In-Tunnel Station Concept on Deep Subway Tunnel Projects in Urban Areas: Barcelona Line 9

J. Roig¹, E. Fernandez², M. Ruiz³, A. Sanz²
¹Dragados Canada Inc., Toronto, Canada
²DRAGADOS, Madrid Spain;
³Gorg J.V. General Manager, Barcelona, Spain;

1. INTRODUCTION

DRAGADOS, as leader of the Gorg JV, is currently constructing several sections of the new Line 9 of the Barcelona Metro. This new line will cross the city from Badalona, on the northeast, to Hospitalet on the southwest. The new Line 9 will be approximately 50 km long, mostly underground with only 4 km at grade, and will have 52 stations, nineteen of which will connect to either Metro lines or other transportation networks.

The Project includes essentially the construction of a new high capacity Metro line, excavated through variable geological conditions and with high safety standards, which connects with the existing Metro network and crosses the city of Barcelona, without major impact on the community.

The In-Tunnel Station Concept, which was developed for this project, consists of excavating one four-track, large, single-bore tunnel fitted with an intermediate horizontal slab, which accommodates two tracks on the upper level and two in the lower level, with one level for each direction of traffic. At the station area, one track from each level is replaced by a station platform. This reduces the space customarily required for underground stations, for by installing the station platforms inside the tunnels it is not necessary to build a 150m long full station along the tunnel axis. In addition, all necessary passageways, shafts, and adits are excavated from the surface in the desired area near the tunnel, thus minimizing disruption at street level. Within the tunnel, a versatile train traffic management is obtained with two tracks in each direction of movement, being also possible the connection between the two levels by installing ramps at strategically located points of the subway line.

With this concept it is possible to build a new deep line, with easy interconnections with the existing Metro network.

2. STATIONS

The In-Tunnel Station Concept substitutes a station platform for one running track at each level within the tunnel cross section, and uses one operating track per level in each direction. Both levels are connected to the surface by an access shaft, where high capacity elevators or mechanical staircases are installed to expedite passenger movement.

An advantage of the In-Tunnel Station Concept is the versatility of the system. As the stations are located inside the excavated tunnel, it is only necessary to excavate the access shaft and its connections to the bored tunnel to build new stations. This is very advantageous, because it is not necessary to build the station from ground level to the top of the tunnel alignment, which adds flexibility to the Project design. It
is only necessary to excavate from the surface the 25m-30m diameter access shafts, upper passageways, and emergency exits; but none of them needs to be at a predetermined location related to the tunnel alignment, for the connection to the tunnel can be made either secant with the access shaft or, through a connecting gallery. Thus, the location of both surface structures and areas of work to be performed from the outside can be limited to areas that produce minimum disturbances.

Thanks to this configuration it is possible to design superficial and deep access shafts adjusting the elevators speed and capacity, as in Line 9, where the access shafts depth varies between 25 and 65 m. Furthermore, because the tunnel and the access shaft are separate structures, it is also possible to build a new station after completion of the Project with minor disruptions in normal operation.

The Barcelona Metro line 9 conceptual design called for shaft-type stations bored from the surface in strategic areas with short disruptions and open box cut & cover stations at TBM launching sites, when needed, which results in important savings in station construction.

![Figure 1. Metro Barcelona Line 9 Stations concept](image)

**2.1. Shaft excavation**

Several excavation methods were used to respond to the varied geological/geotechnical properties of the ground. When soft ground was encountered, slurry walls were erected along the perimeter of the shaft; the ground was excavated with backhoes, and then finished with rings of reinforced shotcrete or cast in place concrete, using climbing formwork. Drill and blast excavation was used when rock was encountered, with reinforced shotcrete as main support along the shaft.
3. TBM TUNNELS

The In-Tunnel Station Concept consists of incorporating the station platforms within the tunnel cross section, which requires sufficient usable space to install both platforms and tracks in the tunnel. Using a typical circular cross section bored with a TBM, there are two possibilities:

a. Boring one single tube for both directions of train operation, 12m excavation diameter and 10.9m internal diameter, as is the case of Line 9 of the Barcelona Metro.

b. Boring two parallel tunnels of approximately 9m diameter with one tunnel per train operation direction.

The excavation of a larger face, 12 meter diameter tunnel is more complicated than that for a 9 meter diameter tunnel but it can be balanced boring with at least a two-diameter cover of good quality ground - normally found at higher depth -. On the other hand, it has advantages, for a deep tunnel solution eliminates interferences with existing infrastructure, such as other Metro lines, underground services, sewer tunnels, etc. Therefore, the proposed station concept fits perfectly within a deep tunnel solution.

![Figures 2a and 2b. Running tunnels 12 meter diameter cross section (2a) and station cross section with one track and platform at each level (2b)](image)

In terms of design, a single 12m tunnel is more versatile, because it is easier to make the shaft-station connection to one single tube rather than to two tunnels. For the latter, the access shaft should be placed between the two tunnels; otherwise, long connecting passageways would be necessary. The dimension of the access shaft, whether for a double or single tunnel, is determined by the location of the adits, elevators, stairs and facilities, but its internal diameter is usually not less than 29 meters.

In terms of construction, a deeper single 12 m diameter tunnel may have a smaller influence area than that of a twin 9 m tunnel, which would, at a minimum, affect a 27 meter wide horizontal area considering the two tunnels and one clear diameter between them. This is an important advantage because the surface area eventually affected by settlements, which depends on the width of excavation, may be reduced to a smaller area. A one tunnel solution makes it easier to work the tunnel alignment under streets and to avoid excavation under buildings, so that there is less impact on existing structures and less specific ground improvement treatments are needed.

In terms of quality and safety, a single tunnel can reach the same levels of quality, and even improve fire safety conditions, for the intermediate slab acts as a barrier between the two levels of circulation, with the same behavior as with twin tunnels. But with a single tunnel, the two track levels are connected by stair provided with fireproof doors, placed in the extra track as close as wished.

Following these concept, the new Line 9 of the Barcelona Metro is being constructed. To date, more than 28km of the 50km long line have already been excavated with 12m diameter TBMs.
3.1. Geological conditions

The Barcelona subsoil is formed essentially of deposits from the Besos and Llobregat deltas and from material brought down from Collserola by a large number of streams and torrents during the Quaternary period. The local geology in the Barcelona urban area is complex and varied, and it has many types of materials, presenting an alternation of more than 40 geological units along Line 9.

Among the varied materials found within the deep Line 9 tunnel sections constructed by the Dragados-led Gorg JV there have been a variety of granitic, batholith, and Quaternary deltaic silt deposits, and Pliocene clays overlaying some Miocene breccia. These geological conditions required a mixed-ground cutter head design to bore the tunnels.

3.2. TBM excavation

The tunnels included in the Gorg JV contracts are being excavated with two identical EPB (Earth Pressure Balance) TBMs. The TBMs have an excavation diameter of 12.06m, a length of 92m and a weight of approximately 2,500 tons. The TBMs allow the installation of universal type (6 +1) 10.90m internal diameter, 1.80 m long, 0.40 m thick precast concrete segment rings.

Each TBM has excavated more than 3,000 meters. More than 7.8 km have been excavated to date with maximum excavation rates in excess of 750m per month, using different cutting heads to accommodate variable geological conditions.

Since the TBMs had to excavate in both cohesive and non cohesive materials with high water table, their design had to respond to these geological-geotechnical constraints. As such, an EPB type, mixed cutting head machine was chosen, able to excavate through mixed soils in urban areas, and suitable for settlement control.

Ground improvement has been fundamental for excavating through this heterogeneous geology, so several additives, such as dispersing agents, polymers and foams have been used depending on ground conditions.

Figure 3. EPB TBM used in Barcelona’s new metro line 9 (12.06 m excavation diameter)
3.3. Hyperbaric interventions

Due to the deep vertical alignment of the tunnels and the difficulty to check and to repair the cutterhead during excavation because of the pressurized TBM face, hyperbaric interventions are been performed in the Line 9 subway project without any action from the ground level.

Through a combination of bentonite injections and breathable compressed air, it is possible to create a pressurized air bubble inside the mixing chamber that enables the entrance of skilled personnel into the tunnel face to check, change or eventually repair the cutter tools. For that purpose, each TBM has two auxiliary pressurized chambers that connect to the TBM mixing chamber and allow for a gradual transition from atmospheric to working pressure, thus providing the necessary tools to carry out maintenance work with the required safety conditions.

3.4. Intermediate slab

The intermediate slab is a 0.4 meter cast-in-place reinforced concrete structure designed to resist the high dynamic loads that the trains will transmit in the future. Due to the large diameter of the excavation it has been possible to build the intermediate slab without major interferences following TBM excavation. Mobile formwork was used that doesn’t interfere with the TBM supply trains and that maintains continuity of the conveyor belt, ventilation duct, piping and electrical wiring.

The slab casting procedure involves moving the formwork forward after completion of the last operation, placing of rebar, installation of the front plug, and pouring of the concrete. Due to the high rate of excavation of the TBM, high outputs of intermediate slab are necessary, and, therefore, large concrete volumes are needed. As such, concrete pumps are installed at the stations or at ground level, pumping concrete at distances farther than 800 m. When the distance between two stations is too long to permit the use of a concrete pump, it is also possible to make a borehole connecting the ground level and the bore tunnel and use it to reduce the distance between the pump and the pour site, placing the concrete pump at the borehole entrance.

![Figure 4. View of the intermediate slab](image-url)
3.5. TBM curved slide

As part of Section IV (Lot IV) of Line 9, the 12 meter TBM first excavated the 3,500m long tunnel between Gorg Station and the Sagrera Junction Shaft. Both stations were excavated by cut & cover. At the Sagrera Junction Shaft, the TBM had to go across the station and then continue excavating an additional 1500m to the Havaneras disassembly shaft.

The usual procedure is to move the TBM by pressing the TBM’s thrust cylinders against the last invert segment erected, and the only preparatory work required is a concrete cradle on the shaft invert to guide the TBM advance and the thrust frame at the end of the shaft. Since on this project the TBM had to be designed for curves of up to 300m radius in order to negotiate an “S” curve (two opposing curves of 285m and 300m respectively) within an 80m range due to shaft geometry, the customary normal TBM slide was rejected and an alternative method was used.

There were two options: To partially disassemble the TBM and back up decks in order to lift them and reassemble them later, or to use a special mechanism to raise and push the TBM. In either case, the work included moving a 12m diameter, over 100 m long, 1,500-ton TBM with a 1000-ton back-up.

The second choice was selected because it was found to be easier and faster. It was decided to design and construct a frame, weld it to the main shield, raise the TBM without damaging it, and push it onto a tailor-made guide, pulling the back-up as the TBM advanced.

For that, special brackets and a transmission frame were designed, in coordination with the TBM manufacturer, to hold the weight of the TBM without fear of damage. This mounting arrangement was then held by two pairs of 500 ton capacity skid-shoes that elevated the TBM and let a couple of cylinders push it a stroke of 620 mm over steel skid tracks. The skid tracks were positioned at the desired alignment and TBM guidance corrections were possible thanks to a pivot located on top of the skidshoes. An auxiliary structure was also used for back up slide.

The operation of sliding the TBM along the Sagrera Station shaft was completed in only 8 working days.

3.6. TBM launching in a 27 meter diameter shaft

Due to the limited space available at ground level at the Pozo Bifurcación launching area for the Pozo Bifurcacion to Zona Universitaria Station excavation section, the assembly and launching of the 12m diameter TBM had to be performed in a 27m diameter, 36m deep shaft.
The assembly of a 12m diameter TBM in a small shaft, never performed before, was made possible thanks to a detailed assembly procedure, which considered every stage and associated difficulties.

Prior to shaft excavation, a smaller diameter, 3km long tunnel linking Pozo Bifurcacion to the Parc Logistic cut&cover station was excavated, so it was possible to extend the required utilities from - and to locate the necessary auxiliary facilities at - Parc Logistic to support the excavation of the larger 12m tunnel from Pozo Bifurcacion. This solution facilitated TBM operation and reduced the installation of site facilities in a more sensitive area.

Once the shaft was excavated, the TBM was assembled at the bottom of the shaft using high tonnage cranes and a series of pneumatic hoists for precision lifts.

![Figures 6a, 6b, 6c and 6d. TBM and 1st deck of the back up in the shaft bottom, and 2nd deck over the TBM (6a), rear part of the 2nd deck (6b), remaining back up decks in the surface area (6c) 1st back up deck in the shaft (6d).](image)

Outside the shaft, assembly of the TBM back-up decks proceeded simultaneously, so that installation of the reacting frame and the first back-up deck was completed upon TBM assemblage. The first back-up deck contains primarily the mortar equipment, the operator's cabin, and a set of conveyor belts especially designed to carry the spoil material through the existing tunnel since the start of excavation.

Since there was no more space available at the shaft invert, an auxiliary structure was built over the shield of the TBM and the second deck of the back-up was placed there, rotated 90 degrees. This deck
was placed close to the TBM because it contained the electrical substation and the electrohydraulic pumps which had to be placed near the TBM drives.

Meanwhile, the remaining back-up decks continued to be assembled outside the shaft and connected to the TBM, thus providing the TBM with its back-up at three different levels.

At this point the excavation started, continuously adapting the mucking system to this temporary situation. Following the TBM advance, the second deck was rotated and lowered into position in order to continue with the excavation until the first 40 rings were completed. The remaining back-up decks were then lowered and fit into their final position, completing the TBM assembly, at the tunnel level, while all connections and supplies for the TBM were brought through the existing tunnel to the open-box station at Parc Logistic.

The TBM assembly was carried out in a very small space, in a very short time, and with minimal impact to the community.

4. LESSONS LEARNED

Line 9 of the Barcelona Metro is a real-life tunneling school in terms of new experiences in tunneling through variable soils and poor ground conditions.

From the very beginning, the design, manufacturing and operation of the largest EPB in the world at that time was challenging and highly risky due to the unpredictability of the city's subsoil structure, including the presence of scary boulders in some areas. Despite that, the good performance of the machine and the skilled personnel assigned to the operation allowed the excavation of the first two sections to proceed with minimal delays resulting from ground conditions along the alignment.

EPB excavation in mixed ground conditions under a maximum 3.5 bar pressure is not an easy task, but it taught us how to properly operate the big excavation "monsters" and also what to avoid. The high production rates achieved in some areas were compensated by the TBM stops due to continual hyperbaric interventions to replace and repair the cutter tools. For this reason, the overall production rates to date do not provide a proper reading on the capabilities of the TBM and its operating team. Short excavation sections and multiple assembly and disassembly processes, at times quite complicated as noted for the Bifurcation shaft, also reduced the overall production rates.

The main lesson learned has been that proper and deep knowledge of the geology along the tunnel alignment, along with a comprehensive inspection of utilities ahead of the tunnel excavation, are key for meeting tight construction schedules. That knowledge allows for a proper design of the TBM and its components, especially the cutterhead, and helps choose the most suitable additives for any ground conditions. Unknown situations and ground conditions may have dramatic consequences.

The TBM slide at the Sagrera shaft and the TBM assembly at the Bifurcation shafts were new and innovative experiences that can be applied in the future to new projects, minimizing impacts and schedules, and that were a breakthrough against the inertia that characterizes the tunneling industry.

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