ordinary maintenance without including the time spent for extension of services, major repairs and cutters replacement.

From table 4 we can argue:

**TABLE 4 - YINDARUQIN PROJECT - TUNNEL 30A & 38**

TBM PERFORMANCE

- **BORING** 35.8%
- **GEOLOGY** 10%
- **BREAKDOWN** 11.7%
- **SURVEY** 3.1%
- **CUTTERHEAD AND MAINTENANCE** 19.5%
- **REGRIPPING** 11%
- **LINING ERECTION** 8.9%

First, the excavation time increases with the hardness of the rock.

Second, in soft rock, where the excavation time is shorter, it is necessary to wait longer for the completion of the installation of the precast segments, if compared with the excavation in hard rock. But, the total time for excavation regripping and lining, which represents the utilization of the TBM, does not change greatly in the two situations.

Third, the time loss due to geological reasons was smaller in tunnel 30/A than in tunnel 38. But, the average progress was higher in tunnel 38. This shows that it "could" be more convenient to
select the equipment and tunnelling system which will provide the best advance techniques, rather than selecting a system that can be adapted to whatever ground is found.

Fourth, as obvious, the derailments and other problems on the muck haulage and extension of services, increase with the length of the tunnel.

Fifth, the electrical and mechanical breakdowns at the TBM and Back-up, remained very low, showing a good reliability of all the construction equipment. The greater figure obtained for tunnel 30/A is mainly due to the problems caused by the underground water at chainage 8.790.

GEOLOGICAL AND EQUIPMENT PROBLEMS

The geology related problems encountered during the tunnels construction can be summarized in two categories:
- Problems related to the peculiarities of the rock formations crossed by the tunnel.
- Problems related to extraordinary events occurred during the 17 km of driving.

In the first group we can include the argillaceous conglomerate encountered along 2300 m in tunnel 30A. Due to the stickness of this material, buckets, chute, hopper and cutter housings became often clogged forcing to continuous stoppage of the excavation in order to scrap the compacted material and to free the buckets.

In the second group we include the high water inflow of about 15000 l/min at chainage 8+790 in the 30A tunnel. The water flow was hindered by the low slope of the tunnel and the presence of the backup platforms. The water raised up to 0.8 m in the TBM, and overpassed the head of the rails by more than 20 cm all along the tunnel, causing some breakdown of electrical and mechanical components. Especially great difficulties was faced in placing the invert segment and laying the rails.

In these conditions some karst caves were encountered, one of these very wide and some meter deep under the tunnel level. The TBM was indeed able to advance through the karst caves. It was also decided to connect the segments with steel plates and bolts, making extensive backfilling at every stroke.
During the following 20 days after the high water inflow was encountered, the daily advance rate decreased to 12 m/day.

The second unpredicted event occurred during the excavation of tunnel 38.

A section with rapidly squeezing ground was encountered at chainage 3+330 in the clayey sandstone formation.

Just in the previous days a conspicuous inward movement of the rock was observed, but the advance rate of the TBM makes the machine moving ahead before becoming trapped in the squeezing ground. The stop of the machine for maintenance and cutter replacement was a mistake, so that at the start up the TBM was unable to regrip.

The first measure adopted was to move the front shield forward and backward, with the cutterhead rotating, and to increase the pressure of the auxiliary thrust cylinders reacting against the lining, but without satisfactory results. The use of additional thrust cylinders against the invert segment was not sufficient.

Based on the observation that on the last installed segment ring there was still some gap between the rock and the segment itself, it was concluded that the deformation was not excessive, but enough to block the long double shield of the TBM on both sides.

At this point it was decided to free the TBM by demolishing as much as possible the surrounding rock and for this purpose the articulation cylinders were removed. The inner telescopic shield moved forward under the outer telescopic shield in order to let an open space from which the material surrounding the TBM was removed.

Working 24 hours per day with pneumatic hammers and small blasting charges the TBM was free again, in 13 working days. We decided to increase the boring diameter to excavate the remaining squeezing ground by means of installing steel plates at the seats of the peripherical cutters which moved these cutters outwards.

This solution caused problems for the vertical steering of the TBM because the invert cut was below the bottom of the shield causing the TBM to dive, therefore the enlargement of the bored diameter was limited to 30 mm beyond its normal size.
The intervention solved the problem and the machine was able to cross the remaining section of squeezing ground without any problem.

In this way the machine was effectively contrasted keeping the head of the machine to a positive look-up. Being the two shields articulated between them, this way of operating the TBM did not affect the level of the rear shield nor the final level of the tunnel.

Concerning the TBM and Back-up equipment, no serious problem occurred.

**TABLE 5 - PERFORMANCE OF CUTTERS**

In spite of the generally low strength of the rock units, cutter ring wear was relatively high, mainly due to the effect of the sandy conglomerate or of the sandy-clay which have been acting as an abrasive medium. For this reason, after analysing the cutters consumption in the first 2600 meters of tunnel, the type of ring
originally foreseen, (type AM 1723 and AM 1724, were replaced in the conglomerate rock by a different type with bigger thickness, (type AM 1720), reducing the quantity of rings replaced. While, in the limestone, were used the original rings. In this way, the cost of cutters was reduced to about 1 US$ per cubic meter excavated.

Cutter hubs started to wear very fast too, but the problem was satisfactorily solved by covering the surface by manganese welding at every replacement of the rings. While the fast wearing of the bucket lips remained unsolved. Also the steel plates of the cutter-head, especially at the peripheral sectors were completely worn out and all the cutter-heads were severely tested by the abrasive muck.

With regard to the performance of the cutters under different rock conditions, from the analysis of the number of replacements, number of changes and their position in the cutter-head, and the length of tunnel excavated per cutter, we can conclude: the wear of the cutters in the conglomerate was quite uniform independently of the cutter position. While in the limestone the cutters wear varied proportionally to the distance from the cutter to the center of the cutter-head. Table 5.

Table 5. (Remarks)

The performance of the cutters has been recorded on the following stretches:
- limestone 1246 m
- conglomerate 6620 m

the third line, tunnel, is a weighted average of the cutter wear in the tunnel.