Construction of a new Metro line in Barcelona: design criteria, excavation and monitoring system

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ABSTRACT: A new metro line is being built in Barcelona metropolitan area. The line is over 40 km long and crosses a great variety of ground types ranging from soft soils to hard rocks. Deep underground tunnelling is the predominant construction mode. At present, a 12 m diameter dual TBM-EPB machine and a 12 m diameter EPB machine are being used. Later sections include the boring of more conventional 9.4 m diameter tunnels. The intricate layout of the urban area crossed by a large part of the line, implies that the tunnel often underlies or is close to existing buildings. An extensive monitoring scheme was implemented to assist in movement control and to assess the construction process. The paper describes the main features of design and construction of this new Metro line, the monitoring system installed and gives information on the performance of the excavation in the sections already tunnelled.

1 INTRODUCTION

Barcelona's metropolitan region with a population of more than 4 million inhabitants is a dense urban area and one of the most important industrial and commercial centres in the Mediterranean area. This has led to an increasing traffic and transportation demand. In response, the metropolitan transport authority ATM (Autoritat de Transport Metropolità) has established a master plan for public transport infrastructures PDI 2001–2010 (Pla Director d'Infraestructures). The most important new infrastructure of this master plan is the construction of the new metro lines L9 and L10 (or L9 for short). They include fourteen interchanges with other metro and suburban railway lines. There will also be a connection to the high-speed railway system.

During civil engineering planning, L9 was divided into four sections that were designed separately within a common conceptual framework. The project includes the construction of 47 km of new lines including:

- 26.4 km of 12 m diameter tunnel
- 11.9 km of 9.4 m diameter tunnel
- 5.0 km of cut and cover tunnel
- 0.9 km of conventionally mined tunnelling
- 2.8 km of viaduct

The project includes the construction of 48 stations, three of which will be built on the surface and 45 underground. Of those, 12 stations are cut and cover, 26 stations use a deep shaft concept described subsequently and 7 stations have special features due to specific constraints (Borràs et al., 2003c).

It is envisaged that the total construction cost is about 2.7 milliard euros. Construction began in June 2002 and the planned schedule foresees an initial partial usage of the line in 2005. The whole line should be in use in 2008.

2 DESIGN CONSTRAINTS AND CONDITIONS

In the case of Barcelona's new metro line L9 there are different constraints, from a wide variety of sources that were taken in account right from the first planning steps (Borràs et al., 2003b). Focussing only on technical and construction matters, the main conditions are briefly described below.

2.1 *Terrain*

The line spans from shallow nearly horizontal areas in the deltas of Llobregat and Besòs rivers, up to mountainous areas in the vicinity of Collserola ridge, away from the sea.

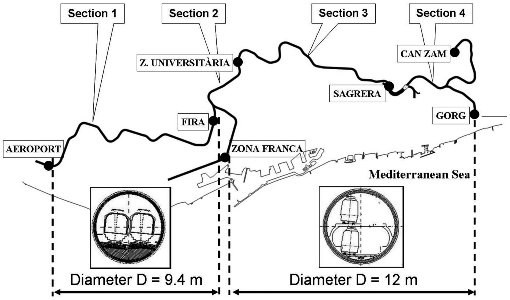

Figure 1. Layout of the new Metro line 9.

2.2 *Geology*

The geological conditions encountered by the alignment can be separated into three main zones:

- igneous granitic rocks (including some deeply weathered profiles)
- soft rocks: Pliocene conglomerates and Miocene conglomerates, overconsolidated clay and gravel
- soils: quaternary cover materials and alluvial deposits in deltaic areas

The granite is affected by the regional fault system and joints are observed with a frequency of a few decimetres and never more than one meter. In the central part of the line a zone of weathered shale materials will be crossed.

The line crosses a number of fault zones of a varying degree of importance. They are expected to cause problems for open mode tunnelling especially when located in valleys and transporting groundwater.

Quaternary materials include layers of gravels, partially saturated clays, sandy materials, and weak calcareous conglomerates. Finally, the deltaic deposits are mainly composed of sands and soft clays and silts. A deep gravel layer, constituting an intensely exploited aquifer, generally underlies the softer soils.

2.3 *Urban environment*

In most of the districts crossed by the new line, there are neither large open spaces nor large avenues, but an irregular mesh of relatively narrow streets. Therefore cut and cover construction is not normally possible and the surface occupation of stations has to be minimized as much as possible. As the new infrastructure has to pass through mainly well established urban areas, the optimal location of the stations and their effect on the neighbourhood was explicitly studied.

Beneath the surface other infrastructures exist, such as the tunnels of existing metro lines, road tunnels, large sewers and other services. The presence of these elements determines, in many places, the maximum elevation of the tunnels to be constructed.

2.4 *Mechanical engineering*

As a project of this kind could stretch the limits of tunnel boring equipment, it proved necessary to coordinate the civil engineering requirements and the mechanical engineering capabilities at every phase of the project. Requirements and capabilities were reviewed as more information on ground and groundwater conditions became available.

3 POSSIBLE TUNNEL SECTIONS

Since cut and cover construction was only possible in short sections, the main decision concerned choosing either a mined tunnel or a TBM-excavated tunnel. Obviously no open face mining is possible, under atmospheric conditions, in soft soils with high ground water level and containing some layers with significant permeability. In hard soil or soft rock a mined solution may be possible, but there are some considerable risks especially when crossing the abundant fault zones. The control of surface subsidence would also be more difficult. In addition, the use of drill and blast methods has limitations when used in a dense urban area. Consequently, excavation by TBM was the general construction method adopted.

Another important decision concerned the section of the tunnel to be bored, as it has important implications for most design items. Some of the main arguments leading to the final choice are summarised below.

3.1 *Two tunnels – one single track on each tunnel*

A classical solution for tunnelling in soft soils, but also used for deep tunnelling in rock, consists in excavating two parallel tunnels and placing one track in each one. Considering normal train profiles and emergency catwalks the diameter of the excavated tunnel should be about 6.3 meter (31.2 m^2) although the exact value may depend on the requirement for inside services and the thickness of concrete segments.

One advantage is that the geological exploration and construction experience of the first tunnel can help to avoid problems in the second parallel tunnel. As the cross-section is small, the ground at the tunnel face will be more homogeneous than in the case of larger diameters.

A disadvantage is that two machines are generally required if the work schedule is to be kept. This doubles the requirements for experienced tunnelling crews, a critical factor in some cases. In this kind of tunnelling, junctions of two lines usually require complex structures or long auxiliary tunnels.

There are a number of possibilities for constructing stations. A classical option is to use cut and cover construction (Figure 2). It requires, however, a large

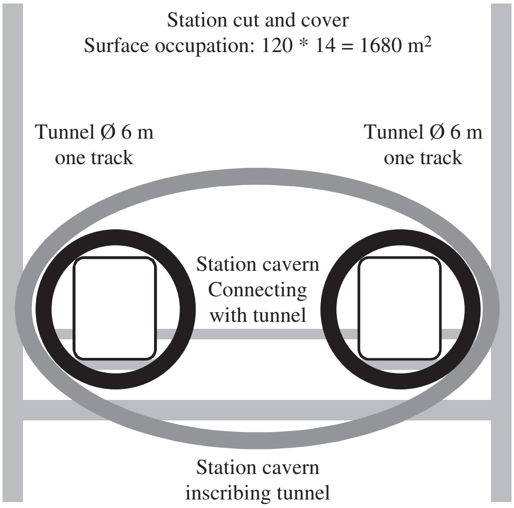

Figure 2. Solution involving two 6.3 m diameter tunnels with a single track in each tunnel.

temporary surface excavation and may become too costly if tunnels run deep. For deep tunnelling, alternative solutions consist in excavating either a cavern comprising the two tunnels or a cavern located between the two tunnels once the TBMs have gone through.

Emergency exits can be provided by shafts to the surface or by connecting galleries located between the two tunnels.

3.2 *One single tunnel with two tracks on same level*

Another typical solution for metro line tunnels is constructing a single tunnel to contain a double track (Figure 3). Considering the train profile and the necessary emergency catwalks, an excavated tunnel diameter of about 9.5 meters (70.9 m^2) is necessary although again it may vary somewhat depending on the concrete segment thickness.

Now all geological exploration has to be done in advance of tunnelling. The larger cross-section also implies that the ground conditions at the face will be generally less homogeneous. The requirements for experienced crews are smaller than in the previous case.

Junctions of two lines require normally very complex crossings that can be constructed either by cut and cover sections, or using smaller tunnelling machines or by drill and blast mining.

Typical station layouts may involve cut and cover stations for shallow tunnelling, again requiring a large temporary surface occupation. For deeper tunnelling, caverns including the single tunnel may be constructed. This system makes it necessary to place stations for the two tracks at the same point. Normally the station cavern is designed to accommodate lateral platforms; if a central platform is required a wider cavern may be necessary.

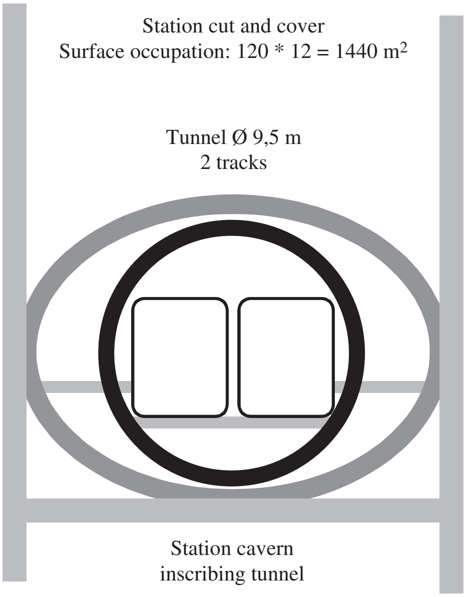

Figure 3. Solution involving a single 9.5 m diameter tunnel.

Emergency exits are normally vertical shafts to the surface, and so the depth of this tunnel type for metro lines is limited. Only in special cases a parallel emergency exit gallery is constructed. This alternative has been adopted for Metro Line 9 in the areas where surface occupation is not a significant constraint.

3.3 *One tunnel with two tracks at different levels*

Finally, a non-conventional solution involving a single 12 m diameter (113.1 m^2) tunnel has been adopted for most of the line length (Figure 4). Up to four tracks on two different levels can be placed in the tunnel. The station platform can also be incorporated in the tunnel cross section.

In some respects, this solution can be viewed as two 6.3 m diameter tunnels incorporated in a single excavation. However, the solution also shares many features with the 9.5 m diameter tunnel alternative. Again, all geological exploration has to be done in advance of the tunnel and the ground conditions at the face may exhibit less homogeneity. Alignment adjustments are also likely to be somewhat more difficult. The requirement for experienced crews is of course similar to in the previous case. On the other hand, connections between lines are now easier to build.

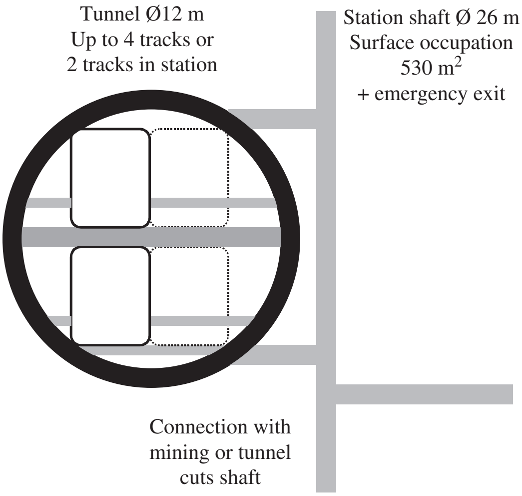

Figure 4. Solution involving a single 12 m diameter tunnel.

The station layout is similar in all cases, the platform is integrated in the tunnel cross-section and shafts are provided for vertical people transport, normally using elevators or mechanical stairs and, for emergency situations, in separated secure staircases. The temporary surface occupation is about 700 m^2 including emergency staircase. The final occupation depends on the final design for surface access. Minimizing the surface occupation in a densely built area was a critical factor for adopting this alternative as the basic construction scheme in most areas.

Emergency exits consist of staircases between different levels. If ventilation shafts are required, they can be equipped with staircases to provide additional emergency exits apart from those provided at the stations.

4 MONITORING SYSTEM

4.1 *Instrumentation*

In addition to the monitoring undertaken by contractors and site inspectors, a comprehensive system of site monitoring for topographical, geotechnical and structural control has been installed independently.

The tasks are divided into various types: topographical (automatic and manual) for surface movements, geotechnical for measurements at depth in the ground, measurements performed from inside the tunnel and general data-management. All the parties involved in the construction (site inspectors, owners, contractors), have access to the data-base and receive automatically-generated alarm messages via the Internet.

The goals of the monitoring programme are several. Firstly, the monitoring is a real-time indicator and analysis tool for building response to tunnelling and other ground works. For this purpose, automatic total stations are mainly used. The measuring frequencies are of the order of 20 to 30 minutes depending on the number of the prisms to be read from the automatic total station and on the magnitude of the displacements of those points. Each cycle of lectures is transmitted by a digital cellular phone system to the central database computer, validated and introduced automatically. If street lighting is sufficient, night observations are possible so that permanent monitoring can be achieved. Automatic topographic control is complemented by manual topographic readings, performed normally on a 12 or 24 h schedule, with higher frequencies whenever necessary.

A second goal of the monitoring refers to the control of excavation parameters and observational method for the excavation of shafts in soils. For this purpose there are topographical and geotechnical measurements, using extensometers, inclinometers and piezometers. Some of the boreholes drilled for the installation of geotechnical instruments are also used for geological and geotechnical exploration including the performance of "in situ" testing and sample retrieval for laboratory testing.

A third aim of the monitoring system is to check the effects of tunnelling on the groundwater regime, both in the short and in the long term. There are a number of zones where the possible effects of the tunnel construction on hydrogeological conditions are very strictly controlled and imply a very significant constraint. An independent monitoring system involving arrays of piezometers of different kinds has been installed for this purpose.

4.2 *Research and development*

Finally another monitoring goal is to provide the necessary data for research and development tasks. To this end, a number of sections have been instrumented more intensely with additional topographical surface points, extensometers, inclinometers and piezometers. Critical and unusual sections have been selected for this purpose.

Indeed, the public agency GISA, responsible for the construction of L9, recognises the importance and opportunity to increase knowledge of ground engineering in general and of shield tunnelling in particular, based on the experience gathered in this project. The different geometrical conditions and various geological and geotechnical settings are deemed worth a detailed analysis that should be useful in subsequent underground constructions of this project and others. The systematic monitoring in dense urban areas and in some possible "green fields" should increase the knowledge of ground conditions, tunnelling effects and ground-structure interaction.

GISA has founded the Underground Research and Development Unit (URD-L9) as an office independent from the general management of L9 construction. The duties of this office are to coordinate the monitoring programme, maintain the data acquisition and analysis and perform numerical simulations of critical and interesting sections. With the experience gained from back-analysis of instrumented sections, it is expected to predict more reliably ground subsidence and subsequent effects on buildings and, hence, to optimise future protective measures. Following successful precedents (Burland et al., 2001), the results should be of use, in the long term, for future tunnelling projects in Barcelona and elsewhere.

5 EXCAVATION PERFORMANCE

At present two 12 m diameter tunnelling machines are operating, one is a pure EPB machine (Figure 5) whereas the other is a dual EPB/TBM machine that can accommodate both open face and closed face tunnelling (Borràs et al., 2003 a). The first one will work in the zones where soils (soft and stiff) predominate whereas the other will be devoted to the more rocky sections of the layout.

5.1 *EPB Gorg Section (Badalona – Besòs Junction – Sagrera)*

Tunnelling began in September 2003, excavating in the Miocene conglomerate for about 900 m. Afterwards there was a stretch of 100 m of granite before the machine arrived at the junction shaft close to the Besós river. The cover/diameter (C/D) ratios were in the range of 1.5 to 5. The geological conditions ensure that the tunnel face in this first part of the line is completely stable and no significant excavation difficulties arose. The high stiffness of the overconsolidated clay conglomerate and large excavation depth reduced the surface settlements to very low values without generating any damages in the overlying buildings. As Table 1 shows, the volume loss derived from surface settlements is in the range of 0.0% to 0.2%.

In July 2004 the advance continued through the quaternary deltaic deposits of the Besòs river. Here the ground cover is only 0.6 to 1 diameter. Initially, the materials encountered at the face were, from top to bottom: medium sands with gravels and silt, silts with organic content and gravels. This soil profile provided sufficient fines for the correct operation of the EPB machine. However, when the fine fraction decreased and gravel predominated, performance difficulties were encountered that led to a long stoppage of the EPB machine in September 2004. The volume loss naturally increased in this material, to values ranging from 0.4% to 0.9% (Table 1).

Figure 5. 12 m diameter EPB machine.

Table 1. Observed Volume Loss based on surface measurements*.

Material	Volume loss V_s (%)
EPB machine	
Miocene conglomerate	0.0–0.2
Besòs river alluvium	0.4–0.9
Dual TBM-EPB machine	
Granite (open mode)	0.0–0.2
Mixed face Granite/Residual soil**	0.1–0.5

* The sections with protective measures (jet grouted, columns, compensation grouting) are not considered to compute the values in this Table.
** Includes drainage effects.

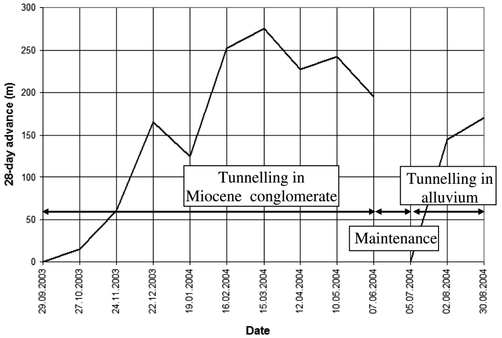

Figure 6. Tunnel advances of the EPB machine.

Figure 6 shows the evolution of the tunnel advances over time. The best weekly advance (7 days) has been 107 m and the best monthly advance (28 days) 316 m, lower than expected.

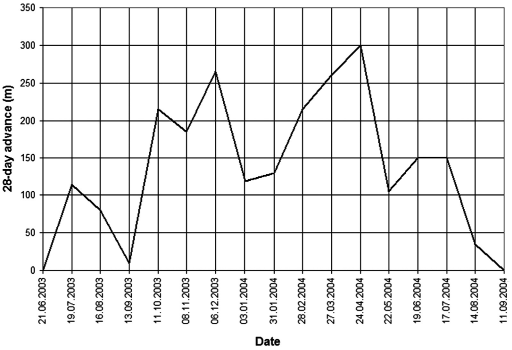

Figure 7. Tunnel advances of the dual rock TBM – EPB machine.

5.2 *Dual EPB – TBM Can Zam Section (Santa Coloma – Besòs Junction)*

The tunnelling section Can Zam – Besòs Junction begins in the area of the Can Zam park. The Can Zam station and the workshops for rolling stock maintenance were built using cut and cover method. Proper tunnelling started in July 2003 in a cavity previously excavated in hard rock.

The geological conditions of the tunnel face in this section are mainly granitic hard rock. However, there are a number of faults where highly fractured rock, weathered granite and even residual soils are encountered in part of the tunnel cross-section, implying a mixed face. In fractured rock conditions, it proved necessary to reduce the size of the openings in the cutting wheel (consequence of being a convertible rock TBM – EPB machine) because large blocks (up to 80 cm long) were entering the excavation chamber. This was achieved by inserting steel sections across the openings.

The main difficulties encountered corresponded to the crossing of two faults. At the end of 2003 the tunnel had to cross a fault zone below a city motorway and in summer 2004 another fault zone in the Fondo district was also crossed.

In the first case the tunnel elevation was lowered slightly to ensure that the tunnel face always was in rock, with a minimum of a 2 m fractured rock cover above the shield, avoiding in this way intercepting residual soil.

In the second case more than one third of the tunnel face was in intensely weathered granite, so that in this case mixed face excavation conditions were encountered. Because of the large piezometric head (more than 20 m above the tunnel crown), special measures were adopted: the machine was turned to EPB operation, ground water level was lowered and microcement grouting above the tunnel was performed.

As Table 1 shows the volume loss is very small when boring through granite but it increases when mixed face conditions are met. However, it should be pointed out that the larger volume loss values include the effects of water table lowering on settlements.

Figure 7 shows the pattern of tunnel advances with time as excavation progresses. The best weekly advance (7 days) is 110 m; the best monthly advance (28 days) is 356 m, again lower than initially expected. Advances increased when alignment was straight and in good rock conditions. It reduced very significantly when crossing fault zones and in curved sections.

6 CONCLUDING REMARKS

The development of a new Metro project in Barcelona involves the construction of 47 km of new lines, most of them underground. As the alignment crosses mainly dense urban areas, the design has tried to minimize surface occupation as much as possible. This has led to the use of large diameter tunnels able to accommodate both tracks and platforms inside the same underground opening. Two tunnelling machines: a 12 m diameter EPB and a 12 m diameter dual rock TBM – EPB are being used at present in the project. Their performance in the early stages of the project has been discussed.

A comprehensive system of site monitoring for topographical, geotechnical and structural control has been implemented as an integrated part of the project. An independent Research and Development unit has been set up to exploit the data gathered and the general experience to be gained in the project and make it available for future works.

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