Vertical Access Shaft Replaced by a Decline TBM Access Tunnel

E. Fernandez¹, G. Rojo², A. Gullón ³
¹Head Underground Technical Dept. Dragados, Madrid Spain
²Pajares Lot 2 General Manager Dragados, León Spain
³Chief Quality and Environmental Dept. Obras Subterráneas, Madrid Spain

1. INTRODUCTION

The construction of the high speed rail link between Madrid and Asturias, in the North of Spain, has faced its biggest challenge at the Cantabrian mountain range, with the excavation of the 25-km long Pajares High Speed Railway Tunnel, through a known, but difficult, geologic formation. The tunnel was divided into four construction sections:

• Section 1: Pola de Gordón- Folledo. L=10.7 km. Twin tunnel.
• Section 2: Folledo-Viadangos. L=4.2 km. Twin tunnel.
• Section 3: Viadangos- Los Pontones. East Tunnel. L=10.4 km.
• Section 4: Viadangos- Los Pontones. West Tunnel. L=10.4 km.

The Dragados S.A./Obras Subterráneas JV was contracted to design and build Section 2. This section, the second one downward from the upper face of the tunnel at Pola de Gordon, presented the additional challenge of constructing two shafts from the ground surface, as the only access for the tunnels excavation. Due to the risk of squeezing ground at the deepest points of the tunnel, the use of TBMs was not mentioned on the Feasibility reports, nor contemplated in the Preliminary Design. Conventional NATM excavation of the twin tunnels and ancillary works, including the access shafts, was anticipated by the client due to the poor ground conditions that were foreseen during the early construction stages.

2. PRELIMINARY DESIGN

The Preliminary Design for the bid considered the construction of two access shafts, 580 m deep and 9 m diameter, respectively, to provide access to a cavern perpendicular to the centerline of the tunnels, which would have been used to excavate 2 x 2 km tunnels, East Tunnel and West Tunnel, using NATM. Above the cavern, a series of galleries were to be used to install long fiberglass grouted bolts to improve the ground above the cavern. The design was based on geotechnical studies that anticipated very low geotechnical quality ground - San Emiliano shales - in the area of the cavern. Similar ground conditions were also anticipated for the last 3 km of Section 1, and a decline tunnel with an access at Sta. 7,000 had been considered to construct those 3 km using NATM.

This technically complex preliminary design would have made it impossible to meet the 5-year contract construction schedule, so the main challenge of the final construction design was to find a technical solution to meet the contractual schedule.
3. CONSTRUCTION DESIGN

The first activity on site following contract award was the drilling of very deep boreholes in order to verify the ground conditions at the tunnel level. These boreholes provided invaluable information related to squeezing ground conditions. Based on this information, the Preliminary Design was completely modified to a final design that allowed us to meet the contract schedule.

The proposed and approved solution consisted of substituting a decline access tunnel with a 6.2% downward slope for the Viadangos access shafts, which would allow access to the main tunnels at the start of the Section 2 project. The TBM would then excavate first the 5,467m long East tunnel. The access tunnel portal was located in the village of Buiza, very close to the Section 1 ramp portal, mentioned above. A double shield TBM was selected to build this decline access tunnel.

From the access ramp tunnel, the double shield TBM proceeded to drive the East tunnel using a transition curve onto the main alignment and leaving a short unexcavated section at the Section 1/Section 2 contract boundary. The connection between the access tunnel and the main tunnel required the construction of a wide-span Bifurcation Chamber (“Bifurcation East”) and a short mined tunnel, which was constructed using the New Austrian Tunneling Method.

The Final Construction Design called for the excavation of the two main tunnels to be carried out by the same TBM. This required the following complex execution process sequence within the rock mass, 800 m deep:

- TBM disassembly in a cavern after finishing the first tunnel (East Tunnel)
- Construction of a large cavern for TBM assembly to excavate the second tunnel (West Tunnel)
- TBM assembly inside the cavern and excavation of the West Tunnel

In addition, cross-passages were constructed between the main tubes every 400 m, as galleries that accommodate the signaling and electrical equipments. The design also included the construction of a 400 m long preferential stop point next to the junction between the access gallery and the main east tunnel. This preferential stop point is comprised of a third, smaller cross section tunnel, located between the two main tunnels, and connected to them through 25-m long cross-passages.
4. GEOLOGY AND HYDROLOGY

The Cantabrian Range is mainly the result of an upsurge by compression of faults and areas of hercynian nature. This compression was caused by the rising of the Pyrenean and Betica mountain ranges during the Alpine orogeny, giving rise to the current and very complex geological structure formation. In the area of the Pajares Tunnels corridor there are materials which form a very complete sequence of the Paleozoic era.

The hercynian processes, which experienced greater intensity during the Superior Carboniferous stage, molded these materials until their subsequent reactivation by a highly complex orogenic dynamic that gave rise to the strong deformation of these materials and their low ensuing geomechanical quality.

The access ramp tunnel was bored through numerous formations:
- Slate-sandstone formations: Oville, Formigoso, La Vid, San Pedro
- Sandstone-quartzite formations: Barrios
- Carbonated formations: Láncara, La Vid

Two different aquifers were encountered during the excavation, as shown on the lithological characteristics of the bored materials: detritic and carbonated.

4.1. Geological and hydrogeological problems

From the beginning of the project, the engineers and technical personnel were conscious of the difficulties of tunnel excavation through the Cantabrian Range. This resulted in their decision to excavate the tunnels with the help of intermediate access tunnels, in order to supposedly guarantee higher performance, and to assure the feasibility of the project even in case of potential serious incidents that might limit the advance of excavation at any of the portals. Different problems have turned up during the construction of the four Sections, most of them the result of geological or hydrogeological reasons. The main construction issues on Section 2 were:
- Flooding caused by water leaks in fractured and/or sandy quartzite formations
- Operation and maintenance logistic problems during excavation of the 6.2% downward slope access ramp tunnel
- Presence of deflagrating gases in the Carboniferous stage slate formations. Gas concentration has appeared in the plane between slate and carbonate formations. Gas has been encountered in the “Grupo La Vid” (limestone) and “San Emilio” (slate) formations in the access ramp tunnel,
and in the main tunnel. Both the TBM and the ventilation system had been configured to detect and decrease gas presence.

4.2. Flooding caused by water infiltration in fractured and/or sandy quartzite formations

Some flooding occurred inside the TBM shield during excavation of the intermediate access ramp tunnel. The most noticeable flooding was recorded on 11 August 2006.

Flooding began when the cutterhead started excavation of a sandy fracture in the Quarzite formation, and a huge water and sand flow came toward the shield. Neither the dewatering system nor the pipe net could control the huge quantity of water and sand which moved so fast into the TBM.

The water reached a height of 7m, and the sand carried by the water filled up the whole shield. Once the water and the sediments were stabilized, cleaning and dewatering began. Sediments and muck handling was made with auxiliary conveyor belts and mud pumps.

After the cleaning, the TBM electrical/electronic systems were repaired and reconstructed. Production work resumed 25 days after the incident.

5. CONSTRUCTION PROCEDURE

The access ramp tunnel was excavated with a 10,160-m diameter double shield TBM. This avoided the shaft construction risks and made evacuation easier in case of emergency. The TBM proceeded to drive the East main tunnel using a transition curve onto the main alignment. Once the first drive – East Tunnel – was completed and the squeezing effect along the main tunnel alignment was negligible, the site staff decided to disassembly the TBM and, instead of reassembly it again to excavate the West Tunnel, bore the West Tunnel Section 2 using the TBM which had excavated the West Tunnel Section 1 from the south portal. This eliminated the construction of the assembly chamber and the two bifurcation chambers required to move the TBM from the east tube to the west tube, thus saving substantial time on the overall schedule.

Figure 3. Bifurcation cavern for connection between access tunnel and main East tunnel
6. DOUBLE SHIELD TBM

6.1. TBM main characteristics

The TBM type chosen to excavate the “Folledo- Viadangos” stretch was a new generation double shield TBM. The geologic formations in the area of the tunnel alignment were favorable to the use of a double shield TBM due to two characteristics of the rock:
- Its medium or low compressive strength
- Its low abrasivity

There were known conditions that could have resulted in delays during the excavation;
- Excessive convergences that could cause squeezing problems
- Heading instability in fracture zones
- Probability of presence of karstic zones

In accordance with the geologic conditions detected, the TBM design fulfilled its two most important goals:
- Keep high excavation rates
- Overcome the known problem zones with minor delays

This new TBM was designed to bore through hard rock with high thrust per disc cutter, high power due to the “gripper system” mounted on the rear shield, and high torque at the cutterhead, allowing it to advance safely in unstable grounds and in soft or low cohesive ground.

![Figure 4. Double Shield TBM at the tunnel portal](image)

The TBM was designed with the minimum possible length compatible with the designed lining, and additional disc cutters were placed, up to 300 mm, to increase, if required, the free space between the shield and the rock, adapting to possible convergences and avoiding the TBM squeeze. Its conicalness,
the difference between the diameter of the cutterhead and the tail shields, helped decrease the squeeze risk.

On every type of ground, the lining erection was always protected by the rear shield. This allows for maximum safety.

The segments had two different thicknesses, 500mm and 600 mm, and variable steel quantities and concrete strength, as required by the quality of the bored rock and the existing overburden.

The double shield TBM allows simultaneous excavation and segment placement achieving elevated performances.

6.2. Operation and maintenance logistic problems during the access ramp tunnel excavation with a 6.2% downward slope

The excavation of the intermediate access ramp tunnel of Buiza was one of the challenges of the Pajares Tunnels Project. With a 6.2% downward slope and a length of 5.45 km, its construction presented a complex logistic and operational problem. There is a 310m drop between the portal and the end of the tunnel.

The equipment within the Herrenknecht S-281 TBM had to be adapted to the tunnel’s slope. The main project-specific conditions that affected the design of the TBM are detailed below:

- Bending overstresses caused by the normal component of the loads on cranes and suspension elements in the shield and back-up (container unloading, segment cranes, erector, etc.)
- Special brakes for the longitudinal component of the loads.
- Conditions affecting hydraulic devices due to the variation on slope grades: the TBM excavated a transition between the access ramp tunnel and the main tunnel, which produced a slope change from 6.2% to 1.7%, always downward. During the excavation of the access tunnel, all the impurities and metallic particles congregated at the front end of the 16 main bearing reducers, and due to the slope change all these impurities came into the hydraulic system circuits causing many problems and breakdowns.

7. FACILITIES

The use of a TBM provides a continuous working mode of excavation with high rates of advance, and even more when using a Double Shield TBM. This continuous work needs continuous supply from the outside, and the required number of connections to the facilities outside the tunnel.

In this case, for the TBM supply and feeding, a variety of equipment was installed near the portal, and the corresponding connection lines extended along the tunnel to the TBM. Facilities and connections were designed based on the needs of the excavation equipment, the significant downward tunnel slope, 6.2% in the first 5 km, and the hydrogeological conditions of the rock massif.

7.1. Dewatering system

Significant high pressure water inflow with the subsequent danger of TBM flooding was anticipated on this deep tunnel project subject to an overburden of almost 1,000 m and to the hydrogeological conditions of the rock massif. Dewatering was a prerequisite for the execution of this tunnel, for, as a result of the high downward tunnel slope and anticipated water inflows, estimated at about 350 liters per second, the TBM would have flooded in a short time if a failure in the dewatering system occurred.
The solution adopted was a phased pumping system with 5 intermediate pumping stations. Each pumping station conveyed the inflow water to the next pumping station above, as well as the water running on the tunnel floor toward the tunnel face, which was picked up at a specially made precast metal, open box, invert segment and carried to the nearest pumping station.

This way, a gradual, step by step, dewatering system was created, which could be adapted to changing conditions of water inflow and was not entirely concentrated on the TBM, thus minimizing the risk of TBM flooding because the water that leaked into the tunnel was not allowed to reach the work face.

Each pumping station, placed in metal structures on the side of the tunnel so as not to disturb the movement of trains, comprised the following:
- Three 18 c. m. capacity metal tanks.
- Group of three 90 liter per second, 100 meter height capacity pumps, placed in each tank.
- Three parallel, 300 mm diameter, steel dewatering pipe connection between pumping stations, and another 300 mm pipe and two 200 mm pipe connections between pumping stations and the precast metal open box invert segment, in addition to other auxiliary lines, for a total of over 60 km of drainage pipes.
- A 1000kVA transformation center 20 kV / 0.38 kV for each pumping station.
- Two emergency 500KVA generators at each pumping station to ensure dewatering in case of power outages.

In addition, 22 precast metal, open box, invert segments were used to collect water that seeped through the walls of the tunnel and moved toward the face, each with a 110 liter per second, 80 m height capacity pump.

The open box precast invert segments, open at the top to facilitate the collection of water inside, proved to be a problem for the excavation due to the fact that the TBM had to lean on them with its auxiliary thrust cylinders, so they were fitted with steel beams that were removed when the TBM was far enough not to push against the empty segments.

7.2. Materials Transport

Supply trains were used for material transport throughout the tunnel. Muck removal from the TBM excavation was done by a conveyor belt along the tunnel. The trains included fixed-body segment cars for segment rings transport, mortar tanks cars (w/mixer), personnel car and one flat car, all as needed for one TBM advance stroke.
Since it was necessary to go down a 6.2% slope with a maximum load of 320 Ton, the main problem was to control their descent not the power needed to return empty trains to the surface. Given the peculiarity of this situation it was decided to have 2 diesel locomotives (510 HP each) and 1 hydraulic tandem for each composition, 180 ton in total. Locomotives had a triple braking system to work with the diesel engine machines, a pneumatic brake system, a hydraulic brake system, and a Voith brake hydraulic retarder.

In order to improve safety conditions, a project maintenance of railroad tracks plan was established, as well as a protocol for sandblasting the tracks with "dry" silica sand, which was essential to ensure both train traction and braking.

8. LESSONS LEARNED

Several interesting lessons were learned from the construction of the Pajares Section 2 contract. The bid documents must include better documentation on the ground conditions to be encountered along the project. This will result in fewer stoppages or delays during construction. It's true that deep bore logs are not always easy to prepare, nor to understand the results, but in this specific case the squeezing ground conditions, not anticipated, were the key determinant in terms of using TBM or NATM excavation methods, and the soundness of our decision to use a TBM was confirmed during construction.

The construction of the access tunnel to build the main tunnel was challenging and well performed, but, as described above, it required a very involved conceptual and final design of the TBM and ancillary facilities. The production rates achieved on the access tunnel and the main tunnel confirm the adequacy of the chosen method.

The construction of the Bifurcation chamber shows that TBM and NATM technology can and must work together on tunnel design, as the most cost effective way to develop Mega projects, such as Pajares.

Finally, the Client’s decision to divide the project into five contracts, using five TBMs was a conservative but realistic decision to accomplish the tight construction schedule. The problems faced during construction, as described above, were also faced on the other contracts, but the existence of 5 machines gave the client extra peace of mind to see the project completed for the benefit of the Spanish citizens.

9. ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance given by colleagues within the Pajares Section 2 Joint Venture in the preparation of this paper, especially Juan Luis Magro, Sergio Rodriguez, and Ernesto Lago, and also to ADIF, who have allowed its publication.