Metrosur

Second Edition

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Commuting in the 21st Century

a tunnelbuilder reference edition

PROJECT METRO SUR MADRID

High Pressure for the Metro Sur.

Madrid is extending its underground railway system. A Herrenknecht EPB machine (Ø 9.33m) was advancing a 6.45km long tunnel in soil with a high plaster content, as well as clay and siltstone. In order to master the compact geological conditions optimally, the EPB-Shield has been equiped with special performance features. 12 high pressure nozzles on the cutting wheel inject water at 300bar into the tunnel face. Torque of 20,236kNm provides the power to effectively excavate the soil.

Best weekly performances of up to 187.5m are evidence of the efficiency of this design. In this project Herrenknecht had a total of three machines in deployment.

Herrenknecht. Drilling for progress.

View of the screw conveyor

Cutterhead with installed performance of 2,800kW

Contractor:
Ferrovial-Agroman S.A.

Machine data:
EPB-Shield, Ø 9,33m
Cutterhead power 2,800kW
Tunnel length: 6,840m

Geological conditions:
crystallised plaster with clay and siltstone

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Tunnelling Systems

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Introduction

Madrid Metro and Railway Infrastructure 1995-2003

The Madrid Metro Extension designed and built during the period 1995-99 comprised a total of 56 km of new railway lines, of which 38 km were in tunnel, together with 37 new stations and 4 interchange stations with the commuter train system. The project started in August, 1995 and was completed in March, 1999 at an overall cost of €28.2 million/km. The unit final cost of the 38 km-long underground section was €41.3 million/km, which included the new rolling stock.

The correct application of soil mechanics was the most important element of the project, and the best geotechnical expertise in the country was retained and employed. No financial restriction was imposed on soil investigation, monitoring and ground treatment.

The 1999-2003 metro extensions described in this edition involved a total 75 km of railway lines, with 58 km in tunnel, and 39 stations. Once again, they have been built within the allotted time span, without compromise on safety or dramatic cost increase.

Extensions to Madrid Metro 1995-2003.

Balance of Costs

Some tunnelling experts were advising in 1995/1996 that open face methods such as NATM, SCL or Precutting were both faster and cheaper than small section methods, such as the traditional Madrid Method. Even contractors were not recommending the use of TBMs, maintaining that methods such as NATM were cheaper and faster than EPB machines for tunnel

Metres Built by EPB Machines 1999-2003

	Start	End	Days	Metres	M/day	Rings	Stations Crossed	M Total	M/month
HK Paloma, Line 8 Airport	04-sep-00	24-jun-01	293	3,357	11.5	2,238		3,357	355
HK Paloma, Fuenlabrada	19-sep-01	03-apr-02	197	2,840	14.4	1,893	3	2,841	447
HK Almudena, Alcorcón	26-oct-00	19-feb-02	481	7,439	15.5	4,959	5	7,440	479
HK Mares del Sur, Getafe	21-oct-00	02-mar-02	499	6,467	13.0	4,311	6	6,467	402
NFM Chata, Leganés	06-oct-00	21-sep-01	350	6,282	17.9	4,188	6	6,282	556
NFM Adelantada, Linea 10	02-nov-00	23-mar-01	141	2,760	19.6	1,840		2,760	607
NFM Adelantada, Móstoles	05-jun-01	10-dec-01	188	3,963	21.1	2,642	4	3,963	653
Lovat, Cuatro Vientos	20-oct-00	26-nov-01	402	6,089	15.1	5,074		6,089	470
Total metres tunnel EPB				**39,195**				**39,198**	

Starting date	**04-sep-00**
End date	**03-apr-02**
Working days	**576**
Metres built	**39,195**
M/day, global	**68**
M/month, global	**2,109**

construction. This was because of long delivery times on this specialist equipment, and problems at the time with TBM projects such as Storebaelt in Denmark, and Pinglin in Taiwan.

It was clear that they were not prepared to invest the necessary capital in TBMs, if it could be avoided. For the Client, it was clear from the beginning that, if a collapse were to occur using a supposedly faster and cheaper method, more than 4 or 5 months might be lost, resulting in huge economical and political penalties. The cost of recovering the collapse would, no doubt, exceed the additional costs of the supposedly more expensive method, as had occurred at the Heathrow Express project. It was also thought that the recovery time might well match the delivery time of the EPB machines.

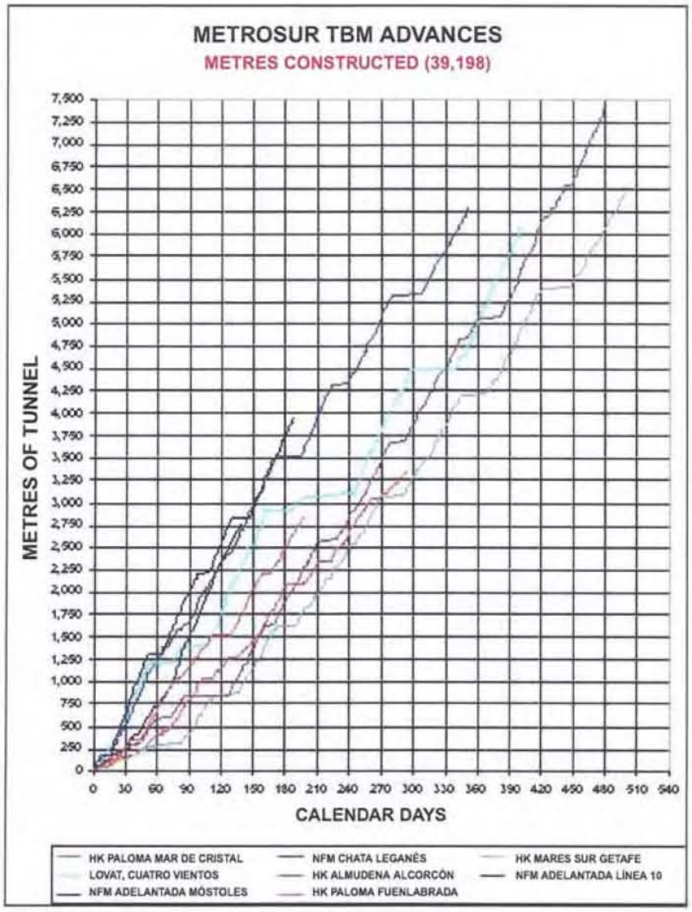
Construction Priorities

The priorities applied to the construction methods were: maximum safety for the workers inside the tunnel; maximum safety for the buildings and other surface structures above the tunnel; minimum exposure of open faces, at every stage of tunnel construction; and no cost or timing factors to take precedence over tunnel safety and quality.

Other matters decided at the start of the project were as follows:

No tunnelling project, including this 38 km soft ground tunnelling construction, should be contracted under a fixed lump sum contract. It was, and still is, the author's opinion that it is scientifically impossible for any Client to provide complete geotechnical information. Even with the use of a pilot tunnel, geotechnical conditions can vary so substantially as to make the contract invalid and useless, as has occurred elsewhere. If any problem does appear, litigation or arbitration is likely, and a huge amount of time and money can be wasted in this process. According to Spanish law, it was decided that the contracts would be fixed price, but with a bill of quantities, so that any additional work could be easily priced, and agreed promptly with the contractors.

The selection of the contractors was undertaken with the greatest care, and included consideration of the soft ground tunnelling experience of the engineers and technicians proposed for the works. Of especial importance was the selection of the person to be in charge of tunnel construction. A well-executed tunnelling project is a work of art, and the Client was prepared to spend the necessary time in choosing the artist. In the evaluation of the tenders, cost consideration amounted only to 30% of the evaluation. Some 20% was allocated to the evaluation of project time, and the remaining 50% was allocated after an evaluation of the technical merits of the proposals, and of staff considerations.



Metres built by EPB machines 1999-2003.

Disputes Avoidance

A system was needed to enable the Client to: foresee problems during tunnelling activities; make a timely study of the most appropriate solution; and agree the solution economically with the contractor concerned. The objective was to avoid disputes, and to always reach agreements before the problems become unmanageable.

No large firm of consulting engineers was hired as general project managers. It is the author's opinion that experience in other cities and countries has shown that such an approach does not actually produce savings in time and cost. The project management of the civil engineering and architectural elements was carried out by just three Chief Engineers, and six further engineers, all of whom were direct employees of the Madrid Regional Government. Electrical and mechanical installations have been carried out by this group, together with other Madrid Metro staff. Profs J M

Monthly Production EPB Machines 1999-2003

Production	TBM TOTAL	Herrenknecht Paloma L8 Airport	Herrenknecht Almudena Alcorcón	Herrenknecht Mares Sur Getafe	NFM Chata Leganés	NFM Adelantada Line 10	Lovat Cuatro Vientos	NFM Adelantada Móstoles	Herrenknecht Paloma Fuenlabrada
Sep-00	165	165							
Oct-00	1,033	236	62	47	471		218		
Nov-00	2,549	381	240	156	750	258	764		
Dec-00	2,000	363	314	119	452	494	260		
Jan-01	2,574	344	234	380	665	786	167		
Feb-01	3,225	560	212	345	588	761	761		
Mar-01	3,000	276	516	420	600	462	726		
Apr-01	1,610	327	488	252	410		134		
May-01	1,903	426	513	512	401		52		
Jun-01	2,765	281	422	491	719		329	525	
Jul-01	2,869		674	365	275		775	782	
Aug-01	2,419		444	486	528		316	645	
Sep-01	2,490		638	635	426		157	528	107
Oct-01	2,072		323	176			896	434	245
Nov-01	3,236		542	723			533	816	623
Dec-01	1,640		690	294				234	422
Jan-02	1,449		683	485					282
Feb-02	1,554		449	575					531
Mar-02	608			11					597
Apr-02	35								35
Total metres	39,195	3,357	7,439	6,467	6,282	2,760	6,089	3,963	2,840
Calendar days	2,170	294	481	499	352	141	403	188	188
Average m/day	18.1	11.4	15.5	13.0	17.8	19.6	15.1	21.1	15.1
Average m/mth	354	479	402	553	607	468	653	468	

Rodriguez and C Oteo were the geotechnical experts on site. Each one of the fourteen separate civils contracts had another two contracts involving specialist consultants, one for technical assistance, and the other for quality control.

EPB Specification

EPB machine specification was undertaken by the author, in conjunction with EPB manufacturers and suppliers, and the contractors' specialist staff. As a result, the five 9.4 m-diameter EPB machines that were ordered had the maximum power-to-diameter ratio found anywhere. Whereas others had decided that a maximum thrust of 6,000 t was appropriate, we increased this figure to 10,000 t, so that at shallow depths we could confidently overcome the passive pressure of soil, and the soil/shield adhesion. The recommended torque of 1,600 mt was increased to 2,000 mt in order to sustain the sticky soil on site, up to a liquid limit of $w_L = 150\%$. These parameters, together with excellent design work by Herrenknecht, NFM, Mitsubishi and Lovat have been, along with other matters, the reason that the machines have succeeded so well in their job.

Designer Exclusion

Finally, the serious issue of the interference between the designer and the construction works was considered. The designer of each contract was never allowed to interfere with the construction of that contract. Experience has shown that a tunnelling project is always essentially incomplete. All tunnelling projects have a great number of errors and shortcomings, the most important being the lack of soil data, water data, geological and geotechnical information. It is common for the average distance between exploratory boreholes to be 50 m to 100 m or more, so that, for long lengths of tunnel driving, there is no information whatsoever about the soil and its condition. Protection needed in buildings and structures is not accurately known until well into the construction process, and the same applies to the eventual need of soil improvement measures, or other type of actions, such as compensation grouting, that have been widely and extensively used in the project. Accordingly, it was decided from the beginning that the design of a tunnelling contract was, at best, only an approximation to the works actually needed. If the designer was allowed to participate in the works, he would always try to defend his work, his ideas, or his construction methods, leading to errors and inaccuracies.

1999-2003 Extension

After the successful completion of the 1995-99 project, another, even bigger, project was agreed by the Regional

Government of Madrid for the period 1999-2003. A grand total of 75 km of railway lines, 58 km in tunnel, together with 39 stations and 8 interchange stations were to be planned, designed, built and commissioned in the period, together with the rolling stock needed. This feat has now been completed, with a final unit cost, including rolling stock, of €42.1 million/km. This figure includes three new depots and an electrical substation, items that were not needed for the 1995-1999 extension.

Works started in August, 1999 and were finalized and commissioned in March, 2003, as described in this issue.

The same management principles have been applied to this latest project: absolute prohibition of the use of NATM, ADECO, Precutting or any other open face method in tunnels; no external project manager; and a very small group of experienced engineers driving the works, more like close friends and colleagues, than people under a rigid hierarchical organization. The results have been good, although the author believes that the project could have been finished six months earlier, had some of the tunnels been built by EPB instead of by manual methods. However, at the time of deciding the construction methods, smaller rates of advance were expected, compared to those actually returned by the TBMs. Moreover, there were several serious geotechnical problems, due to the difficult ground conditions pertaining in Madrid and the gypseous zones of the southeast.

Madrid Metro Railway Infrastructure 1999-2003

	Total km	New Stations	Interchanges with RENFE
Underground RENFE Getafe	3.10	1	1
Underground Line 9 Connection	1.51	0	0
Line 8 N.Ministerios – Mar de Cristal	5.90	2	1
Amplification Line 10	1.93	2	0
Line 10/1 Ext Colonia Jardin-C. Vientos	3.00	2	1
Line 10/2 Ext Cuatro Vientos-Alcorcon	3.29	1	0
Metrosur			
Contract 1 – Alcorcon	9.65	5	1
Contract 2 – Mostoles	5.99	5	1
Contract 2 – Section 3B-I	1.32	0	0
Contract 3 – Various	2.69	1	0
Contract 4 – Fuenlabrada	6.51	4	1
Contract 5 – Getafe	7.35	8	1
Contract 6 – Leganes	6.99	6	1
Subtotal Metrosur	40.51	29	5
Workshops			
Loranca			
Cuatro Vientos			
El Bercial			
Cercanias to San Martin de la Vega	15.50	2	
TOTAL 1999-2003	74.74	39	8

Ground Monitoring

The greater part of the tunnelling works were carried out by six EPB machines, three of which were manufactured by Herrenknecht, two by NFM-Mitsubishi, and one by Lovat. The remaining tunnels were constructed using the traditional Madrid Method, or cut and cover with diaphragm walls.

More than 8,000 control points were installed to monitor the tunnelling works, as follows.

Subsidence: 5,400 sensors installed. Structure movement detection: 317 buildings monitored. Soil pressure in tunnel linings: 52 instrumented sections. Diaphragm wall movement: 65 sections instrumented. Soil data: 410 drilled samples with 12,000 m total and 43,750 soil samples analyzed. EPB data: 384 variables per minute.

Construction Methods

It was difficult to decide the construction method to use in each of the tunnelling contracts.

As said before, the output of the EPB machines was higher than foreseen, and some of the parts built by traditional method, or in open cut, could have been done by EPB, such as the southern part of Line 10 to Alcorcón. However, at the time of the decisions, it was thought that the final completion date would be jeopardized.

Not a single accident occurred during the underground works. Safety was the top priority of the whole project.

Conclusions

The project demonstrates once again, in the author's opinion, the following facts:

EPB tunnels in soft ground are less expensive than open face tunnel construction such as NATM, SCL, ADECO or Precutting methods.

EPB tunnels in soft ground are much safer and faster than open face tunnel construction methods.

The Madrid Method of tunnelling in difficult ground is less expensive, and safer, than open face methods such as NATM, SCL or Precutting.

Consulting or other companies were not needed as Project Managers for Madrid Metro Extensions, which ran on time and on budget without such assistance.

It is wrong to contract tunnel construction on a fixed price lump-sum basis. It will not work.

The designer of an important tunnel should never be allowed to interfere in its construction.

Architecture of stations should not be confused with that for a museum or an

Cost of the overall project

Madrid Metro Infrastructure 1999-2003 Contract	Total Cost €
Getafe Underground	78,646,362
Line 9 Underground Connection	41,570,414
Line 8 N.Ministerios-Mar de Cristal	314,186,065
Line 10 Enlargement (*)	197,627,523
Line 10/1Ext. C Jardin-Cuatro Vientos	130,619,197
Line 10/2 Ext. Cuatro Vientos-Alcorcon	130,262,051
Line 10 Electromechanical Installation	38,950,018
Metrosur	
Contract 1 – Alcorcon	331,769,444
Contract 2 - Mostoles	273,263,293
Contract 2 – Section 3B-I	
Contract 3 – Various	91,560,398
Contract 4 – Fuenlabrada	238,812,414
Contract 5 – Getafe	277,934,100
Contract 6 – Leganes	268,974,716
Electromechanical Installation	75,216,724
Subtotal Metrosur	1,557,531,089
Workshops	
Loranca	51,610,214
Cuatro Vientos	95,741,424
El Bercial	11,087,779
Cercanias to San Martin de la Vega	87,815,759
Civil, Architectural and Installations	**Total 2,735,647,895**

Rolling Stock

	Total Cost €
Trains 8000 Line 8, 10 trains 3 cars	36,388,278
Trains 8000 Metrosur, 37 trains 3 cars	133,853,209
Trains 7000 Line 10, 30 trains 6 cars	194,929,862
Series 6000, 22 cars	17,771,928
Systems ATP- ATO 8000 Line 8	2,692,534
Systems ATP- ATO 8000 Line Metrosur	6,875,578
Systems ATP- ATO 7000 Line 10	4,315,267
Driving Simulators	4,056,832
Auxiliary vehicles	9,285,637
Total Rolling Stock	**410,169,125**

emblematic building for the city. Several million people will move each day across the stations of the metro network, and the design must emphasize this fact, giving easy and simple movements to the users from the street to the trains, wide escalators and corridors, and shallow stations and platforms.

Design should be focused on the needs of the users, rather than on architectural beauty or exotic materials, and never on the name of the architect. Errors of this type have been common lately in Spain, especially on the new high-speed railway lines.

Time is extremely important in transportation projects. Every year after the first extension of Madrid Metro was commissioned, 170 million new users entered into the system, with an overall time saving of 23 million hours in the Madrid region. Social savings can easily be estimated, at an hourly value of about €12, the average cost of employment. This gives a yearly social saving in Madrid of about €275 million, not including other social benefits such as reduced traffic congestion, air pollution or noise in the city centre.

Transport infrastructure, be it railways, underground metros or highways, are lineal projects. They can be easily divided into manageable parts. All parts can then be designed simultaneously, taking around eight months for the entire process. All construction contracts can similarly be awarded simultaneously, and any manageable contract of, say, €150 million, can be built in 36 months. Even enormous tunnelling projects such as the Channel Tunnel have been excavated in 36 months, and the land facilities could have been finished simultaneously. Although this theory is probably not applicable to other types of civil engineering projects, such as a big dam, or a long and complex suspension bridge, the conclusion follows that any lineal project, such as a Metro, can be designed and built in 40 to 45 months, provided funds are available. Madrid Metro has demonstrated this twice in succession.

The reasons for delays, or cost overruns, are explained in great detail, usually by politicians in charge of failed projects.

We engineers are not here to explain why our project has failed in meeting the completion date. The author believes that we are here to meet our dates and our costs. If we have to explain why we have failed, we should leave engineering management, and shift our activities to other fields where we might find more appreciation, say in opera composing or ballet dancing.

Several colleagues from other cities involved in similar works, in asking us about the details of the management of our projects, were particularly impressed when they heard that all decisions by the top politicians with responsibility for the project, President Alberto Ruiz-Gallardón of the Regional Government of Madrid, and Sr Luis Eduardo Cortes, his Regional Minister for Public Works, were taken within 24 hours. In most other cities, similar decisions might take several months. It is therefore correct to say that, the undoubted success of the Madrid Metro Extension Project was due to both the close and supportive relationship provided by those with political responsibility, and the careful consideration and implementation of engineering principles and practices.

Manuel Melis Maynar, Madrid, April 2003

Contract 1
Sections XI, XII and 1A

Contractor: ACS VÍAS

From Leganés to Alcorcón and Móstoles

The Public Works Council of the Madrid Local Government awarded Metrosur construction Contract 1 to a joint venture of ACS and Vías y Construcciones. The initial contract budget was €226,314,208, with a 30 months completion deadline, beginning May 23rd, 2000.

At 9,637 m-long, the contract section is the longest, and has the biggest budget, of the whole Metrosur project. It represents 23.6% of the total alignment, and includes the construction of 642 m of tunnel as part of Metro Line 10. The contract comprises civil works, railway superstructure and stations in the towns of Leganés, Alcorcón and Móstoles, but is mainly focused on the works around Alcorcón. Here, four of the five contract stations are located, and the project will cover the transport demands of 50% of the population of around 150,000 inhabitants. The fifth station is in the neighbouring town of Leganés.

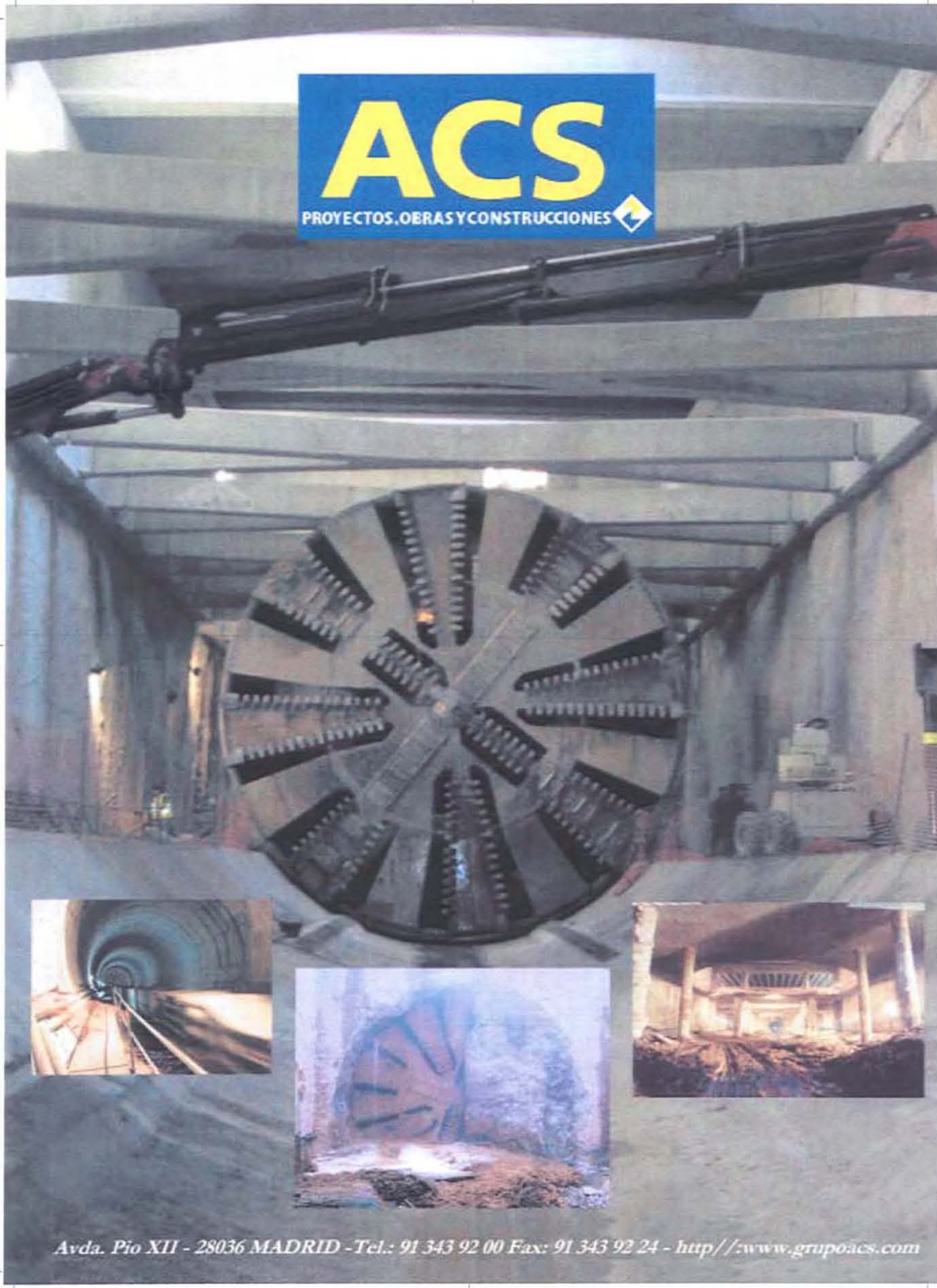
ACS was involved in the earlier Madrid Metro Line 9 extension, between Pavones and Puerta de Arganda, and is using the same 9.38 m-diameter Herrenknecht EPB TBM at Metrosur. This has been a great advantage to the present joint venture, not only for production planning, but also for the availability of experienced, skilled personnel, for both operations and maintenance.

Project Description

The first length of tunnel begins in San Nicasio station, and ends in the first drive shaft for the EPB TBM at metreage 1,408 m (PK 1+408). Being located outside the urban area, this shaft has been excavated and constructed by the cut and cover, between reinforced concrete diaphragm walls. The rest of the tunnel, having a circular section of 8.43 m i.d., has been excavated by EPB TBM, up to sector's end at metreage 9,646 m (PK 9+646). Of the five stations, one connects with Metro Line 10 at Puerta del Sur, and another provides an interchange with the RENFE suburban train network at Alcorcón Central.

The station structure generally consists of a diaphragm wall enclosure, excavated down to platform level, and covered by concrete beams and slabs. The exception is the Parque Lisboa station, which is covered by a post-stressed flagstone, allowing the hall's mezzanine to hang from it. It is also different in being cross-shaped with two levels, with the lower one for Metrosur, and an access difference in level from surface to station platforms of 20 m.

TBM transit through station box.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Design Constraints

The tunnel layout was designed so that, even when using an EPB machine, execution problems are mitigated whilst catering for potential demand. To achieve this, all the stations are constructed by cut and cover, and most of the tunnel passes through areas being considered for further urban development. Nevertheless, the layout is conditioned by several constraints, of which the following are the most significant: reduce the depth of the stations, generally to 15-17 m, while allowing the EPB machine to pass under the intermediary concourse hall; interchange with the RENFE suburban railway network; give service to the universities Rey Juan Carlos and Carlos III universities, and Alcorcón hospital; and connect with Madrid Metro Line 10.

Estimating Subsidence

Following the layout design, a detailed subsidence study was carried out to determine surface effects. This could lead to new modifications, both in layout and/or longitudinal profile.

A semi-empirical method was used, known as the 'Madrid Model' (Oteo et al, 1999). This was developed according to experience in metro tunnelling in Madrid-specific soil conditions. It compares the settlement law to a Gauss bell-shaped curve, adjusted for different i and V values, where i and V are the distance between the tunnel axis of symmetry and the inflexion point of the Gauss curve, and the settlement volume, respectively, based on Madrid practice. The Madrid Model recommends the use of graphics obtained on the basis of a large amount of direct measurements. Given the tunnel's depth and the relative thickness of Tertiary soils and non-consolidated or Quaternary soils above the tunnel's crown, one can estimate the settlement volume.

The measured settlements are verified by means of a finite differences analysis using the FLAC programme. La Coruña University carried out the numerical analysis in this case. Estimated and measured settlements were compared, leading to the conclusion that, generally, the estimations were rather pessimistic.

The high settlement values observed at metreage 8,300 m (PK 8+300) are consequent from an existing collector sewer, possibly previously broken, which caused erosion of the soil.

Tunnelling

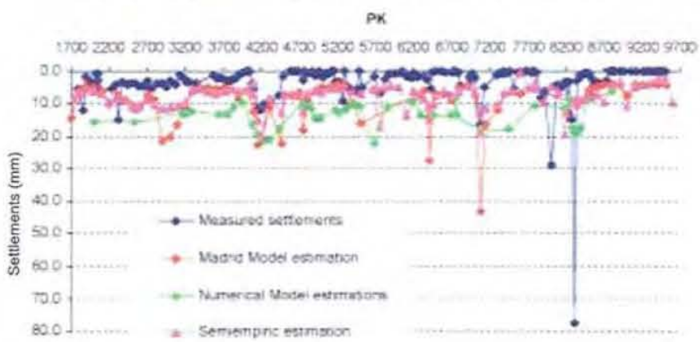
Up to this point, the main analysis and studies performed during the early stages of the project were generally utilized. The following focuses on the main contingencies occurring during tunnel excavation with the EPB machine.

Of the tunnel's 9.6 km length forming Contract 1, about 7.9 km were executed using Herrenknecht EPB La Almudena. This machine had already excavated a 3,500 m-long tunnel for Line 9 during the 1995-1999 Madrid Metro extension programme.

The EPB was launched from a shaft 247 m-long and 15 m-deep, located next to the concrete segment casting plant. The shaft's length was sufficient to allow the whole machine to be launched at once, including the complete back up.

Excavation began on October 26th, 2000. Given the considerable soil cover of about 20 m, and its geotechnical characteristics of a first layer 4–5m thick of alluvium and thicker Tertiary clays with sand intercalations, the Contractor was authorized to begin excavation in open mode, using

PK VS. MEASURED AND ESTIMATED MAXIMUM SETTLEMENTS



Measured and estimated maximum settlements.

Applying the waterproofing layer to the external roof of the cut and cover tunnel.

skips and conveyors for spoil removal. Despite the conditions, the excavation began with several difficulties, including ground collapses, which appeared at the surface. Therefore, it was decided to excavate in closed mode from metreage 1,890 m (PK 1+890), with earth pressure values of 0.5-1.0 bar at the upper pressure cell of the cutting head. Faced with the necessity to cross under the heavily-trafficked M-406 highway, and given the voids detected behind the machine, it was decided to carry out soil treatment by cement grout injection. This ensured that the crossing under the highway could proceed without any danger of further void development.

Working the EPB in closed mode slowed excavation progress to only one or two rings per day, and problems were experienced with overheating of the cutting head, excavated material and hydraulics cooling system.

Under the circumstances, the Contractor crossed under the M-406 highway by alternate deviations of highway lanes. This made it possible, by means of boreholes on a planned pattern, to detect any voids above the tunnel crown, and fill them with liquid cement mortar. This was successful, but the excavation problems remained.

Cutter Erosion

Scheduled advance rates of about 80 mm/min were achieved by varying the polymer and foam ratios in the water injected to the face and inside the EPB pressure chamber and, especially, by adding two new water supply lines to the pressure chamber, with a maximum flow rate of 30 lit/sec each. The resulting advance rates were finally brought close to the machine's design parameters.

Repairing TBM cutting head at PK2 +589 shaft.

Cement injection on highway M-406.

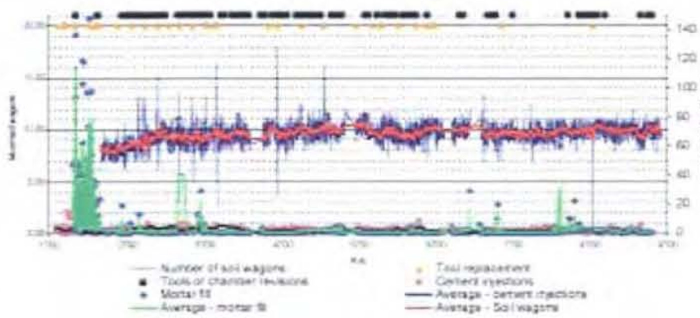
The soil type caused rapid erosion and serious damage to the TBM cutting tools, and it was found necessary to replace a great proportion of them at 150 m intervals. At each such stop, the pressure chamber was emptied, with the consequent pressure loss at the face. Direct observations showed clearly that the pressure reduction prompted soil collapses in front and above the TBM cutting head. These developed along the machine's direction of advance, and mortar injection performed from the machine couldn't successfully fill them. As the tunnel route lay along urban communication axes, it was decided to track the TBM from the surface, with one or two drillrigs, in order to detect voids and fill them up with cement mortar grout.

When cutter inspection and replacement had to be done in sandy soils, the work conditions were considered unsafe for the operating personnel. Therefore, it was decided to always stop in predetermined locations, which had been equipped with retaining walls of mortar piles. In this way, replacement could be made under safe conditions.

In spite of all the precautions, the inspection carried out at metreage 2,589 m (PK 2+589) revealed very serious damage to the cutting wheel. Access to the cutting wheel was achieved through a special shaft excavated within a reinforced concrete pile and jet-grouted enclosure that allowed partial exposure of the cutting wheel for welding. These operations caused a delay of about two months, and necessitated traffic deviation at the surface.

As a consequence of these latest experiences and in order to avoid similar incidents, it was decided to adopt several systematic measures, as described below.

PK VS. EXCAVATED MATERIAL, MORTAR FILL AND CEMENT INJECTION VOLUME WITH REVISION AND TOOL REPLACEMENT POINTS



Volumes of excavation and fill.

Excavation and Grouting

Advances were achieved at normal rates by means of higher water content in the injection mixture, so as to produce spoil close to a fluid state. As before, two new water supply lines were added to the centre of the pressure chamber. The chamber had to be cleaned and clay agglomerations removed each time, so getting the machine through became difficult.

Tools were inspected and changed, if necessary, every 2–3 days, equivalent to 50 metres advance.

Rigorous controls were imposed on the spoil volume excavated.

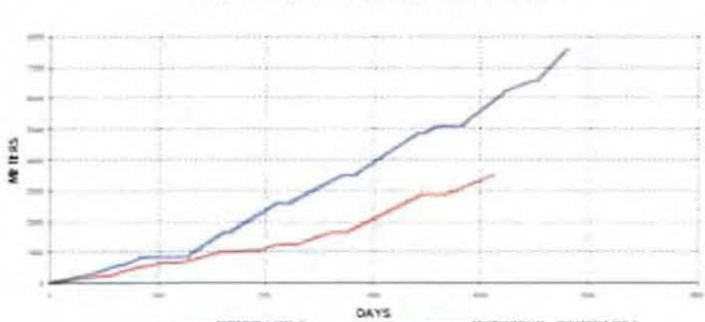
Grouting was better controlled and intensified, including injection at the tail shield.

The Herrenknecht EPB machine has six mortar injection lines, served by two pumps, working at variable pressure between 200 and 600 kPa (2-6 bar). The theoretical mortar volume to be injected at each advance, 6 cu m, was verified for each segment ring.

In order to ensure complete filling of the lining annulus gap, additional injections were carried out from the machine's back-up assembly. At every ten rings, the casing was pierced and cement suspension injected until reaching a pressure of 4 kg/sq cm (3.9 bar). The frequency was increased where surface intervention was not impossible. Beginning with the zones where initial collapses appeared, systematic injections were carried out from inside the tunnel.

Comparison of TBM advances on Line 9 and Metrosur.

LINE 9 VS. METROSUR OUTPUTS
TUNNELLING MACHINE "LA ALMUDENA"



Surface Interventions

As the tunnel alignment passed under urban communication axes, a series of surface treatments was also carried out.

Mortar grout injection holes from the surface were always located about 15 m behind the shield face position, every 10 m. The distance between boreholes, and their density, depended on the injected volume. Logically, boreholes had to avoid existing obstacles, so this determined variations of borehole numbers and intervals. When crossing high traffic intensity traffic axes, such as the M-506 highway, traffic diversions had to be arranged, in order to ensure correct ground consolidation without any danger from further significant settlements or collapses. Occasionally, such as when crossing under the RENFE railway line C-5 at metreage 6,200 m (PK 6+200), where it was impossible to apply the above methods, earlier soil treatment was carried out by means of cement suspension injections through small-diameter tubes.

Additional Work

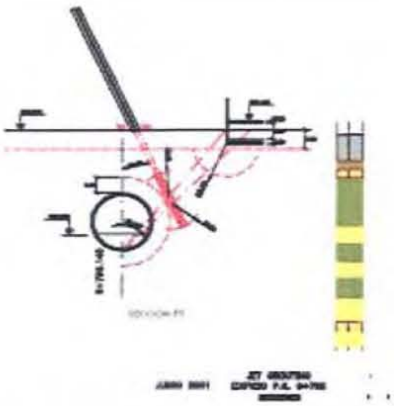
As previously described, the presence of sandy clays or clayey sands made cutting tool replacement dangerous. However, this had to be carried out due to the serious damage produced by the high silica content of Madrid Tertiary sands. Based on latest experience, every 150-175 m a retaining wall made of mortar piles was constructed, in the most accessible

Main Characteristics of Herrenknecht EPB

EPB Parameters	
Excavation diameter	9.36 m
Shield diameter	9.34 m
Shield length	8.21 m
Total length	145.5 m
Total weight	1,350 t
Thrust cylinders (no.)	26
Maximum thrust	10,000 t force
Working torque	17.05 MNm
Release torque	20 MNm

Parameters of Concrete Rings

Inner Diameter	8.43m
Length	1.50m
Thickness	320 mm
Concrete strength	400 kg/sq cm (3.92 MPa)



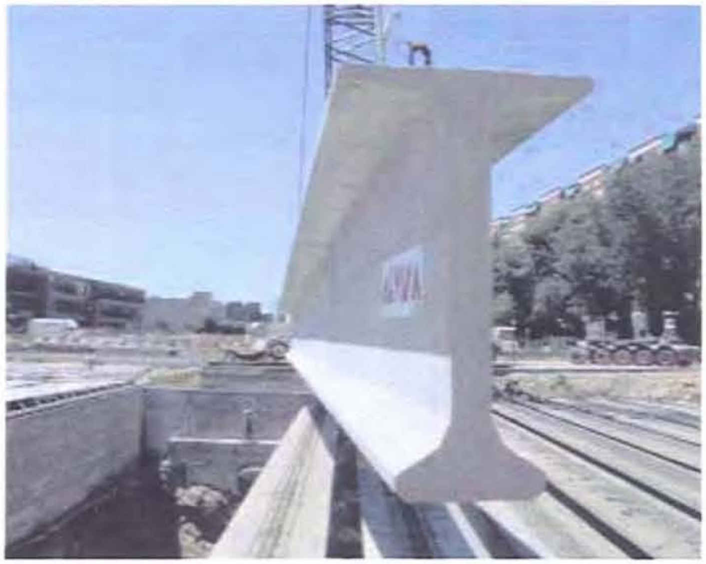
Jet grouting treatment to protect a building.

location, allowing the tunnelling machine to stop within it and tool replacement to be carried out under safely. In some locations, with no direct access, retaining walls were constructed using jet grouting.

In order to avoid the serious damage observed at the machine's cutting wheel, and given the long distances of excavation without passing through stations, two inspection and repair shafts were constructed, designed to allow the inspection of the whole cutting wheel. One shaft was located at metreage 3,375 m (PK 3+375), using some of the diaphragm walls intended for the Puerta del Sur station, through which the EPB machine passed. The other, located at metreage 8,754 m (PK 8+754), used the diaphragm walls of a ventilation shaft under construction. Station breakthroughs were also used for complete machine inspection, improvement and remediation operations.

In addition, it was decided to protect existing buildings, and those under construction near the tunnel corridor, by means of jet-grouting-based soil treatment. Treatments were carried out at metreage 4,970 m (PK 4+970) to protect an existing building, and at metreage 6,795 m (PK 6+795) to protect a new building not included at the project planning stage. Besides the cited interventions, and based on designer's recommendations, other services like gas pipelines, wastewater collectors, or public light towers were also protected.

Alignment variations were also prepared in order to mitigate the subsidence effects. Between Puerta del Sur and Parque Lisboa stations, the tunnel's horizontal alignment is lower than specified in the initial plan. The same measure was adopted in the final tunnel length, beginning at metreage 7,800 m (PK 7+800), where the tunnel is about 7 m deeper, to reduce settlement near an existing building in Fragua Street.



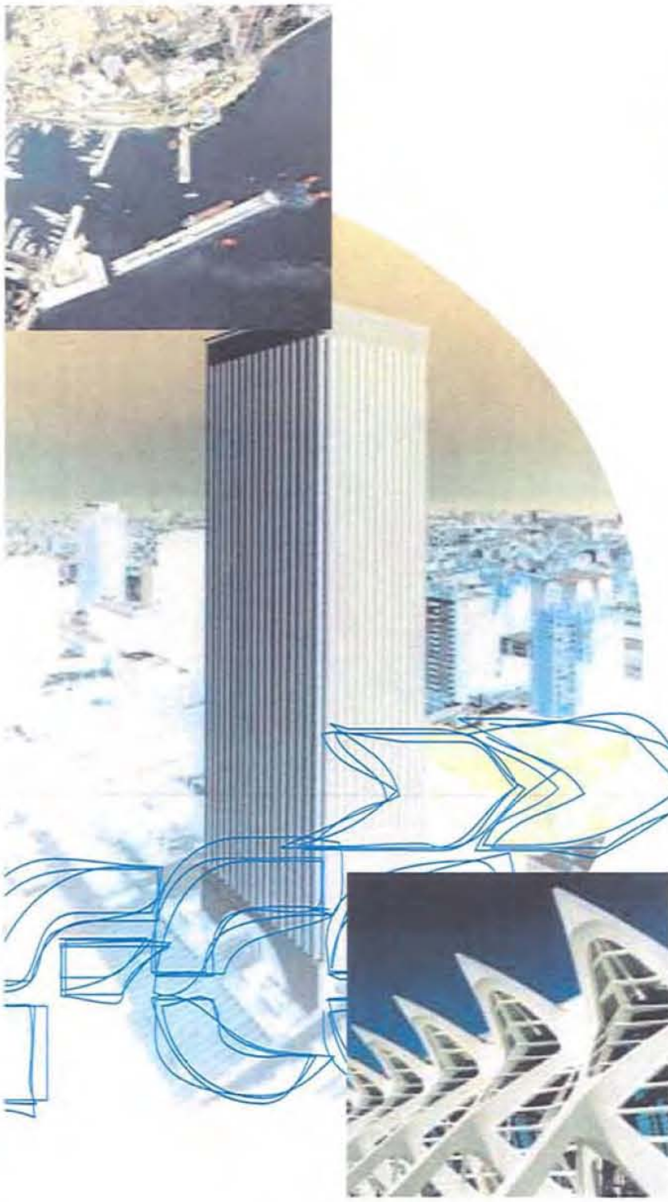
Placing the roof beams at a station.

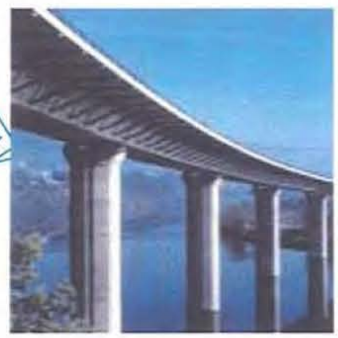
Conclusions

As a consequence of detailed analysis performed at the early project stage, and of decisions made during the construction phase, the goal of excavating 7,900 m of EPB tunnel between October 26th, 2000 and February 18th, 2002 was achieved. The tunnel completion was initially programmed to take place on February 17th. In spite of adverse incidents, the works were satisfactorily completed within the deadline, and without any incidents contrary to operators' safety conditions.

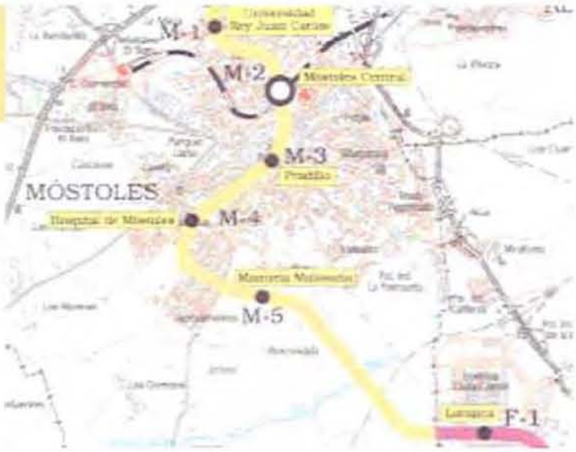
The advance per natural day was 15.4 m, and per working day, 20.4 m. The maximum advance occurred on November 29th, 2001 with 42 m of excavation. The average monthly advance was 309 rings, equivalent to 464 m. These rates were made possible with excavation and segmental ring placing times of about 30 minutes.

Beamed roof and invert slab with mezzanine support pillars at Alcorcón 3 station.





Contract 2 Sections II and III



Contractor: FCC Construccion, SA.

Tunnelling Beneath Urban Móstoles

Metrosur Contract 2 is 7,312 m in length and crosses the municipal districts of Móstoles and Fuenlabrada. Connected to the adjacent section of Contract 3 in Fuenlabrada, it starts at the King Juan Carlos University station portal, and ends adjacent to Loranca station (F1). Construction methods used are EPB TBM tunnelling, and cut-and-cover tunnels, shafts and station construction.

The Department of Public Works awarded Metrosur Contract 2 to the contractor FCC, with an initial budget of €153,666,700 and an execution period of 30 months. Work began on May 23rd, 2000. The objectives of Contract 2 can be summarized as: infrastructure necessary for the railway operation to carry the new 8000 series 6-car trains, including tunnels, stations, ventilation shafts, civil works for the electric power substations, transformer rooms, pumping wells, emergency exits, etc; architecture, decoration, lighting, water connection and drainage for stations; facilities for tunnel lighting and for pumping of drainage water; rail superstructure; and replacement of existing services and traffic diversions.

Apart from the tunnelling, Contract 2 also includes five stations, five tunnel ventilation shafts, four emergency exits and two pumping shafts, as well as a link tunnel to access the new wagon sheds at Loranca.

Geotechnical Data

The line passes through ground belonging to formations typically found in Madrid. Specifically included is detritus located in the project section that comes from the erosion of granite and metamorphic formations of the Sierra de Guadarrama, produced by widespread flooding. These are partially covered by other colluvial materials from the Quaternary Age and by anthropic fills.

Research, together with previously existing data and subsequent analysis by the project office, allowed a distinction to be made between the different materials present in the ground. However, its grouping into defined strata along the route presents greater difficulties, due to the frequent lateral changes of composition that the Miocene presents. In accordance with the soil classifications normally found in

La Adelantada TBM launching at Manuela Malasana station.

Madrid, four different types of materials corresponding to the Tertiary, as well as the Quaternary anthropic fills and alluvial deposits, were identified. The notation and classification criteria used are as follows:

F	Fill
AL	Alluvium
AM	Arena de Miga (fines <25%)
AT	Arena Tosquiza (25% <fines <40%)
TA	Tosco Arenoso (40% < fines <60%)
T	Tosco (fines >60%)

In the project section, sandy layers alternate with clayey layers. Alternations of toscos arenosos with arenas tosquizas are located at the beginning of the section, up to around metreage 2,100 m (KP 2+l00). The toscos prevail between the latter point and metreage 2,800 m (KP 2+800). Arena de Miga strata appear with alternations of arena tosquiza between metreage points 2,800 m and 4,200 m (KP 2+800 & KP 4+200). Between the latter point and metreage 6,200 m (KP6+200), the succession of tosquizo and tosco arenoso layers is predominant. In the final section of the route, the alternation of arenas de miga with arenas tosquizas prevails. Anthropic fills up to 8m-thick have been located at the surface, as well as alluvium up to 5 m-thick. Numerous water tables have been detected lying over more impervious substrata.

Tunnel Construction

The first part of the tunnel, which begins at the King Juan Carlos University Station and finishes at the Manuela Malasaña Station, is 3,959 m-long, and was constructed using a Mitsubishi NFM EPB TBM. The EPB method was considered the safest for both operators and buildings, offering maximum mechanization of both the excavation, and the lining of the space created.

The lining comprises bolted precast concrete segments that form cylindrical rings with an interior diameter of 8.43 m and a thickness of 320 mm. A waterproof material covers the surface of the gaskets.

The thrust of the shield comes from jacks resting on the last-placed lining ring. These machines are capable of compensating the counterthrusts of the earth and any possible water at the working face by creating a pressurized chamber in the spoil collection area, and by the use of various systems such as foams and bentonite muds to compensate for differences of counterthrusts as efficiently as possible. The stability of the working face is achieved by adjusting the speed of soil excavation in the pressurized chamber.

The tunnelling process was as follows:

- Assembly of the TBM in a pit, of length 365 m and depth 16.5 m, between diaphragm walls at the Manuela Malasaña Station. The length of the pit allowed for launching of the complete machine, including back up;
- Creation of a thrust reaction structure, to which the forces from the shield thrust jacks are transmitted until the friction between the installed rings and the ground is sufficient;
- Soil excavation by means of cutters on the shield machine's rotating head. The head transfers the thrust force against the face from the last-placed ring by means of hydraulic jacks, which retract sequentially as the lining segments are placed.
- Grout injection is carried out between the ground and the segment lining ring, and between the last injected section and the back of the shield, where the wire brush seals are located.

The particular Mitsubishi NFM TBM had been used in earlier metro extension work in Madrid, and on the access drive to Alcobendas for RENFE.

Main Features Mitsubishi NFM TBM La Adelantada

Thrust cylinders	26 cylinders with a piston diameter of 320 mm. Total thrust force – 10,000 t; feed rate – 0-80 mm/m
Cutting tools	Cutting wheel with 148 teeth, double 17-inch (432 mm) discs and 2 peripheral cutters
Cutting-wheel drive	Speed – 2.4 rev/min. Torque – 16,000 kNm. Releasing torque – 20,000 kNm. Installed output power – 2,000 kW. Bearing diameter – 4,950 mm.
Electrical installation	Voltage – 15 kV. Installed output power – 3,750 kVA
Guidance system	Leica electronic laser
Spoil removal	Auger screw conveyor with an external diameter of 1,000 mm and capacity of 663 cu m/h. Belt conveyors of 1,200 mm width and a capacity of 1,200 cu m/h
Mortar grout injection system	Four dual-injection pipes between segment and ground (capacity 5.6 cu m/m)

Contract 2 major quantities

TYPE	ELEMENT	UNIT	QUANTITY	TOTAL
Total lengths	EPB tunnelling	M	3,959	
	Cut-and-cover tunnel		2,576	
	Stations		777	**7,312**
Reinforcing steel	Diaphragm walls/piles	kg	5,617,000	
	Tunnel segments		2,618,000	
	Rest of work		12,024,000	**20,259,000**
Excavation	Diaphragm walls/piles	cu m	64,719	
	EPB tunnelling		270,089	
	Open-cut tunnel		932,454	
	Stations between diaphragm walls		301,996	**1,569,258**
Concrete	Diaphragm walls/piles	cu m	64,719	
	Tunnel segments		34,825	
	Rest of concrete		154,127	**253,671**
Rail-track	Rail – 54 kg/in	No	31,328	**31,328**
	Elastic block for 125 t	No	34,928	**34,928**
Station panelling	Vitrex	sq m	4,174	
	Ittalfilm		14,447	**18,621**
Paving for access lobbies and platforms		sq m	21,552	**21,552**

TBM Progress

Boring began on 4th June, 2001 from the launch pit at Manuela Malasaña (M5) station, and the entry portal to King Juan Carlos University (M1) station was reached on 12th December. The tunnelling advance rate was 20.75 m per calendar day. The maximum rate was achieved on 22nd July, 2001 with 49.6 m of excavation, and the average advance was 422 rings/month, which is equivalent to 633 m/month. Excavation was about six weeks ahead of the original work schedule.

The semi-empirical Madrid Model was used to calculate settlement. Starting from the depth of the tunnel and the thickness of the different Tertiary strata at the top of the tunnel, maximum settlement on the tunnel axis and the volume of settling can be calculated. Real settlement obtained was less than that calculated in the Madrid Model.

All along the approximately 3.9 km of tunnel excavated, the TBM worked in closed mode. As a result, only three small cave-ins were experienced, at the entrances of Hospital de Móstoles (M4) and King Juan Carlos University (M1) stations, and at the exit of Móstoles Central (M2) ststion. These were filled from the surface with fluid mortar grout.

Three types of treatment were used to protect the buildings within the settlement zone of the tunnel excavation. Nearby buildings were protected with jet grouting or reinforced micropiles, while compensation grout injection was carried out for buildings located above the tunnel route. In total, five treatments were carried out with jet grouting, five with micropiles, and six compensation grouting, covering a total of 28 buildings, one of them a public school, and another a health centre.

Madrid Method

The Madrid Method was used to form the shaft connections between the running tunnel and the ventilation shafts, pumping wells and emergency exits. It has been widely used in the construction of Madrid Metro because of its versatility in adjusting to soil conditions, using timber for temporary support.

The process is as follows:

First an advance pilot gallery is excavated at the crown of the tunnel or gallery. After boring soil control probe holes in front of the working face, temporary support is installed by shoring with planks, wooden props, and steel bracing. The pilot excavation is widened until excavation of the crown section is complete and shored with planks. The crown section is arched and concreted. Bench excavation is commenced with a certain amount of lag time compared to the pilot section. Excavation and concreting of the sidewalls is then carried out using staggered props, positioned to support the two adjoining half-rings of the arch. This is followed by excavation and concreting of the invert. Pre-designed contact grout injection of the lining is carried out, according to the ground and other conditions, and to the results of primary support of the excavation.

Cut-and-Cover

The cut-and-cover tunnel was constructed between metreage points 4,940 m and 5,786 m (KP 4±940 & 5+786) in the following phases. First, the ground was excavated to the lowest level, followed by casting of the concrete floor slab. The sidewalls of the tunnel were constructed, followed by forming and concreting the crown arch. Finally, the remaining excavation was filled with earth up to the natural ground elevation.

Also constructed between stations were open-cut ventilation shafts, pumping wells and emergency exit shafts, either between diaphragm walls or using the conventional method. In the latter, concrete horizontal rings are formed, with an approximate height of two metres, with staged excavation.

An open-cut tunnel between diaphragm walls was excavated between metreage points 5,786 m and 6,055 m (KP 5+786 & 6+065) as follows. First, the diaphragm walls that will constitute the sidewalls of the tunnel are formed. The roof slab shuttering is then assembled on the surface over the wall positions. The ground is excavated between the diaphragm walls, in order to lower the roof slab down to the intermediate shoring level. The intermediate shoring is erected by means of rams or slabs. The remaining ground between the diaphragm walls is excavated down to invert level, after which the invert is concreted.

King Juan Carlos University

The King Juan Carlos University (M1) station is located between the university campus and Alcalde de Móstoles Street. The exit portal position was moved 6.90 m to avoid affecting that street. The planned location of the station was influenced by the need to incorporate four siding tracks for rolling stock, two on each side of the two platforms.

Shafts for TBM removal from Contracts 1 and 2 were also constructed at both ends. An electric substation and a pumping shaft are sited at the intersection of the access incline and the station enclosure.

The dimensions of the station access hall, as in all the stations, are conditioned by the need to incorporate the access escalator into the lobby inside the hall. At this station, the Vitrex panelling is red, the polished masonry Terastone floors are Galicia Pink, and the ceilings are painted with a blue Titanic paint. On the surface, a parking lot was built for use by university staff.

The Móstoles I station, as well as M2, M3 and M4 are built to the standard Madrid design. This consists of a large enclosure of diaphragm walls and reinforced concrete slabs, flared at one end to accommodate the access lobby and the enclosures of stairways that go from there to the platforms. The rest of the width of the enclosure is limited to all that is necessary to house the train running section and platforms.

King Juan Carlos 1 University station.

The standard construction sequence was as follows. First the construction service areas were formed, service routes diverted, and the rail route set out. Concrete diaphragm walls and piles were then formed. The surface was then prepared, steel reinforcement for roof slab assembled, and concrete casting undertaken. The surface could then be restored for urban use. The access incline to the lobby level was formed, and the ground enclosed by the station structure excavated down to the level of the lobby. The lobby slabs and struts were cast, and excavation continued for the incline and interior to the invert level. Steel reinforced concrete was cast on the invert, and the interior structure was then built, including emergency stairways and platforms. Finally, masonry work and general installation was completed. After passage of the TBM through the station, the rail tracks were laid, and platforms finished.

Central Móstoles

The plan view of Central Móstoles (M2) station is an irregular and asymmetric shape with flared areas that house the stairways. It is influenced by the location and the proximity of the buildings on Paseo de Goya and line C5 of the RENFE commuter railway. The tunnel lining thickness was increased between Stations M2 and M3, where there is a maximum of 3.50 m cover under the buildings on Luis Jimenez de Asua Street.

Móstoles Central station.

This influenced the depth of the station, which is 18 m from the rail level.

The construction system procedure was the same as that previously described for the Móstoles 1 station. A steel and wood mural that figuratively represents the large cutting head of a TBM was erected in the access lobby. At this station, the Vitrex panels are white, the polished masonry Terastone floors are grey granite, and the ceilings in the access lobby and sublevels are painted with blue Titanic paint and, over the platforms, with red Titanic paint.

The station design allows for the transfer of passengers on line C5 of the RENFE commuter train system, avoiding long and complicated journeys for users. For the same reason, the project included the remodelling and extension of the current commuter train station. The new commuter train station connection with the Metrosur Station consists of two platforms with a length of 160 m and a width of 7 m, protected from the weather by enclosures. Two other buildings were also constructed for railway use. The first consists of two floors, each 300 sq m, where technical rooms, offices, dressing rooms and locker rooms are located. The linings are of Trespa panelling.

Móstoles Central station entrance hall.

The second building is of 370 sq m on a single floor, and is for commercial use and overnight stays. It consists of a cafeteria, a newsagents and public toilets, along with a lounge area. The lining of this building is made partly with curtain wall, and the rest with windows. An area of approximately 200 sq m, covered with a glazed enclosure, connects the buildings. There are two access doors from the street to the interchange concourse. These buildings have polished masonry terrazzo Terastone floors, while the rest of the spaces are in granulated Terastone.

In order to improve the connections between the Móstoles 2 Station and the new commuter train station, a reinforced concrete box was jacked under the RENFE railway tracks. This facilitates passage beneath the platforms, and protects the passengers from the weather on their way to the two zones of Móstoles separated by the commuter train tracks. Finally, access areas off the Paseo de Goya and the Parque Vosa Street area, leading to the surface interchange area, were redesigned to facilitate the circulation of vehicles and the flow of passengers. As there are different street and platform levels in the access to Vosa Park, stairways and an access ramp were built, formed by walls with special blue bricks and delimited by a RENFE-type metal enclosure.

Pradillo Station

Pradillo (M3) station is located under Pradillo Square, between Agustina de Aragon, Dos de Mayo and Martires Streets, in the centre of the historical centre of Móstoles.

The depth of this station was increased by approximately 3.5 m for the same reasons as Móstoles 2 station, having a depth of around 18 m from the rail level. This depth made it advisable to go through an intermediate sublevel concourse to get to the platform from the access lobby. The Vitrex panels at this station are blue, and the floor is red polished masonry Terastone for the sublevel, and blue for the rest of the station.

Given the location of the square in the centre of Móstoles, and its emblematic nature, its refurbishing was deserving of special attention. The redevelopment was executed with great care, introducing different urban elements such as two fountains, a kiosk and a gazebo that benefits from what was an access ramp for station construction. The materials used in the urbanization of the square, such as paving setts and flagstones, are in accordance with the importance it holds for the municipality.

Móstoles Hospital

Móstoles Hospital (M4) station is located underneath the Villa Europe Park, between the Rio Sella and Rio Ebro Streets. The Móstoles General Hospital was taken into account in determining its location, so that the access from the station to the health centre is quick and comfortable. The station is approximately 14 m-deep. It was necessary to relocate it, in order to move it away from adjacent buildings. It also houses an electrical power substation.

At this station, the Vitrex panels are yellow, and the polished masonry Terastone floors are the colour 'Seville', while the ceilings are painted with a blue Titanic paint. As in the other stations, the railing is in stainless steel with 10 mm-thick glazing. Handrails are also of stainless steel at two different heights. The lighting is continuous, provided by fluorescent luminaires in a stainless steel box.

On the surface, the existing square was improved. An enclosure with a multiple-use sports court was built, surrounded by a dressing room building.

Manuela Malasaña

Manuela Malasaña (M5) station, the last of Contract 2, was executed as an open-cut tunnel on land not yet designated for development, and therefore free of nearby buildings. It will be urbanized in the PAU-4 programme. Open-cut construction is more economical than that of the diaphragm walls and slabs for the other stations.

In order to form the launch pit for the EPB TBM, it was necessary to lower the ground level by 1.20 m to allow commencement of the tunnel at the correct level. The depth from the surface is around 11 m, measured from the rail level. It is the only station in Contract 2 that was planned as a reinforced concrete wall structure, with a foundation laid directly on the footings. Access lobby slabs, and a reinforced concrete roof, are formed in situ, the latter over a steel arch. This part of the station houses the lobby, accesses to platforms and concourses, telecommunications rooms, and other accommodation related to station operation. At the platform level, the station structure was built by means of a reinforced concrete box. This allowed the cost of the station to be optimized.

At this station, the Vitrex panels are orange, the polished masonry Terastone floors are blue and the ceilings of the vaulted station are painted with a gray Titanic paint while the rest of the station is painted in blue.

Pradillo station.

Móstoles Hospital (above) Manuela Malasana (below).

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Contract 3
Section IV, Sub-Sections III-B, IV-A & IV-B

Contractors: Sacyr OHL

Loranca to Fuenlabrada in Cut and Cover

Construction of sub-sections III-B and IV-A of Contract 3 was awarded to the contractor Sacyr, for a total initial budget of €21,819,480 and an initial term of 15 months; sub-section IV-B was awarded to OHL, for €39,123,152, to be completed in 20 months.

Section 4 is unique within the Metrosur project, because it was built entirely without a tunnelling machine, giving it some very special characteristics. A variety of three or four different tunnel faces could be open at any one time, as opposed to the single-face tunnel type. This provided enhanced flexibility for unforeseen circumstances, and made it possible in one tunnel to offset delays at another, or accelerate progress by opening new faces.

Loranca station and surroundings, looking towards Fuenlabrada Hospital.

Project Alignment

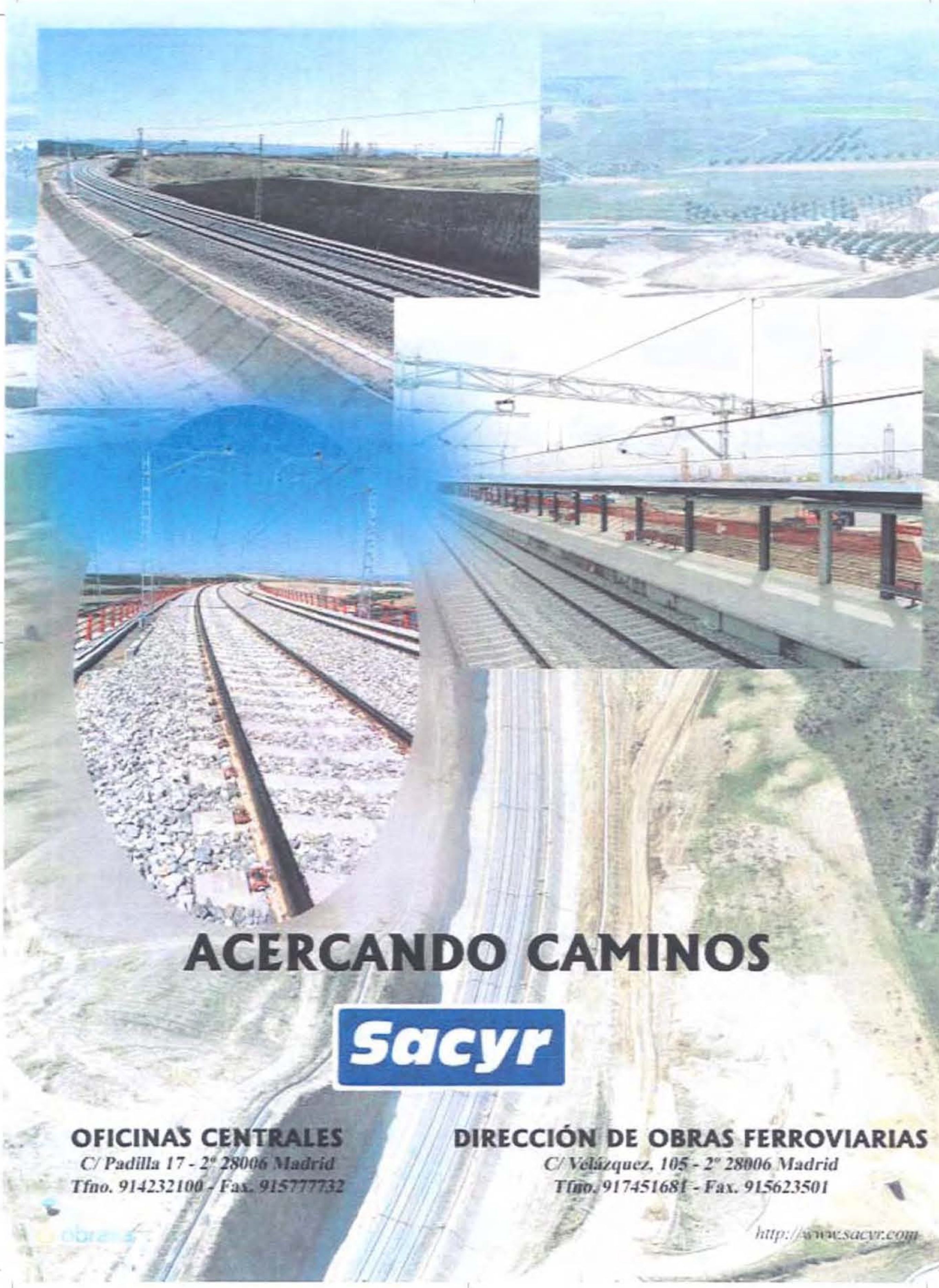
Another feature of Section 4 is the discontinuity in the construction methods used, adapting to the peculiar conditions of the tunnel. This resulted in six changes over 2,400 m of tunnel. Such compartmentalization required activity and connection times to be co-ordinated but, by the division of work, also allowed any scheduling error accumulated over the section to be better controlled. In particular, sub-section III-B contains 275 m of diaphragm-walled tunnel and Loranca station; sub-sector IV-A has 413 m of tunnel using traditional methods; and sub-sector IV-B has 270 m of diaphragm-walled tunnel, 1,273 m of open-cut tunnel, and Fuenlabrada Hospital (F2) station.

The contract work location is close to the Metrosur train sheds, making two diagonal track crossovers necessary at Loranca station, in order to handle the rolling stock.

Section 4 is situated on the Fuenlabrada-Móstoles axis, to the south side of the Metrosur ring. This axis is in an area where the existing major communication routes are radial: four are highways (M-409, M-407, R-5 and Avda. Móstoles), two are rail (the C5 commuter line); whilst two are orbital (the M-506 and M-50 highways).

The Fuenlabrada-Móstoles axis, therefore, provides a balance for the communication system, offering a rail transverse to relieve pressure on the radial routes, and opening up other Metrosur line possibilities.

The III-B and IV-A sub-sectors are located in the Loranca housing development, a


ACERCANDO CAMINOS
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satellite residential neighbourhood of Fuenlabrada on the municipal border with Móstoles. Sub-sector III-B runs through a major area of services in the heart of the neighbourhood, while IV-A runs through the oldest part.

Sub-sector IV-B links the Loranca housing estate with the urban centre of Fuenlabrada, in an area that is currently open country. A hospital and university are now being built there, and further urban development projects are imminent.

Station Areas

The station spaces must accommodate the service elements required, conducive to the special features of the surroundings.

Loranca (F1) station is located on an open space bordered by parks and gardens in the South, extending into Calle Pablo Iglesias with a wide landscaped median, and, on the North side, an adjacent service area.

The architectural details are notable: a health centre with a central module in the shape of a truncated cone; the District Council offices with a glazed frontage; and a two-level shopping mall. Between these elements, there is a square giving access to the northern station shaft, where the paving and fittings planned are for pedestrian use.

Accessibility is very good, with platforms some 14 m below the surface. Passenger shafts are arranged for quick and easy access to the commercial service area on the one hand, and Calle Pablo Iglesias on the other. The dimensions of the station halls are limited, because of their proximity to the mall. Their metal and glazed structure fits perfectly into the square's architectural surroundings.

Although sub-section IV-B ran through open country at the time of construction, the surrounding conditions were as decisive as if this had been consolidated urban land, or more so. This was not just because the proposed developments had to be respected: the fact that they were not defined or exactly located prevented decision-making and, in many cases, affected the rate and distribution of the work.

Fuenlabrada Hospital

These circumstances became more patent at the Fuenlabrada Hospital (F2) station, where three urban schemes converged: the hospital, the university and development for residential and sporting uses.

The station environment is therefore an important centre of educational and health services including: a high school for 1,100 pupils, 2.3 hectares of land and 5,000 sq m of buildings; the King Juan Carlos I University for 4,000 students, about 50 hectares of land, and with six units now built. A variety of disciplines are taught here,

Traditional tunnel from Loranca station.

such as journalism, advertising and public relations, telecommunications engineering, and audio-visual communication; a 400-bed hospital with 68,000 sq m of buildings.

For access to the University, a passenger escalator shaft has been designed and constructed to run under Camino del Molino, so reducing interference between traffic and pedestrians. The shaft runs oblique to the station, and has a portal for a perfect exit to the footpath around the university land.

The hospital exit was moved to the south side to emerge outside the hospital fence. This required creation of a new enclosure at the vestibule level, at the connection point between the two passenger shafts. This enclosure incorporates a lift, to reduce surface area, at a point where a hospital entrance has been planned.

The work was thus adapted to the surroundings, in co-ordination with the Fuenlabrada Municipal Corporation and the technical teams for the various activities involved. The station is perfectly adapted to future requirements, ready to serve students, health service users, and residents in the urban developments planned in the adjoining zone.

Future Station

Of the housing developments in the area, the first covers 52.2 hectares and contains

Future station between F1 and F2 to serve proposed housing development.

Open cut tunnel under construction.

1,850 single and grouped family homes, 58,000 sq m of 'green belt', and 46,000 sq m for public facilities. There will be a large sports complex, and the Fregacedos lagoon is to be restored, to form part of a large public park. On the other side of the tunnel route, a second development is to be built, on 26 hectares, with 750 homes and 55,000 sq m of 'green belt'.

To provide a transport service for this future demand, in the hub of the two housing developments, a 'first' tunnel enclosure was built, with the dimensions and elements necessary to facilitate later construction of a station. It is 120 m-long in a straight line, with a width between gable walls of 8.6 m, and a removable vault section formed by prefabricated slabs on geotextile-covered metal trusses.

The area is designed for the incorporation of perimeter screens around the future station, interior excavation, removal of the vault, and 120 m slabs to be erected on the present gable walls to form platforms. Cast concrete can be formed for vestibule slabs. In any case, it will be necessary to protect the interior with a plate, or similar liner, to prevent anything from dropping on to the lines.

Construction Methods

The construction procedures used in sub-sections III-B and IV-A were appropriate to a dense urban area: diaphragm sidewalls for the tunnel and station in sub-section III-B; and the traditional Madrid method on sub-section IV-A.

In sub-section III-B a 8.2 m-wide tunnel, straight over a length of 275 m, was constructed under the Calle Alegria to Loranca Station between diaphragm walls. The simplicity of this section made high levels of performance possible during the first phase of work.

The procedure was as usual: surface preparation; building a low guide wall before construction of the side diaphragm walls; excavation between the walls to the lower level of the upper slab; removal of tops of the diaphragm walls; installation of the top slab including its tie beam; excavation under the slab; finally, casting the invert on the exposed ground.

In this case, excavation was mostly by access from the upper level, driving down the station ramp, and the remainder from the station invert level, with the spoil removed along the tunnel access ramp.

Performance can be assessed using the criterion of area of diaphragm wall constructed per month.

In the first four months, 97.4% was built, at a monthly average of 2,096 sq m, and a maximum of 4,064 sq m. On the other hand, the presence of gas and telephone utility service lines led to delays in completion of the diaphram walls. For nine months the sidewalls had to be built by underpinning from inside the excavation.

Built between diaphragm screen-walls, the central box of the sub-section III-B station has pre-stressed beams 29.6 m-long and 1.85 m-high. The top slab was assembled on site from pre-fabricated slabs. The other upper and vestibule slabs are lightweight. Also accommodated are an electricity substation with load-bearing slabbing at the bottom of the cable floor, and eight pile-piers supporting the vestibule.

The station perimeter is a 12-sided polygon, so that progress was less than that for the tunnel: an average of 1,843 sq m/month in the first four months, and a maximum of 2,800 sq m/month. Completion of the northern passenger shaft created a minor schdule delay.

The sub-section IV-A tunnel begins in Loranca station, and is cut by the access ramp at 70 m on the right. Here the diameter changes from 8.2 m to 7.8 m at a distance of 142 m from the end of the station. Some 14 m before, it has a curve of radius 300 m, 97 m-long and ends in a straight 413 m from the station, to connect with sub-sector IV-B. Construction was by the traditional Madrid Method as below.

Traditional Madrid Method

The main characteristic of this procedure is the construction of the crown arch (vault). It begins with an advance gallery in the keystone area, measuring 2.5 m x 1.5 m in section. This is lined lengthwise at the top with timber planks and bars, supported every metre by sections at right angles to the advance These are in the form of vertical supports, on which the cross-setts rest.

With this advance gallery completed, the most critical moment is over. By successive repetitions of the procedure, with similar small excavations towards the sides and downwards, three or four steps are taken, until an advance of 2.5 m is achieved.

With the vault timber-lined, the concrete formwork is then installed, the bars removed, and then the concrete crown arch is cast. About 25 m back from the face, the excavation is enlarged to the top edge of the invert and sidewall outside dimensions, in a process known as the 'destroza' (literally 'wrecking' – or benching).

A 900 mm side ground mass is replaced by underpinned concrete in a panel 2.5 m-long and 3.7 m-high. The ground is manually excavated using a pneumatic drill, and formed on one side.

Each underpinned segment carries two crown arches. Simultaneous with this work, a gable sidewall was concreted on each side, but in order to synchronize the work, and maintain support (as both bases of a single crown arch could not be left excavated at the same time), the minimum time necessary between underpinned segment construction was that for two modules.

In a normal week, five 2.5 m rings would be concreted, with lower excavation moving forward proportionally. On Saturday, the invert could be advanced 13 m, with a rest on Sunday. On Monday, work could proceed under sufficiently cured concrete.

A team of about 12 men carried out the work: two or three with pneumatic tools, two or three with shovels, another two or three fitting the supports, two on the gable sidewalls, and one labourer for auxiliary jobs or back up. There was also one very experienced foreman, and present at the work at all times, for quick responses to unforeseen situations. On working days there were three 8-hour shifts, with a half day on Saturdays and a rest day on Sundays.

A small backhoe excavator was used to remove the spoil to the benching area, while the lower excavation was carried out by a standard backhoe. The spoil was removed by truck.

Performance

The progress measurement is according to the number of rings constructed, or total length, achieved in one month. Once the vault, or crown arch, is concreted, this ends the most critical time for the stability of the section.

In normal conditions, 2.5 m half-ring crown arches were formed, except when the ground presented difficulties. The greatest complications occurred at the beginning and the end of the tunnelling. On the night of September 29th, 2000, noises were heard in the wood planking in the crown of vault I08 on the ramp-station sector, and the team evacuated the face in a matter of seconds. A ground cavity had been hit when the crown was excavated, and loose ground was released. The vault was injected with grout from the surface, and three 1.25 m rings were built to get through the bad area.

Later on, when just a few metres of the tunnel remained to be completed, a saturated layer of sand appeared at the head of the crown. This caused scouring in the sand and slips in the adjacent ground. Eleven 1.25 m-long runs had to be built to get through this bad zone.

Monthly average progress was 17 rings or 41.3 m, which was close to one ring per working day. During five of the ten months, the optimal one ring/day was maintained.

Progress using the traditional Madrid Method

Month	No. of Rings	Progress (m)	% acum.
Sep '00	16	40.0	9.7
Oct '00	20	46.6	21.0
Nov '00	18	45.0	31.8
Dec '00	17	40.0	41.5
Jan '01	21	52.5	54.2
Feb '01	22	55.0	67.6
Mar '01	21	52.5	80.3
Apr '01	13	32.5	88.1
May '01	21	39.0	97.6
Jun '01	4	10.0	100.0
	Total	413.1	

Sub-section IV-B Procedures

In general, the cut-and-cover tunnel method was used in open country, but diaphragm walls were needed at the edge of the Loranca urban area, over a distance of 80 m adjacent to nearby buildings, and at Fuenlabrada Hospital Station.

The diaphragm, or screen wall, method was used on two sections: one 190 m-long starting from sub-section IV-A, under the football ground, with 0.8 m-wide walls, a 7.8 m-wide tunnel, and an average wall depth of 21 m. The upper slab is 0.60 m thick. The other section was of similar section, 80 m-long, running alongside the Aceitunas Barruz facilities, with average screen depth of 22.5 m.

The monthly average installed was 1,421 sq m, and performance during the final three months was twice (63%) that in the first three. Rhythmic cyclical work was interrupted by the large number of existing utility services in the area.

The average production was even lower, at 860 sq m/month, because an archaeological site was discovered. This delayed the start and continuation of work. Also, sand strata, up to 5 m-thick, with large amounts of water, made the use of bentonite slurry necessary.

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MADRID METRO. NEW DESIGN FOR LINE 10. SECTION: PLAZA DE ESPAÑA-LAGO, 2.0 KM. LONG TUNNEL.
INFRAESTRUCTURE OF THE EXTENSION OF MADRID METRO. LINE 1 TO VALLECAS-VILLA. THREE UNDERGROUND STATIONS. 2,5 KM. LONG TUNNEL AND AN INTEGRATED METRO AND BUS TRANSPORT CENTRE.
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CONSTRUCTION PROJECT FOR THE INFRAESTRUCTURE OF THE SECOND SECTION OF METROSUR: MÓSTOLES 1 STATION– MÓSTOLES 4 STATION.
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TECHNICAL ASSISTANCE TO QUALITY CONTROL OF THE WORKS: EXTENSION OF LINE 7 OF MADRID METRO. SECTION: GUZMAN EL BUENO – VIRGEN DE LA PALOMA.
COMMUNICATION CORRIDORS FOR PASSENGERS BETWEEN LINE 5 OF MADRID METRO AND THE PASILLO VERDE FERROVIARIO RAILWAY LINE IN PIRAMIDES STATION.
TECHNICAL ASSISTANCE FOR THE SUPERVISION OF RAILWAY BURYING WORKS IN GETAFE.
COVERING OF A STATION IN RIVAS-VACIAMADRID (EXTENSION OF LINE 9).
INFRAESTRUCTURE WORKS FOR METROSUR. SECTION 3: MOSTOLES 4 STATION – KM. 11+582

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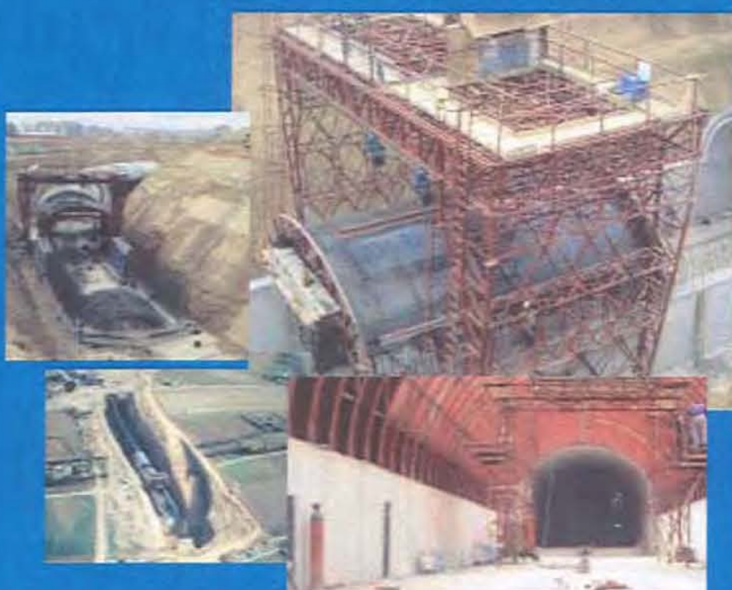

METROSUR, work well done

We have been collaborating in the Madrid METRO's development since we were set up 38 years ago. We have provided technical assistance throughout this time to a large part of the Madrid Regional Government's underground (metropolitan) network, using state-of-the-art technology. The most recent undertakings relating to METROSUR are the following:

Construction design of Metrosur's stretch I and line 10's new carriage sheds.
Technical assistance for constructing Metrosur's stretches III-b, IV-a and IV-b.

Intecsa-Inarsa plans all types of infrastructures in a complete, interdisciplinary fashion, particularly for railway transportation, both intercity and metropolitan (underground). Activities range from drawing up feasibility studies involving the planning of each phase up to construction supervision and management.

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Progress using open cut tunnel method

Month	No. of Vaults	Progress (m)	% acum.
Nov '00	6	60.8	4.8
Dec '00	8	80.1	11.1
Jan '01	9	91.1	18.3
Feb '01	10	101.3	26.2
Mar '01	7	71.4	31.9
Apr '01	12	122.9	41.5
May '01	18	184.4	56.0
Jun '01	3	30.7	58.4
Jul '01	5	51.4	62.4
Aug '01	18	185.0	77.0
Sep '01	4	33.8	79.6
Oct '01	16	164.8	92.5
Nov '01	9	85.2	99.2
Feb '02	1	10.2	100.0
	Total	1,263.1	

At the station, two work phases can be considered. One is the construction of the perimeter wall at the start of the work, achieved with high performance. The other is the passenger shafts, constructed as the design of surroundings became more defined.

The monthly average production was 2,348 sq m of diaphragm screen wall, the highest in any individual section, with the result that the station was finished in three months. For the passenger shafts, walls were built from the lower slab. The hospital exit leads to a vestibule adjacent to the station, formed in two construction stages. The university escalator shaft runs 63 m under Camino del Molino, in order to avoid it.

Open-cut Tunnel

This procedure used was for trench excavation to the tunnel base, and the in situ concrete casting of the invert, gable walls and roof. To build the roofs, a sliding wagon was used on which the interior formwork was placed. Reinforcement and side covers were lifted into place by an external sliding crane jib.

Progress was measured in terms of constructed roof, similar to that for tunnels made by traditional methods. The modules formed are longer at over 10 m.

March, 2001 saw the first break in progress, caused by the adaptation of the formwork wagon from a width of 8.2 m to 7.8 m. In June and July, the roof formwork and wagon were moved to by-pass the future station location, and extraction and pumping wells. Once moved, performance was maximum, at almost one vault a day. In September 2001, progress dropped because of a new transfer to by-pass the 80 m of diaphragm screen walled tunnel.

Fuenlabrada Hospital station and artificial tunnel.

Conclusions on Structures

Interesting conclusions can be drawn by grouping all the above according to whether built by the diaphragm screen wall or vault arch methods.

In sub-section III-B the production rate for diaphragm screen walls was three times that of IV-B; in the first four months, 15,000 sq m were built in III-B, but that took more than 12 months in IV-B.

For vaulted work, the sub-section IV-B production rate was twice that of sub-section IV-A in terms of linear metres constructed. The division of about 210 m between the two was reached in a little more than three months in the former, but took seven months in the latter. This is due to differences inherent to the construction method itself: the Madrid Method constructs 2.5 m advance in the best of circumstances, while the cut-and-cover tunnel modules are 10 m-long.

Adaptations to Actual Circumstances

During work on sub-sections III-B and IV-A, a team was formed from the works management, Madrid Metro, the Contractor, technical assistance, quality control, instrumentation staff, and any other involved agency. This met weekly, to set out and debate the situations arising or foreseen in the work. In this way, problems were detected, assessed and resolved in 'real time'. Detection or resolution at a later date would have been costly and difficult.

In April 2001, greater fissuring than expected began to be seen in some of the station walls, while the inclinometers recorded deformations that went beyond the reference values. A special monitoring period was established, during which conditions did not improve. Consultants were then called in and, one month later, reinforcement

Loranca and Fuenlabrada Hospital stations nearing completion.

began to be built for the screen wall around the technical rooms and substation. This comprised buttresses of 0.5 x 0.5 sq m section every 5 m. Winter rains produced water levels much higher than in previous years, seen from the installation of piezometers, with local stresses above forecasts.

Adaptation to the work circumstances included construction of a box structure alongside the station exit to remove the 'La Paloma' tunnelling machine, which operated in the next section. This is a rectangular enclosure of 21 m x 19 sq m built in 1 m-thick walls, with a continuous central block creating an ellipsoidal hollow 12.5 m above the crown.

The emergency exit was another element of the station to be modified so that the discharge exit was immediately outside the hospital fence, and so of minimum length for emergencies. It was therefore designed at the end of the station, on the south side, at right angles to the fence. This placed the portal beyond the fence, and the final section parallel to the fence on the outside.

Preventive Measures

In other special situations, preventive measures were taken, as follows.

In the sub-section IV-A, there was a building very close to the route where, using the Madrid Method, the tunnel was at a minimum distance of 6 m. To avoid any adverse effects, the following measures were taken.

Jet grouting was performed between the tunnel and building. From an adjoining garden, ten jet columns were put in, 1.25 m apart and 26 degrees from the vertical. Three ends made a fan form. The columns, each 16 m-deep, were a minimum of 3 m from the tunnel, which has about 11 m of cover over the crown in this area. To ensure stability, the excavation face was more than 50 m away while these operations were carried out.

Once the tunnel was built, there was a second grout injection from inside the tunnel, with two rows of ten holes, 2.5 m apart. One of these was in the top of the crown with vertical holes, and the other halfway between the top of the crown and the top of the gable sidewalls, drilled at 45 degrees. There is an 8 m overlap the two areas of grouting.

These measures tended to prevent any ground movement from affecting the building, during or after construction, the aim being to isolate it as far as possible.

A further measure was considered, to counter vibration from passing trains, resulting in installation of an elastomeric coating, used with good results on various sections very close to buildings in the Metro system. Specialist Sylomer coating was installed between kilometre points 14.22 and 14.278. This is 250 mm-thick, with 125 mm end transition strips, and a reinforced slab between the plug and coating. Two frames, 250 mm apart, of 12-20 mm diameter, and about 70 mm from the plugs, were installed.

Track

The 2,689 m of twin-track and two diagonal lines were built according to the following element dimensions and tolerances: distance from sidewall to rail drive face, rail width ± 3 mm, ground deflection ± 3 mm on a 10 m chord, rail head height ± 2 mm, and superelevation ± 2 mm. These are all referenced to pegs every 5 m, except on 300 m-radius curves, which are pegged every 1 m.

Sub-sections III-B and IV-A have the special feature of two crossovers of diagonal lines, at the station entry and exit, to facilitate rolling stock handling for access to sheds. The 820 m of twin-track and diagonals making up the two sub-sections were built in less than two months, with assembly, concreting and track welding being done by the same team. The average daily concreting progress was 74 m linear, and the maximum was 116 m.

1,869 m of twin track was built in sub-section IV-B, from the connection with sub-section IV-A to the tunnelling exit shaft at Fuenlabrada Hospital Station. Different teams did the assembly, concreting and welding. The daily average for concreting was 65 m; performance progressed from 53 m/day in January, 2002 to 64 m in February, 67 m in March and 75 m in April. The longest section was of 105 m.

Conclusion

What must be concluded from the above is that, on the basis of the initial project and the decisions reached on the job during the work, a sector of 2,689 m of Metrosur has been built satisfactorily. This includes two stations, adapted to present and planned surroundings, by the deadlines set, and without significant safety problems.

Contractor: Sacyr

Serving South Metrosur Rolling Stock

The contractor Sacyr SA began the construction project for the new train depot at Loranca in November 2001, over a period of twelve months with a budget of €40 million.

The project can be divided in two main blocks: construction of accesses; and the main depot itself for the parking and maintenance of trains. There is an auxiliary building adjacent to the main bay of 2,400 sq m for offices and other facilities.

Branch Line Access

In order to access the main depot area from the Metrosur tunnel, there are three tunnels of single-track branch lines, each with a length of 350 m. The connection with the main line of Metrosur is made with three side-tracks of TG 0.125, two of which are curved and have a bank of 150 mm elevation. The rail-track in the tunnels is made up of concreted track set on elastic blocks, and elastic monoblock concrete sleepers for the side-tracks. This is the first time that banked side-tracks have been used to preserve the speed of trains on the main track of Metrosur.

At the tunnels exit are two complete rerailers over ballast of TG 0.125. The railway yard is made up of a group of 20 tracks of UIC 54 rails with monoblock concrete sleepers. This group goes into the main depot bay. The are 20 side-tracks of TG 0.125 set on akoga sleepers. This type of side-track is also an innovation for the Madrid Metro.

Main Depot Bay

The main depot bay consists of six tracks for maintenance, 12 tracks for parking, and two tracks for other facilities. Facilities in the maintenance shop are: a wheel pit for work on the wheels of the trains; a raising pit for use of mobile screw-jacks for lifting train bodies. The load capacity of every screwjack is 10 t and there are four screw-jacks in a set. The speed of elevation is 0.3 m/min; and an overhead monorail crane of 10 t load capacity, a width of 7.4 m, and a travelling run of 57 m.

The principal facilities located in this bay are compressed air, grease and oils supply, water supply, electrical power, anti-intrusion protection system, heating and air conditioning, and fire protection systems.

Track 7 is prepared for train washing with a washing tunnel, 99 m-long to suit the new 8000 series trains, comprising three coaches.

Inside the main facility, between tracks 19 and 20, there is loading point with a length of 65 m and an overhead crane of 10 t load capacity.

At each depot bay location are all facilities such as an airline, communications with the new ATP system, TIE, interlocks, and an electrical substation with two transformers of 15 kW. A closed-circuit television system has 37 displays in monochrome, five in colour, and five of high-resolution images. To give an idea of the complexity of these facilities it can be noted that 55,000 m of buried channels have been installed for various wiring to service connections.

As with the main depot bay, the auxiliary building is constructed with prefabricated concrete. The outer cover is also of prefabricated concrete with a white arid finish. The whole basal slab of the structure is concrete, with direct ground contact and with isolated 'shoes' of reinforced concrete.

The principal bay includes footbridges to reach the trains and perform maintenance on them. These extend and open automatically from a control console. This access structure is composed of laminated steel beams (HEB-360, HEB-120), with angles of different sizes.

TUNNELS

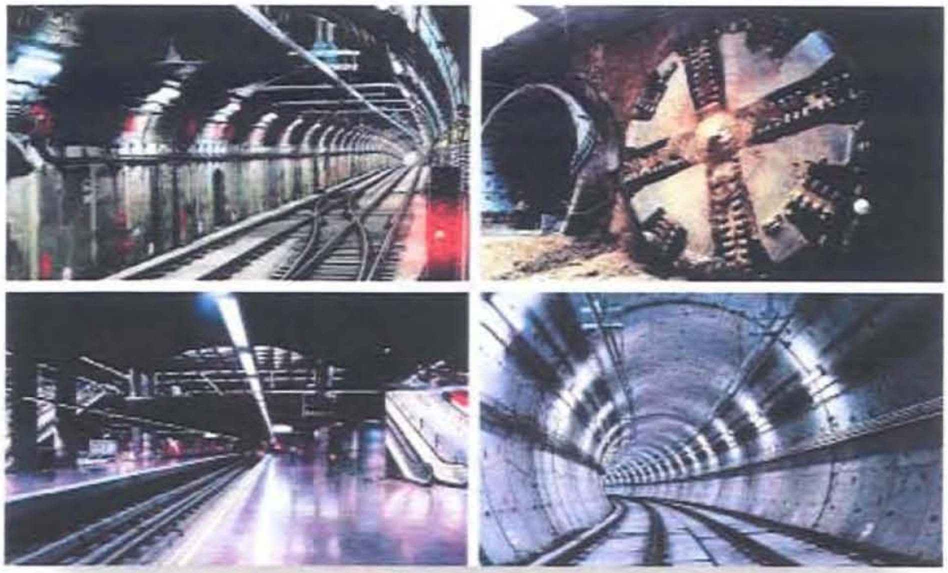
1995 – 1999

EXTENSION OF THE MADRID METRO

1999 – 2003

Comunidad de Madrid

CONSEJERÍA DE OBRAS PÚBLICAS, URBANISMO Y TRANSPORTES



NECSO, Entrecanales Cubiertas is currently building almost 8 kilometres of the new Metrosur circular line in Madrid.

We also recently completed 5.86 kilometres of tunnel for line 8 - 3,366 metres using a tunnelling machine and the remainder by the "Madrid Traditional Method".

Once all sections have been built, we will have built over 30 kilometres of tunnel in the Madrid Metro extension since 1995, including 18 kilometres using EPBS (earth-pressure balance shields).

On line 7, the La Paloma tunnelling machine drilled 3,435 metres of 9.38 meter diameter tunnel, and in just one month it drilled 618 metres of tunnel on a curve of radius 275 metres, setting a world record at the time.

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Contract 4
Sections V & VI

Contractor: necso

Mining Beneath Fuenlabrada to Getafe Conservatorio

Contract 4 covers sections V and VI of the 12 design sections of Metrosur, and was awarded to Necso-Entrecanales-Cubiertas in April, 2000. The total investment was €208,707,333, of which €180,655,932 was for civil works, and the rest for installations and ancillary work.

The contract comprises a 6,517 m-long stretch of Metrosur tunnel, four stations and a connection to Line C5 of the RENFE suburban railway system. It starts at the Hospital de Fuenlabrada station, which is part of the adjacent Contract 3, and runs under the town of Fuenlabrada. There are three stations in this urban area: Parque Europa, Fuenlabrada Central and Parque de los Estados. It then heads in the direction of the town of Getafe and the Arroyo Culebro station before finishing at the entrance to the Conservatorio station, which is part of Contract 5. A fifth station has been excavated along the route, ready for future urban development.

Tunnel Alignment

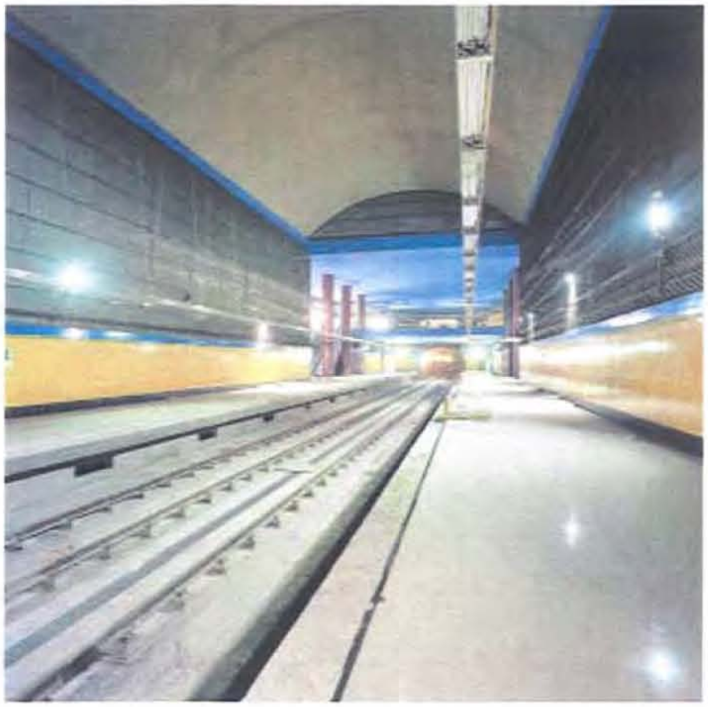
Of the overall length of the project, some 5,192 m are in the municipality of Fuenlabrada, and the remaining 1,325 m in Getafe. The contract includes nine vertical shafts, of which four are for ventilation, one for pumping, two for combined ventilation and pumping, one as an emergency exit, and another for pumping and emergency use.

Starting from the exit from Hospital de Fuenlabrada Station, the alignment crosses the M-506 main road and runs along Calle Francia to Parque Europa station. It then curves one way, and then back, before reaching the existing Fuenlabrada station on the suburban railway, where Fuenlabrada Central Station and the corresponding interchange facilities are being built. The alignment continues through the Fuenlabrada district, north of the old town hall, and arrives at Calle Miguel de Unamuno. Parque de los Estados station is located

8000 series train set.

Specification of Type 8000 rolling stock

Rolling stock type	**8000**
Make-up	M-R-M
Gauge	1,445 mm
Catenary voltage	1,500 V DC
Configuration	Continuous train
Material	Aluminium
Power of convoy unit	1,520 kW
Maximum speed	110 km/h
Maximum acceleration	1.2 m/sec/sec
Total capacity – persons	607
Traction motors per unit	8
Length	55.5 m
Width	2,800 mm



Typical station.

where this street crosses Avenida de Venezuela. The line then runs along Venezuela, crosses Avenida de la Hispanidad, and heads across country towards Getafe.

In Getafe municipality, the line crosses the M-50 ring road, and reaches Arroyo Culebro station in Section III. The line continues through Section III and finishes in Avenida de Arcas de Agua, at the entrance to Conservatorio Station.

The tunnel runs at considerable depths of 20-25 m under built-up areas, which include buildings of up to four floors.

Division of Alignment

The contract work can be divided into three clearly defined parts, described as follows in the order in which they occur along the alignment.

The initial 3,200 m between the new hospital and the by-pass are located more than 20 m below the surface, under the Fuenlabrada town centre. This part was excavated using a TBM as the safest method, affording total support of the ground, including the face, to minimize settlement. This section contains the stations of Parque Europa, Fuenlabrada Central and Parque de los Estados, and four vertical shafts.

Work with the tunnelling machine, 'La Paloma', started on September 19th, 2001 from a shaft close to the by-pass. Some 2,840 m of 9.4 m-diameter tunnel were bored, running through three stations, and moving from west to east under the old quarter of the city. The TBM finished its task on April 3rd, 2002 at the exit shaft near the Hospital de Fuenlabrada Station. During 197 days of continuous 24 h/day work, the progress was 14.4 m/day.

In the next section, up to the M50 ring road, the alignment runs through 1,892 m of open land, so the tunnel was excavated in open-cut. This section crosses the Culebro gully, which was diverted. It also includes the future F6 station, of which only the hall has been constructed.

Lastly, from the M50 to the end of the contract, a distance of 1,325 m, the tunnel has been constructed using the Madrid Method. This part contains the Arroyo Culebro station and two shafts, one for ventilation and another for pumping.

Stations

The design criteria for the stations are based on an arrangement of space. The idea was to create broad spaces that provide the user with a sense of direction. The chosen finishes and lighting are also aimed at achieving this goal. All of the stations have a single concourse, the location of which was determined by analyzing user habits. The far end of the platform is the location of the emergency exit, in all cases.

The escalators start at street level, and they are protected from rain by glass enclosures with stainless steel frames. These pavilions also house the stairs, and a system of gates to close the facilities when not in use. The stations are fitted with lifts for the handicapped, located next to the main entrance. In the case of Fuenlabrada Central Station, the lift is inside the external hall. At concourse level, there are another two lifts, which provide access to the respective platforms. The concourse includes an equipment room, control rooms for the escalators, a lift machinery room, toilet facilities with changing rooms

Emergency exit stairway.

for males and females, a cleaners' storeroom, refuse storage, spare rooms and a meter room for the power and water utility companies.

The platforms have ventilation equipment, a pump room, machinery rooms for escalators and lifts, a transformer room, a low voltage room, rooms for isolating switches and/or signal closets, a telephone equipment room, communications, station master's office, interlock controls and the emergency exits.

With regard to decoration, the walls up to a height of 2.6 m consist of three bands: the lowest band is a continuous skirting of 300 mm in height consisting of black Spanish granite; the middle band consists of enamel sheet metal in different colours, in large modules of 1.0 m x 1.90 m to facilitate incorporation of the Metro information panels, advertising and doors; the upper band is 400 mm high and continuous. It is made of the same painted metal sheets, and houses the communication and signalling cables. Above 2.6 m, there is variable height cladding consisting of 1 m bands of painted and galvanized steel sheet, leaving a small 100-mm space for the ceiling flashing. The columns are clad in stainless steel.

The station ceilings have exposed concrete surfaces, painted with silicate. Paving on the platforms, in the vestibule and in the corridors, is polished terrazzo tile with granite aggregate. Stair treads and landings are in black granite. The floors of the equipment rooms and emergency exits are terrazzo. In the toilet blocks, Gres-type tiles have been laid.

Railway Interchange

Fuenlabrada Central station is different, because it houses the interchange for the suburban railway, and there is an extra level for the RENFE concourse. This is located under the station tracks, and was created by jacking a concrete box-section. This is used to provide access to the RENFE platforms by means of stairs, escalators and lifts.

Escalators to station.

Box jacking arrangement to cross beneath RENFE tracks at F4 station.

The roof of this station consists of prefabricated beams, painted gray, and prefabricated slabs between the beams, which are blue. The access points are used for both the Metrosur line and RENFE's suburban network, and they are located on both sides of the suburban lines because, being on the surface, the tracks are a barrier to pedestrian traffic. Finishes in the station, and the vestibule of the interchange, follow the same criteria as the other stations on the Metro line. In addition, there is a false polyester ceiling in the jacked box section.

Ground Treatment and Monitoring

The goal of ground treatment is to prevent excessive settlement in sensitive areas, mainly near buildings. The anti-settlement work included eight micropile cut-off walls, and three grouting programmes, to compensate for settlement. Miscellaneous fencing, pipe and duct reinforcing, special monitoring equipment and side-slope stabilization was also installed. 'Umbrellas' of reinforced micropiles were used to reinforce the ground above the TBM, where it passed through the head wall at the connection point between tunnel and station. This prevented settlement on the surface around the station cut-off walls.

Summarized bill of quantities for Contract 4

Item	Quantity
Length tunnelled with TBM	3,300 m
Length constructed in open cut	1,892 m
Tunnel length by Madrid Method	1,325 m
Tunnel lining segments (no.)	14,000
Excavated volume	2 million cu m
Fill volume	1.3 million cu m
Total length with ground treatment	4,700 m
Consolidation grouting volume	2,800 cu m
Cut-off walls (volume)	65,000 cu m
Piling (volume)	1,600 cu m
Precast columns (total length)	1,700m
Concrete volume used	205,000 cu m
Steel reinforcing bar	17,700 t
Rolled steel sections	380 t
Rail – total length	26,100 m
Elastic blocks (no.)	31,000
Cement-gravel track bed (volume)	53,000 cu m
Cladding panels (total area)	11,000 sq m

Lowering the cutterhead of the Herrenknecht TBM.

Analysis of Subsidence

Based on the design of the alignment, a study was carried out to forecast subsidence, vertical settlement and horizontal displacement, which might be caused by the planned excavation. This work was of vital importance, because it affected the choice of alignment, and allowed decisions to be made on the use of auxiliary techniques to correct possible movement. The overall purpose of this is to guarantee the safety of both the public, and buildings in affected areas.

Recent experience on other extension projects for the Madrid Metro network was taken into account in the analysis of subsidence. Specifically, the articles published in the Technical Conference on the Extension of the Madrid Metro in June, 1997 were used as the main technical references. This especially applies to the paper on The Madrid Model: a semi-empirical method for estimating subsidence (C. Oteo, M. Arnaiz, J. Trabada and M. Melis) presented at the World Tunnelling Congress held in Oslo in June, 1999. This model adopts the Gauss bell as the form of the settlement, and the point of inflexion proposed by Sagaseta and Oteo (1996). The degree of settlement, or maximum settlement, is estimated from the correlation established in the model.

As a comparison for the results obtained using the semi-empirical Madrid Model, an analysis was made using a numerical finite difference model for a condition that can be considered sufficiently representative of the typical cross-section on the alignment. This study was carried out by Medina and Núñez at La Coruña University. FLAC calculations software was used with the soil, which was assumed to be an elasto-plastic material. Three basic conditions were analyzed: subsidence as a consequence of the excavation of the tunnel; displacement of a building or structure close to the tunnel, as a result of the interaction of soil/structure rigidity; and improvements obtained by applying a diaphragm wall of reinforced soil between the tunnel and the structure.

Settlement Forecast

In addition, the most critical parts of the alignment were also analyzed using empirical and semi-empirical methods to forecast settlement.

Kilometre point 0.640, where greatest settlement was expected due to a significant amount of poorly compacted fill, did turn out to be the point of greatest settlement. However, the actual settlement was considerably less than that forecast. This was due to proper control of the TBM pressure chamber pressure as it passed through this area.

Monitoring devices record movement, the level of water tables, and other data that define the behaviour of the structure, and any deviation from the forecast situation. The equipment basically consists of levelling benchmarks on the surface, test markers in buildings, convergence marks in tunnels, strain gauges on the tensile reinforcement of two sections at each station, piezometers where water is expected, and pressure cells in the roof and floor. These devices have been fitted to all of the buildings affected by construction, at all of the stations, and in the tunnels at approximately 400 m-centres.

Construction activities production rates

Activity	Average progress rate
Tunnelling with EPB TBM	450 m/month
Tunnelling by Madrid Method (per face)	40 m/month
Open-cut tunnelling	100 m/month
Cut-off/diaphragm walls (per team)	80 m^2/day
Time to jack-in box section	1 month
Superstructure (double track)	2,000 m/month

TBM Construction

The cross-section of the tunnel is circular with an internal diameter of 8.43 m and external diameter of 9.07 m. There are seven lining segments per ring, 320 mm thick and 1.5 m in ring length.

The Herrenknecht La Paloma TBM can work in closed EPB mode, controlling pressure at the face to prevent decompression of the soil and related settlement at the surface.

The TBM mixes the excavated spoil with foam at the face, to make it easier to handle. The mix is removed from the pressure chamber by a worm screw, discharging onto a belt conveyor. This, in turn, discharges into rail-mounted cars, which travel to the surface where the spoil is tipped into a bunker. It is later taken to a tip in lorries.

Concrete segmental liners are produced by the carousel method at a special plant. They are steam-cured and quality is strictly controlled.

Open-cut Construction

An excavation was made, starting at the pit used for lowering the tunnelling machine into position, and it proceeded in the opposite direction, towards Getafe. Immediately following this, the open-cut tunnel was constructed. The total volume of excavation was 1,300,000 cu m. The different stages of construction are as follows: floor slab; haunches, using traditional formwork; and roof, using mobile formwork.

After construction was complete, the excavation was back-filled, and the surface restored.

Traditional Madrid Method

The final part of the alignment was constructed using the traditional Madrid Method. The construction procedure is described for earlier contract sections, with a pilot gallery section 2 m-high and 1 m-wide. This was widened, with full temporary support, until the upper third of the cross-section, the curved part, is uncovered. The haunches were excavated in intermittent vertical sections, staggered with regard to the arch segments, so that the latter is never left without support. The central part was excavated prior to this.

The floor slab was constructed in 20 m lengths.

Station Construction

The cut-and-cover procedure was used for stations, consisting of the following steps: cut-off/diaphragm walls and pile piers; roof slab; excavation to concourse level; concourse slab installation; excavation down to running tunnel level; metro tunnel level crown arch; and platforms and finishes.

Two stations were constructed with a 17 m-span, reinforced concrete arch. In one case, mobile prefabricated formwork was used, and in the other, formwork was supported on the soil.

Concreting alternate sections of false tunnel roof.

Box Jacked Section

At the Fuenlabrada Central Station, the interchange with the RENFE suburban railway system consists of a 40 m x 20 m reinforced concrete concourse structure. This was built in the Metrosur station, and then jacked under the five existing RENFE railtracks, using hydraulic equipment.

The method can be summarized as: preparation of the jacking bed and construction of the thrust anchor block; construction of the box structure, consisting of a rectangular section with two cells separated by a line of columns. The face has two triangular sections in cantilever (a forward shield), which extend the sides to ensure lateral soil support during the jacking process; longitudinal stiffening of the tracks using groups of rails placed either side of each rail in use and notched below to take a length of rail at right angles to the tracks. This length is suspended from the above groups of rails using special clamps. The track stiffeners were supported on soldier beams (RSJ sections) at right angles. The rear of these rested on the structure, and the far end, lay on the ground; jacking forward of the structure. This was achieved by means of jacks located between the structure to be moved and the jacking frame. Prior to each jacking cycle, the ground was excavated using conventional methods from inside the structure; removal of propping and restitution of the tracks; and demolition of the auxiliary construction.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Contract 5

Contractor: ferrovial AGROMAN

Tunnelling Beneath Getafe Town

Contract 5 of Metrosur is located entirely within the municipal district of Getafe, and is completely underground. The alignment length is 7,432 m, and comprises 6,480 m of EPB TBM tunnelling with an inside diameter of 8.43 m, 160 m of open-cut tunnel, and 792 m of cut and cover for station box structures. Six stations were built, including two interchanges with the RENFE suburban train system. A total of 13 shafts for ventilation, drainage pumping, and emergency exits were formed by cased piles.

As well as the main structures, the works also included the rest of the drainage system, the trackwork, tunnel lighting with service specifications, and replacement of the utility services and restoration of the other points where execution of the works could affect the environment. Electrified double track has been installed throughout.

Project Data

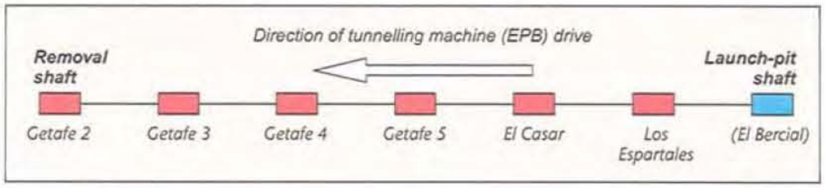
The completion time for the whole set of works referred to in the project is thirty months. The award budget, inclusive of Value Added Tax, for the works is €160,090,230.

The profile of the tunnel runs through different types of ground: sand, clay, marl and clay, black clay, chalk marl and solid chalk. Due to the high compressive strength of the ground, the EPB TBM was designed with special features to deal with relatively hard ground.

Launch pit for Herrenknecht TBM at El Bercial.

Tunnel driving lasted 502 calendar days with an average performance of 12.9 m/calendar day and maximum advances of 34.5 m/day, 199.5 m/week of 7 days, and 772.5 m/month of 31 days. Once the TBM was dismantled, the tunnel was cleaned for laying track. It took 107 calendar days to lay and concrete the 14,665 m of track.

The six station cut-and-cover work employed different types of diaphragm walls, including conventional bucket excavation, Hydrocutter, cased piles and prebores. The roof slabs are either prestressed or reinforced concrete structures, while concourse slabs and inverts were made of cast-in-situ reinforced concrete. The average period for building each station structure was eight months.



Direction of EPB drive.

Geology

The most important of the varied ground types, for their extent, are peñuela (marl and clay), black clay and chalk marl, with a compressive strength of 130-150 kg/sq cm (12.8-14.7 MPa). The tunnel either runs below, or crosses, the groundwater level at all times, with an approximate water head over the tunnel crown of 14 m.

EPB Tunnelling Machine

The main function of the EPB-type shield tunnelling machine is to guarantee the stability of the face of the tunnel and the section where the construction stages are being carried out, thereby assuring minimal surface subsidence. The Contract 5 machine, made by Herrenknecht, is watertight to an operating pressure of 3 bar. Its weight is 454 t, and it consists of a cutterhead, main shield body, and a tail shield.

The tunnel diameter is determined by the operation of the Metro. The tightest situation requires an inside diameter of 8.43 m, which is obtained for the Madrid type segment of 320 mm-thick reinforced concrete with an excavation diameter of 9.38 m.

Named Mares del Sur, the TBM was purchased new for this project, and possesses the latest advances in this type of machine. Amongst these are: total automation; laser-based guidance system; ability to install an invert segment at the bottom of the ring; a mixed-face cutting head with discs for rock cutting; and automatic remote data transmission to the site office.

Tunnelling Performance

Of the 502 days taken to drive the whole tunnel, including, crossing five stations, 398 days were used for tunnelling, and 104 days were used in crossing the stations. The drive started on 17th October, 2000 and finished on 2nd March, 2002.

The effective TBM production time represented 58.7% of the total, with 36.3% boring, and 22.4% erecting rings, while 41.3 % of the time was lost in logistical stops, derails or maintenance.

The TBM was launched at the El Bercial shaft, close to where El Bercial (G8) station was to be located. A stockyard was built, and the segments stockpiled near this access, along with the rest of the installations for compressed air, mortar plant, ventilation system, and so on. The excavated spoil was also removed from this point. The tunnelling machine continued on its path until reaching Conservatorio (G2) station on 2nd March, 2002, where it was dismantled and removed in 39 calendar days.

Once the TBM finished the drive, tunnel cleaning took place. In 43 calendar days, the entire double construction track was removed, and the tunnel was cleaned out. After this, the tunnel was filled up to Metro track level with a dry material made of cement and gravel. It took 39 calendar days to lay and roller-compact the 155,000 t of material into the tunnel.

The tunnel lining is formed of Madrid-type rings consisting of seven different trapezoidal segments, six of them occupying 12/13 of the structure, and the frusto-conical keystone having 1/13th.

Quaternary	Anthropic waste fills Alluvial clay and sand deposits	
Tertiary	**Madrid facies**	Roughs and/or sandy roughs
	Transition facies	Softened stones: brown, green and greyish clays. (Moderately firm to firm). Marl: brown, greenish and greyish carbonated clays. (Hard). Sands and brown and greyish micaceous silt. White and pinkish sepiolite clays.
	Central facies	Chalk marl and black clays Chalks of solid, crystalline and fibrous appearance with centimetre-thick layers of black clays.

Ground types found through Metrosur Contract 5.

The segment adopted is of the precast reinforced concrete type, 320 mm-thick, with an average length of 1.5 m, ranging from 1.459 m to 1.542 m. The rings are jointed by means of 13 equidistant (i.e. 27.692° apart) zinc-plated pin bolts, with two bolts per main segment, with only one in the keystone.

Track Work

The track work planned complies with the Metro de Madrid specification for trains composed of 6.000-type cars. It is of track-on-slab construction with naturally hardened 54-kg/m rail, resting on reinforced-concrete sleeper blocks every metre. These are covered on their inner and side faces with Corkelast type elastomer, and will have to withstand a load of 12.5 t per axle. The anchorage with the rail is SKL-1 type.

The single track took 107 calendar days to lay, using three teams from 6th June to 20th September, 2002. It consumed 29,330 m of UIC 54 rail, laid in 18 m-long strings with 30,500 sleeper blocks, four turnouts, 1,684 rail welding points and 15,130 cu m of concrete.

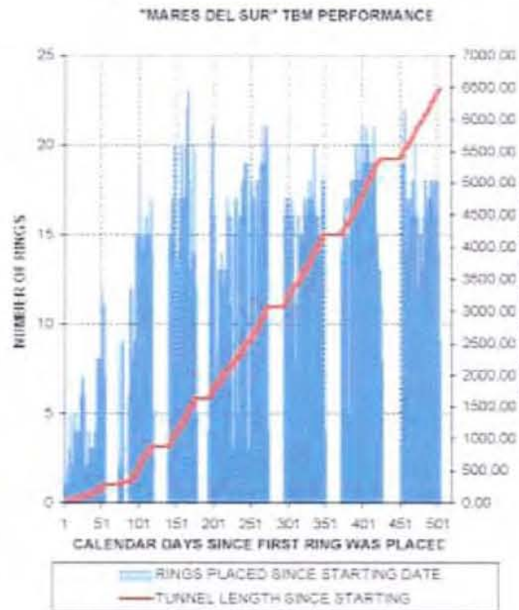
Stations

Metrosur Contract 5 includes the six stations: Conservatorio (G2), Alonso de Mendoza (G3), Getafe Central (G4), Juan de la Cierva (G5), El Casar (G6) and Los Espartales (G7).

The layout of all the stations in this section is similar, and all have an entrance concourse floor and a lower platform floor. There are one or two street accesses to the concourse equipped with fixed stairs, a pair of mechanical escalators and a lift. All are provided with one emergency exit and ventilation shafts.

Two stations have special features designed to offer access both to the Metro and the RENFE suburban train system: El Casar (line C-3) station and Getafe Central (line C-4) station. In addition, these stations are equipped with power substations.

Removing TBM cutterhead through G2 shaft.



Mares del Sur TBM performance.

El Casar station is a shared interchange concourse for access to RENFE, meaning that the station has to align as closely as possible with the route of the existing railway line, and with an orientation parallel to it. At an intermediate level, between the suburban station and the Metro platform, there is a concourse which serves as an interchange between both lines, besides providing access from the outside.

The Getafe Central station forms part of the Getafe suburban complex. The Metrosur track axis lies transversely to the RENFE track axis, and at a lower level. The station is designed with a concourse over the tracks at a midway level in RENFE station platforms. Access to the concourse is gained directly from the RENFE suburban platforms, via two facing stair cores. The route from the concourse level access to the platforms is also indirect, by way of two vertical communication cores.

Construction of the stations started before the passing of the TBM. This offers a number of advantages: first and foremost, saving the tunnelling machine from excavating and installing the lining, which would have to be demolished later when excavating the station; secondly, laying the floor units against the ground, with the resultant saving on formwork; and lastly, execution of the roof slab in a short period of time, so that the streets involved may be re-opened for normal use.

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Cut and cover was used for the station excavations, consisting of the same stages as for most stations in the other contract sections.

Diaphragm Walls

The cut-off diaphragm walls of the station boxes were executed with different procedures, depending on the type of ground.

The Hydrocutter method of excavation was used at Espartales and Juan de la Cierva stations, where the subsoil contains materials such as hard chalks. The system of excavation consists of steadily cutting and reducing the size of the material to be excavated, and mixing it with the bentonite suspension. The mixture is then pumped by a complex centrifugal pump, via a system of pipes, to the sand removal plant, so that the slurry may be reused a number of times until the successive cycles make it unfit. The bentonite supports the earth, and prevents cave-ins. In addition, it does not mix with water, preventing possible seepage from the walls into the excavation.

Conventional bucket excavation was used when the subsoil contains medium-resistance materials such as sands and clays found at Conservatorio station. The system consists of guiding the bucket by means of cables for raising, lowering and opening.

A boring bit was used on hard layers of ground. This is provided with teeth at the bottom and is attached to the sides of the bucket for raising and releasing. In this way, it breaks up the hard layer, so that the earth material may then be removed with the bucket.

Cased piles were used at El Casar, where the subsoil contains such hard earth materials as chalks, but in the upper layers the ground is soft and not very cohesive, with a tendency to crumble. The main advantage lies in its high performance. To prevent the crumbling of the ground in the first 5 m or so, casing is done with recoverable metal liners, so no shoring is required once the layer of anthropic waste fill is passed.

Hydrocutter used at Espartales station.

Internal view of El Casar station.

Conventional bucket excavation with pre-boring was used for Alonso de Mendoza and Getafe Central stations, where the subsoil contains hard materials such as chalks. Two or three preliminary bores were made with a pile driver, breaking up the columns of hard ground in each wall module, to assist subsequent excavation with the conventional bucket. In these particular cases, thixotropic slurry was used due to counter a layer of water-saturated sand in the subsoil, so that ground retention was achieved.

Box Construction

Once the diaphragm wall box is built, the roofing slab is formed on the ground using plain formwork, consisting of grooved and tongued wooden panelling. The roofing slabs for the relatively narrow areas of stations are of reinforced lightweight construction, so as to reduce their actual weight and edge. Prestressed slabs were used for wider areas of stations, in order to be able to do away with the pile pillars that would otherwise support the floor units for such large spans. A more open-plan space is thereby achieved inside the stations. However, in some cases, this space is not completely free, because metal ties are installed to anchor the concourse hanging from the upper slab.

In those stations where arrival of the TBM is imminent, or in the event of it not being able to pass through the space between the invert and the concourse slab, excavation is carried out down to the level of the invert, and construction then waits until the TBM has passed through. The concourse slab is then built, resting on

Main project details

		Unit	Measurement	Total Measurement
m	**Total length**	EPB tunnel	6,480	
		Open cut tunnel	160	
		Cut and cover (station boxes)	792	**7,432**
kg	**Reinforcing steel**	Diaphragm walls and piles	6,107,544	
		Tunnel lining segments	4,765,467	
		Other structural work	7,824,143	**18,697,154**
m^3	**Excavation**	Diaphragm walls and piles	54,028	
		Tunnel	445,880	
		Other excavations	852,296	**1,352,204**
m	**Cased Piles**		6,571	**6,571**
m^2	**Diaphragm walls**		30,142	**30,142**
m^3	**Concrete**	Diaphragm walls and piles	52,727	
		Tunnel lining segments	59,004	
		Other concrete work	79,815	**191,546**
m	**Rail 54 kg/m**		29,444	**29,444**
U	**Sleeper blocks for 12.5 t**		32,680	**32,680**
m^2	**Vitrex type panels for covering vertical facings of stations**		6,550	**6,550**
m^2	**Italfilm panel for covering vertical facings of stations**		19,000	**19,000**
m^2	**Concourse and platform paving**		17,031	**17,031**

concrete pillars on the invert. This is the case of Espartales station.

In those stations where the TBM is not scheduled to pass immediately, and wherever it can pass through the space between the invert and the concourse, top-down excavation is carried out to concourse level. Then the concrete slab can be cast against the ground. This is then anchored by means of metal ties hanging from the upper slab. Top-down excavation will then continue down to the invert level, and this may then be cast to wait for the TBM to pass. This is the case of the stations of El Casar, Juan de la Cierva, Alonso de Mendoza and Conservatorio.

The diaphragm wall formation stage lasted an average of 70 calendar days per station, and it took only eight months from commencement until the invert was concreted.

Ground Monitoring

A control unit was set up for ground monitoring purposes. The system provided real-time information of the behaviour of ground and structures, in order to gauge excavation security. Some 140 boreholes totalling 4,061 m in length were installed for sensor installation.

All of the sensors were installed before beginning excavation, in order to be able to monitor the movements that took place when the TBM approached the location.

In order to carry out adequate monitoring and control of ground movements, the sensors were distributed in 36 subsidence sections, seven critical tunnel sections and 12 station sections. An additional continuous tunnel section was monitored every 30 min, just for academic purposes.

Ground monitoring sensors used in Contract 5

Instrumentation	
87 Levelling bases	Reference (outside of area of influence)
1143 Levelling strips	Vertical subsidence in buildings
693 Levelling points	Vertical subsidence in ground surface
25 Inclinometers (1,064 m of casing)	Horizontal deflexion in depth
101 Steel-Rod extensometers (1,799 m of rod)	Vertical displacement in depth
25 Piezometers (980 m of standpipe)	Situation of groundwater level
188 Embedment Strain Gauge Extensometer	Strain in reinforced concrete
68 Total pressure cell	Total pressure on structural elements

Contract 6

Contractor: Dragados

Serving the Town of Leganés

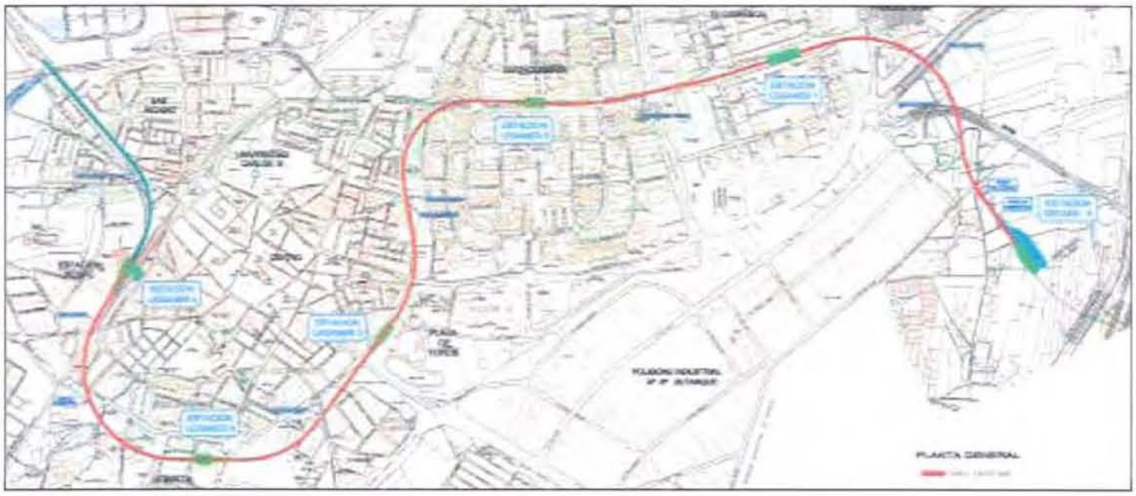
Contract 6 of the Metrosur circle line is mainly located in the town of Leganés. The contract value was approximately €176 million and the duration was 29 months. The total length of the tunnel is 6,994 m, of which 6,238 m correspond to the running tunnel, and the remaining 756 m to the six stations included in the project. In the tunnels between the stations there are six ventilation shafts, of which four are also pump stations and two are emergency exits.

Achievements on this section included the almost 7 km of tunnel excavated by TBM in only 352 calendar days. One of the six stations was very complex, with three levels, and had to be connected to a RENFE suburban train station. The old train building had to be demolished and the existing station integrated with the new one without interrupting the train service.

NFM TBM La Chata ready for launch outside Leganés.

Route Alignment

The running tunnel was built using an EPB TBM, built by NFM with Mitsubishi licensed technology. It begins at the Bercial complex at the Getafe urban limits, where the station of the same name is located. From there it continues under Rey Juan Carlos I Avenue, crossing under the Carrascal and Zarzaquemada districts, each of which has one station, named El Carrascal and Julián Besteiro. The tunnel continues along La Mancha Avenue, near the lake in Pablo Picasso Park, reaching Gibraltar Avenue and the fourth station on the route, Casa del Reloj, located next to the 'La Cubierta' bullring and the Leganés Town Hall. It continues along Doctor Fleming Avenue, and crosses Fuenlabrada Avenue to the fifth station located right in front of the door of the Severo Ochoa Hospital, which is named after it. From there it follows Orellana Avenue and Cobre Avenue, reaching the sixth station, Leganés Central, situated next to the existing suburban railway station. The subway line continues under the military railway to a shooting range area, where it connects to the Contract 1 section that crosses the town of Alcorcón.



Route plan of Contract 6 tunnel with station positions.

Geotechnical Characteristics

This section crosses ground formations that are typical in the Madrid area. The water level was around elevation 615 m throughout the zone, coinciding approximately with the tunnel's crown along the entire length.

The crown was always in the strata known locally as 'tosco', which is a mixture of clay and sand in varying proportions. The invert was excavated mostly in clean sand up to the first third of the tunnel section, from where micaceous sand was encountered until the final section, where a very hardened tosco was found.

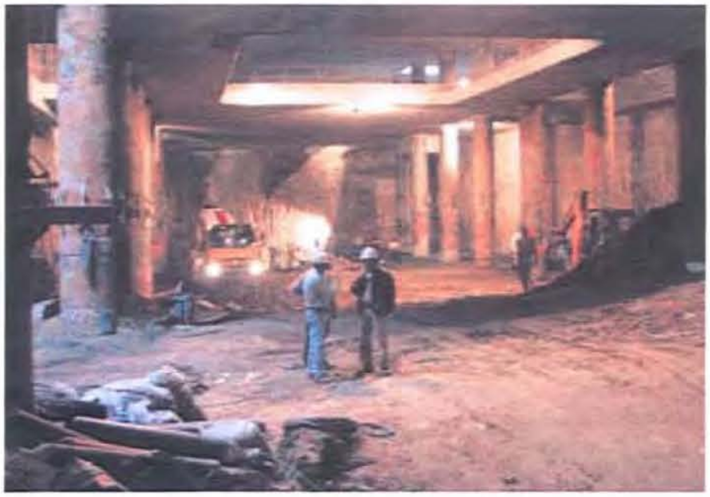
In general, the main difficulty encountered when excavating with the TBM was the heterogeneity of the face. The presence of water was relatively constant, with manageable pressures and flows, except for some sandy layers that produced significant flows at certain points. Areas were also crossed that were influenced by old wells producing massive amounts of water, but for a short time only. Water pockets hanging above the groundwater level were also found, as well as underground rivers flowing between layers with different permeabilities. All of the encountered problems were solved without much difficulty, working with the TBM in closed mode. As a result, subsidence on the surface was minimal, and less than expected. The TBM, which had worked on lines 4 and 8 of the Madrid Metro, can also be used in open mode, but this was not possible in this section due to the presence of water.

Tunnel Construction

The inner diameter of the completed tunnel is 8.43 m, the minimum required for the train sets used by the Madrid Metro. The excavation diameter was 9.38 m, and the tunnel was lined with 320 mm-thick Madrid-type precast reinforced concrete segments, shaped to create a minimum radius of 250 m. Each ring was formed of six segments, plus a truncated cone shaped crown segment, all bolted together. The rings are positioned into place by nodes and matching holes moulded into

The distances between the stations are:	
Bercial to Station 1	1,496 m
Station 1 to Station 2	1,046 m
Station 2 to Station 3	1,364 m
Station 3 to Station 4	900 m
Station 4 to Station 5	1,005 m
Station 5 to end of section	1,183 m

Julián Besteiro station under excavation.



Excavation of Casa del Reloj station prior to TBM arrival.

the edges of the segments, and firmly joined together by 13 equidistant zinc-plated steel bolts, with two per segment, except for the crown segments that only have one. A special floor segment was installed inside the bottom of the ring to support the temporary tracks.

The annulus between the segments and the excavated surface was grouted immediately with cement mortar, in order to keep subsidence on the surface to a minimum.

Heterogeneity at the face made it necessary to constantly change the proportions of foam and polymers injected at the cutting head, to allow fluid extraction of the muck. Furthermore, for a short distance, it became necessary to install six cutters in the head in order to deal with a harder layer of sandstone. Water was present throughout, although without significant pressure.

It is noteworthy that the TBM passed under three underground car parks on D. Juan Carlos I Avenue. For more than 300 m there were only approximately 5 m of cover on the shield, but no significant incidents occurred.

It should also be pointed out that, since the first TBM drive was around 3,500 m, it was necessary to change the tail brushes whilst the machine was in the tunnel. Excessive wear had made it impossible for the brush seals to properly carry out their function of containing the water, and also increased grease consumption beyond acceptable limits. It took five days to completely replace the ring of brushes, dismounting the ring segments inside the TBM shield one by one, taking care to prevent ingress of water.

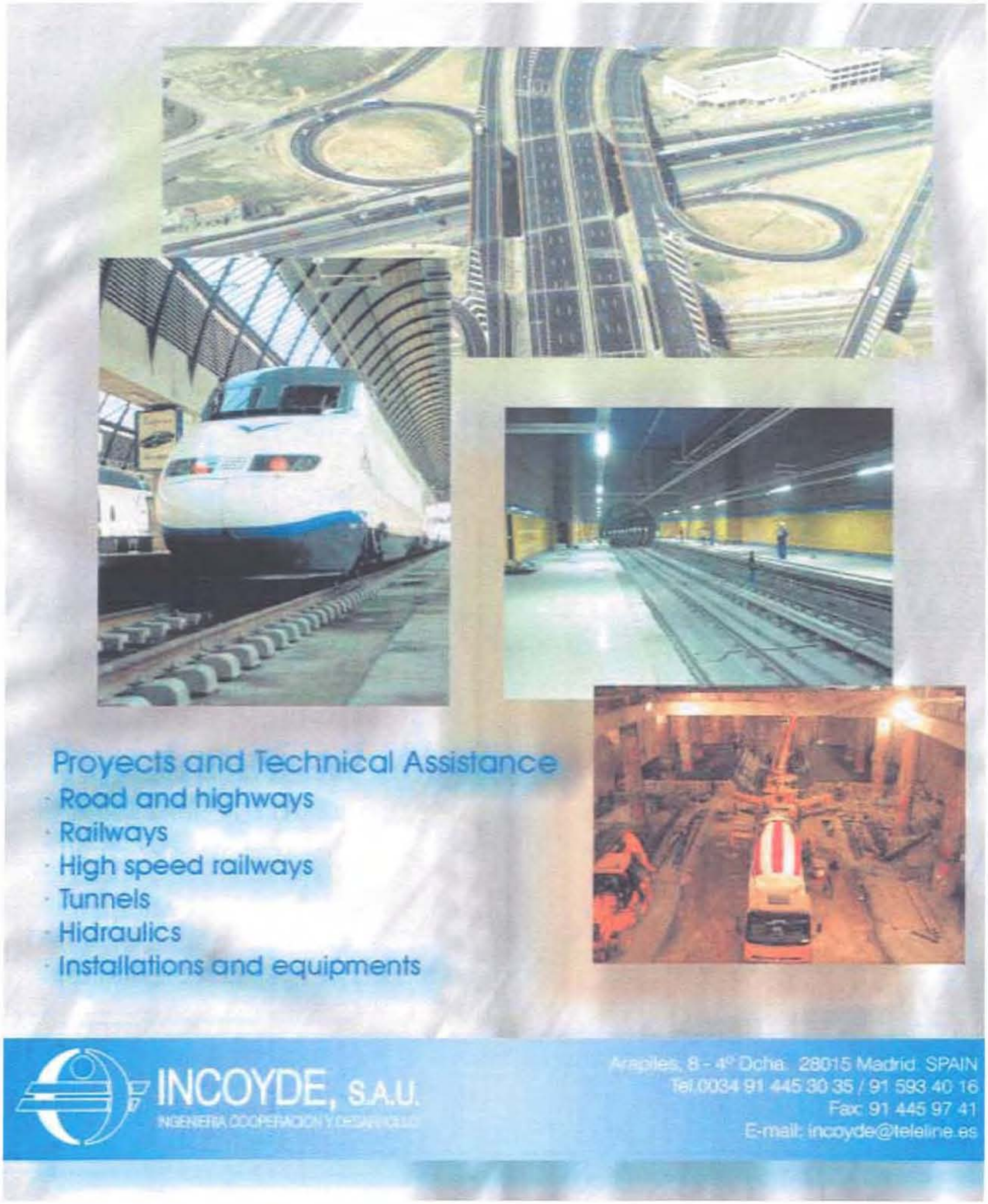
The TBM crossed each station on a prepared curved invert slab. In the case of El Carrascal and Julián Besteiro stations, however, the TBM passed through them before they had been excavated. The crossing was lined with segments, and these had to be demolished when the stations were excavated.

The excavation of the tunnel began on 5th October, 2000, three months after the work on the project had started, and it was completed on 21st September, 2001. During these 352 calendar days, the tunnelling machine dug 6,628.5 m from Bercial to the last section. It worked 8 h/shift, 24 h/day, 7 days/week, with average progress of 18.8 m/day, a real milestone in the construction of tunnels of this diameter. Furthermore, it is noteworthy that during 81 of these 352 days no excavation work could be done since for 63 days the tunnelling machine was passing through stations, 12 days were lost due to breakdowns or maintenance, and six days because of holidays. If the 63 days used to cross the stations and the length corresponding to them are not considered, the average is even more impressive: 21.61 m/day, or 22.97 m/day if the holidays are not included.

Characteristics of the NFM EPB TBM

Shield diameter	9.38 m
Shield length	11.58 m
Back-up length	91.60 m
Length of California switch	23.66 m
Total length of TBM assembly	**127.84 m**
Shield weight	890 t
Weight of back-up assembly	570 t
Weight of California switch	10 t
Total weight of TBM assembly	**1,470 t**
Installed power	4,100 kW
Rotary speed	0-2.4 rev/min
Nozzles for injection of grout and tail grease (no.)	4 + 4
Thrust cylinders (no.)	26
Maximum thrust	10,000 tf
Working torque	1,706 kNm
Release (reverse) torque	2.217 kNm

Preparation for arrival of TBM at Casa del Reloj station.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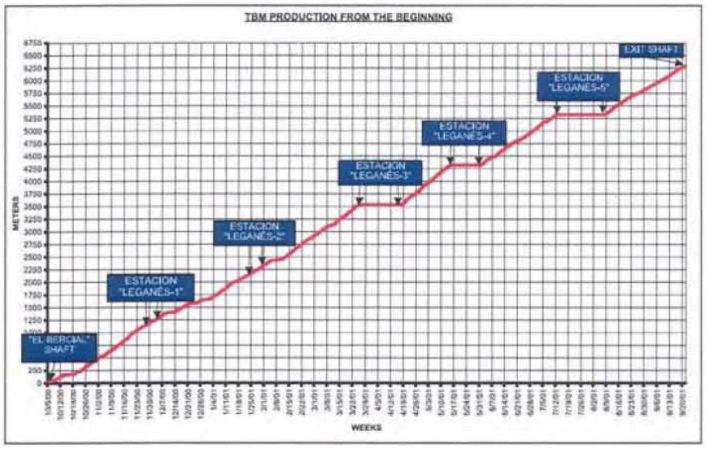


TBM production progress over 6.25 km from El Bercial to the exit shaft.

Station Structure

Given the large surface area of a station, and to minimize the time that this area must be occupied in the centre of a city, the stations were built using the top-down cut-and-cover method, in a similar way to the contract section described earlier, using diaphragm walls with column piles built at the same time.

The roof slab was cast on a flat surface a few centimetres below its bottom elevation. Cement mortar was spread and levelled on this surface, and grooved, plywood forms installed on this for the edges of the slab, prior to concrete casting.

Excavation beneath the slab was carried out via an access ramp from the entrance hall level. Following part excavation, the roof slab was anchored to the diaphragm walls using 250 mm-diameter corrugated steel bolts and resin. In the case of the first two stations the tunnel of lining segments had to be demolished when excavating the lower level.

Mitsubishi NFM TBM arriving at Casa del Reloj station.

Shafts and Galleries

The different shafts in this project were also built using diaphragm walls, in order to occupy a minimum amount of surface area, and solve the problems that might be caused by water in the area. These were then excavated using backhoes to suit the size of the shaft, and spoil was removed in skips lifted up through the shaft.

Interior frames were installed at different levels according to the shaft design, in order to brace the diaphragm walls as the depth increased. When the bottom elevation was reached, the bottom slab was concreted, and the soil treated as advisable before excavating the connection gallery leading to the tunnel.

To connect the running tunnel to the shafts, galleries were dug using the traditional Madrid Method. First the ground was consolidated, if necessary, using jet grouting or an umbrella of micropiles. The face was excavated, and roof, sides and invert supported in same stages as already outlined for some running tunnels.

Track Structure

After removing the temporary tracks, the lower area of the track-supporting slab was filled with a layer approximately 1 m-thick of compacted soil-cement, to reach the level for the pouring of the concrete track slab.

The rails were placed on concrete blocks embedded in the slab with SKL1-type anchors. Due to the length of the project, no on-rail equipment has been used for track laying. First, the track was positioned on the blocks supported by temporary frame supports resting on the cement floor. Then it was concreted into place. The frame supports could be removed easily, because their feet were set in plastic pipes that had been embedded in the concrete.

The concreted sections were some 80 m-long, occupying the complete tunnel section for double track. Three 80 m sections were being worked on at any given time, including preparation, execution and dismounting. The daily concreting of a section required a team to work at night to make the final adjustments of the section to be built the following day.

Station Architecture

The interior finishings of Metrosur were those normally used in the Madrid Metro.

Panorama of open pit excavation of La Bercial station.

Interior wall partitions were generally of brick of different thicknesses for rooms that were plastered and painted or tiled, with false ceilings of different types, and terrazzo floors. Emergency stairs were built of concrete, also finished with terrazzo.

For public zones, halls, platforms and similar areas, the ceilings were either painted, or have exposed concrete. The walls were finished with Vitrex type anti-graffiti panels to the reachable height, and drawn steel for the remainder, so that all galvanized steel structures were covered. The floors were of high strength Terastone type tiles, while the stairs were of granite. Handrails, column linings, and other decorative finishing elements were made of stainless steel.

Subsidence

In order to calibrate ground behavioural models in the different construction stages, check the precision of the design hypotheses, and maintain specified safety levels, an amount was included in the budget for ground monitoring and controlling the behaviour of structures.

Along the entire length of the tunnel, a levelling point was placed every 50 m, and a section that included three strain gauges and eight elevation points was installed in the least problematic areas.

Numbers of subsidence monitoring devices used in Contract 6

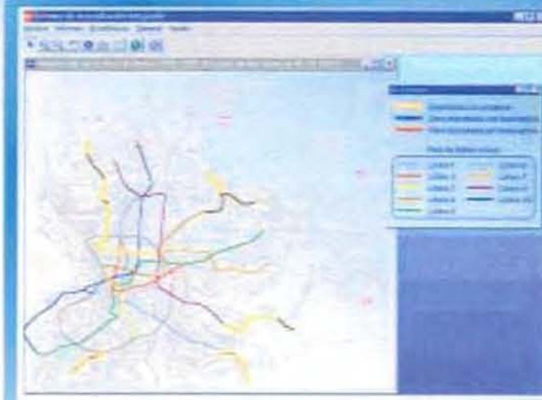
Levelling strips	973
Levelling posts	427
Bar strain-gauges	64
Pressure cells	167
Vibrating-wire strain-gauges	290
Tilt gauges	32
Piezometers	3
Incremental strain gauges	4

Furthermore, levelling strips were installed on the façades of all the buildings located nearby.

A study was made for carrying out jet and compensation grouting, under and adjacent to buildings that might suffer significant subsidence.

In each station, four instrumented profiles were installed in the diaphragm walls, consisting of four pressure cells, tilt gauges and strain gauges. The tunnel lining was monitored using instruments installed in the segments, including pressure cells and strain gauges, and the geometric deformation of the section was controlled regularly by convergence bolts. The total number of devices installed is shown in the table.

View down completed tunnel from Casa del Reloj station.



Line 10 Enlargement

Contractors: ferrovial AGROMAN FCC

Preserving Casa de Campo Park

This project covers the conversion of Madrid Metro Line 10, between the stations Alonso Martínez and Batán, to use the new higher capacity Series 7000 rolling stock in place of the narrower Series 2000. To achieve this, the inner section of tunnels and track gauge had to be enlarged, and the stations extended and modified.

In addition to this modification, Line 10 was extended to connect with Metrosur, requiring the building of a new station located at the border of Casa de Campo park. Casa de Campo Station acts as an interchange link between lines 10 and 5, which, at the same time, will have a link from Aluche.

A substantial part of the civil works had to be done in the park of Casa de Campo, which has great historical and environmental value and, consequently, a high level of protection.

Planned glass dome for Casa de Campo was too intrusive.

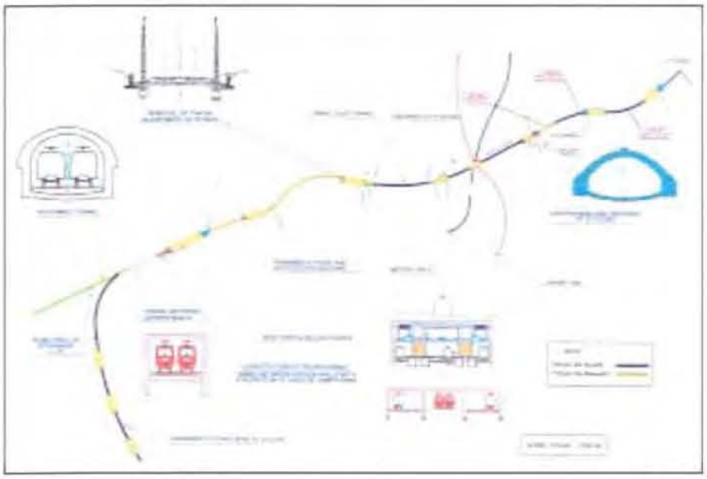
La Casa de Campo

Civils work included building the Casa de Campo Station, the modification of the stations El Lago and Batán, and the modification and extension of tunnels and platforms, which are mostly located within the Historical Park of Casa de Campo. The Park belonged to the Los Vargas family until 1561, when Philip II made it part of the Royal Patrimony. It then became a Royal Site, where the king spent his leisure time, and built waterways infrastructure, paths, ponds and gardens.

During the reigns of Philip III and Philip IV the park fell into decay, until it was revived with the arrival of Philip V, the first Bourbon. It reached another peak again with Charles III, who changed the purpose of the park from being a leisure resort, and conducted several important improvements. Once again, the park deteriorated during the French invasion and reign of Isabel II. Later, under Alfonso XIII, the Royal Site abandoned its productive side, and returned to its recreational role.

In 1931, after the Second Republic was proclaimed, La Casa de Campo was opened to public use, and declared a Historic Monument. During the Civil War, in 1936, it became a war zone, and its environment was ruined. After a campaign of cleansing and improvement works, it was reopened to the public in January, 1946.

On 6th February, 1961, construction of the underground railway between Plaza de España and Carabanchel was completed, going through Casa de Campo. In 1966, the Government Municipal Commission of Madrid City Hall, which owns the park infrastructure, developed an improvement plan. The objective was to keep the original characteristics of the 17 sq km area but, at the same time, some building was undertaken, including an exhibition hall, a



Line 10 enlargement Alonso Martinez to Casa de Campo.

library, and a swimming pool. The Parque de Atracciones, an amusement park with an area of 128,225 sq m, and the funicular railway link with Rosales were also opened. From 4th February, 1999 the General Directorate of the Historic–Artistic Patrimony of the Comunidad de Madrid has run the park as an Historical Garden.

Casa de Campo Station

The brief look at the history of the Park gives an insight into the diverse circumstances the park went through, changing its original characteristics, sometimes for good, but not always. For this reason, any work that has to be undertaken must be supervised and controlled by the General Directorate of the Historic-Artistic Patrimony and the Department of Parks and Gardens of the Madrid City Hall, which is in charge of its conservation.

Both the General Directorate of Transport Infrastructure, sponsor of the Metro civils works, and the appointed contractor consortium of FCC and Ferrovial Agroman, understood the special character of the work site from the beginning. In order to start the works, formal authorization was required from the General Directorate of the Historic-Artistic Patrimony, which imposed some conditions for the station project.

Casa de Campo station was designed initially as a glass dome, 30 m-wide and more than 15 m-high.

Despite the beautiful design, it was considered that the visual impact might be high, so the Historical Patrimony asked for a new proposal. The Civil Works Department decided, immediately, to modify the project and build an underground interchange link. This took advantage of the required lowering of the track to cover 800 m of the final section still within the park Casa de Campo.

Interchange Link

The new Casa de Campo station was built using cut and cover, with the area occupied by the works limited to the rail premises. The structural elements were designed to make it possible to restore the vegetation on the cover tiles once the works were over. In some cases, these elements were designed to support a 3 m-deep layer of earth.

In order to minimize the number of affected trees, the construction procedure was modified. The proposed concrete diaphragm walls were substituted by a piled wall, shotcreting the space between every two piles. The machines required for this work were smaller size and more versatile in their placement.

The cross section of the cut-and-cover tunnel was also modified. The tri-articulated arch was substituted by a reinforced concrete frame, which needed less space, to the satisfaction of the General Directorate of the Historic-Artistic Patrimony.

Structural Gauge Modifications

Civils work for gauge enlargement included not only the construction of the new station Casa de Campo, but also the adaptation of the existing stations of El Lago and Batán to the new rolling stock, and the tunnel widening from the nearby 'telescope' to El Lago. This tunnel had been used as an entry for the TBM during the construction of Line 10 to Príncipe Pío, and so was already dimensioned for the new gauge. Civils work also included the widening of the existing platform by 0.5 m.

The project was revised and modified, in order to minimize civil works on surface, and the impact on the surrounding vegetation. The ramp that was going to be built near the 'telescope' was eliminated, and it was also decided to widen the tunnel between the 'telescope' and El Lago Station, instead of constructing a new one.

Fieldwork was first carried out to identify the different types of trees surrounding the area affected by the Metro, in order to evolve a new design with minimal impact. However, the optimal design affected some trees, and the Department of Parks and Gardens of Madrid Council allowed their transplanting. Every single tree affected, no matter their age or type, was transplanted within the Park.

Growth of these trees was closely monitored during the two-year construction period, and more than 80% of them survived. Additionally, all the trees and vegetation within the Metro limits were cleaned and regenerated.

The construction site was enclosed, to avoid it from spreading further than permitted, and the trees within this area were protected to prevent damage. From time to time, measurement of noise and vibration were taken, to check that they were within the allowed limits.

Environmental Replacement

Once the construction was started, the environmental replacement project also began, with the help of the Department of Parks and Gardens of Madrid Council. The target was to integrate the new green surface of the tunnel's cover into the existing park of Casa de Campo. To achieve this, different expert opinion was solicited to provide ideas. An initial condition imposed was that any replacement had to use the same type of trees already existing in the park.

The project was taken over by Soluciones para el Medio Ambiente (SMA), who have long experience of working on the Casa de Campo park, together with Ignacio Bartolomé, a landscape architect.

The project divides the work into two areas: the interchange; and the rest of the environmental replacement.

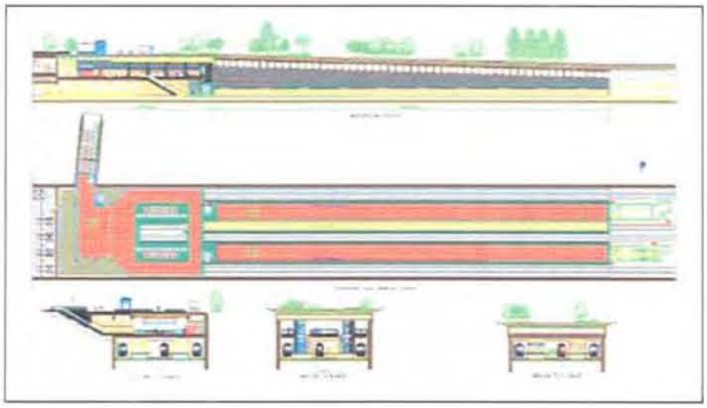
In order to co-ordinate the different bus services of the area and the new metro line, it was decided to form a new interchange area as a small square, to which a more urban treatment was applied. It was placed on the zone where the station cover slab was closest to the surface. In the remaining part of the development, the goal was to achieve a natural environment that could be considered as a genuine extension of the Casa de Campo. Therefore the concrete slabs were covered with soil, the existing slopes were softened and an organic topsoil layer was spread out to allow the subsequent planting of the chosen species.

Some 360 trees were planted, mainly pine trees (pinus pinea) of different sizes, simulating the natural growth in the environment, but also holm oaks (Quercus ilex), almond trees (Amigdalus communis), and ash trees (Fraxinus angustifolia). More than 6,400 large-to-medium size bushes like white thorn, wild rose, rockrose and blackthorn were planted, with a density of 12 units/150 sq m, as well as approximately 25,000 units of artemisia, lavender, thyme, sage, rosemary and small holm oaks, with an approximate density of 30 units/150 sq m. These measures were completed with the planting of another 1,650 bushes by the handrail fences and interchange linking areas.

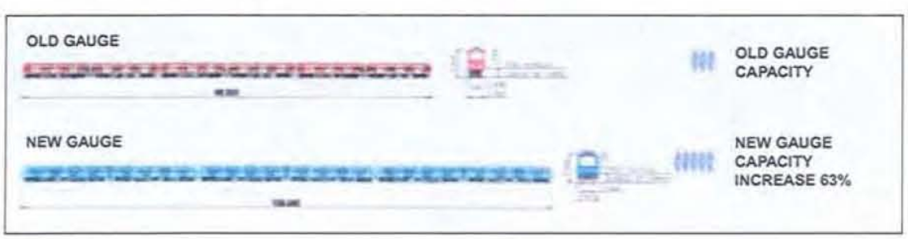
The whole surface, with the only exception of the tracks, was sown with more than 25,000 seeds of dandelion, gramineous plants and leguminous plants using the hydroseeding method.

Finally, at the end section of the construction lot, where the railway line completes its route through the Casa de Campo, the longitudinal profile was conditioned by the Line 5 tunnel, which is an extension to Campamento, and by the railway line design parameters. Due to the land topography, it was not possible to keep the railway line below grade in a 250 m-long section. Although the tunnel cross-section was modified, substituting its arch with a concrete frame having a smaller height, the tunnel-covering slab stood proud of the soil surface by up to 3.5 m. A mixed finish composed of shale plates, brickwork and limestone arches was applied, and the wall was topped with a limestone piece and a handrail. Limestone gargoyles between the arches gave a characteristic image to the platform drains.

Due to the awareness of the involved parties and the good co-operation between the different public entities, metro line construction in the Casa de Campo has avoided disturbing its environment. It has also been a development factor, adding more than five hectares of land to the Casa de Campo.



Casa de Campo interchange link.



Comparison of old and new gauges and capacities.

Line 10, Section 1A

Contractor:

From Colonia Jardín to Cuatro Vientos

Line 10 Extension to Metrosur, section 1, is part of the main north-to-southwest axis of the Madrid Metro and will enhance transport facilities between municipalities located in the southwest and the city centre. The extension comprises a 2,800 m-long tunnel section and two stations, one of which will link up with RENFE suburban railway Line 5.

The new stations will not only improve public transport in part of the Municipality of Madrid, but will also foster the use of public transport for residents in the neighbouring municipalities of Pozuelo de Alarcón and Boadilla del Monte.

The tunnel was constructed with an EPB-type tunnel-boring machine, and the progress achieved set a world record at the time. The ground had previously been treated wherever necessary, to ensure speedy and safe passage of the TBM.

Building the TBM at Colonia Jardín station box.

Functions of Section 1, Line 10

Line 10 extension of the Madrid Metro to Metrosur is intended to link the first and second metropolitan belts of south-western Madrid with the city centre, the main business corridor along the Castellana Boulevard, and Barajas Airport, via Line 8 and the main transfer station at Nuevos Ministerios, as well as with the northern sector of the city.

The 22.65 km-long Line 10 allows for transfer to RENFE suburban railways at Chamartin, Nuevos Ministerios, Principe Pio and Cuatro Vientos stations, and to other Metro lines at Plaza de Castilla (L1 and L9), Nuevos Ministerios (L6 and L8), Gregorio Marañón (L7), Alonso Martinez (L4 and L5), Tribunal (L1), Plaza de España (L2 and L3), Principe Pio (L6 and Opera-Principe Pio Branch), and Casa de Campo (L5) and Puerta del Sur stations on Metrosur (L12). In total, 11 stations out of the 19 along the extended line will allow for transfer to other rail services, enabling travel from Alcorcón to Nuevos Ministerios in 22 minutes and to Barajas Airport in 37 minutes. This represents a rather significant qualitative leap for the municipalities in southwest Madrid, with a population of over one million. The new Joaquin Vilumbrales Station, on section 2, will service the southern area of the San José de Valderas district in Alcorcón.

In order to meet demand forecasts, Line 10 has been entirely refurbished, with an increase of its width in the underground section between Alonso Martinez and Plaza de España, which previously only allowed

Laying the concourse roof at Colonia Jardín.

for narrow-gauge trains, and in the surface-level section between Lago and the new Casa de Campo station. This remodelling will enable use of a new generation of rolling stock, the 7000 and 8000 series. These trains are 2.80 m-wide, and carry over 1,000 passengers in 6 coaches. They run at up to 110 km/h, and use new signalling and train-driving technologies. This has made it necessary to increase the normal Metro electrical supply of 600 V to 1500 V, with renewal of existing sub-stations and building of new ones.

Part of Line 10, the 2,800 m-long section from Colonia Jardín to Cuatro Vientos is one of the longest runs between stations on that line. The section follows the alignment of the N-V National Highway 5, along which is to be developed the town-planning project called Plan Campamento. This will use the land throughout the area that is not required by the extensive military barracks. The town-planning project involves the construction of two new stations, one on each side of that highway, to service the planned housing development.

Tracklaying in the completed TBM tunnel.

Colonia Jardín

Colonia Jardín station is located in the area between the right side of the N-V and the M-511 Boadilla road, and services a hinterland at the southwest end of the La Latina district. The station encloses a park-and-ride lot for over 300 cars, which will extend the serviced area to Ciudad de la Imagen and the housing estates near Prado del Rey, in the municipality of Pozuelo de Alarcón. It will also serve the rest of the municipality, neighbouring Boadilla, and the University of Somosaguas, through an existing city and inter-city bus terminal.

The station concourse is located under the M-502 road and can be accessed from either side of that road. On the right side, the access is level with Calle Sedano and leads directly to the concourse, which is 5.50 m beneath the main road level and accessed by an elevator next to the Madrid-bound bus-stop. The entrance on the left side of the road caters for incoming bus traffic.

This station was also used as launch shaft for the TBM driving the tunnel to Cuatro Vientos station. A space excavated at right-angles to the station centre-line, used as ramp to access the pilot shaft, became the site of a mezzanine level for a future station for a tramway or light rail transit planned to run to Pozuelo and Boadilla. For that purpose, a U-shaped slab has been set perpendicular to the Line 10 centreline, with platforms at that height, and direct entrances from the two tramway platforms, leading to both the concourse and the two Line 10 platforms. Thus, the station will be a transfer node with a new transport system, buses, and a park-and-ride lot.

The concourse roof was built in two phases. First, the southern half was completed, and traffic running on the M-502 was later diverted over that area, until the second half was finished. Finally, traffic was reset to the original lanes.

Finally, the surrounding area has been developed. On one side, a square on a level with Calle Sedano was built, bounded by vitreous-brick walls and a stairway, on the right-hand side, up the slope between the square and the Aravaca road. On the other side of the road, the Arenas de San Pedro Street was pedestrianized in the stretch along the park-and-ride lot, and links up to the existing street layout through Calle Sanchidrián, and a newly

Cuatro Vientos station.

Patio station entrance.

opened thoroughfare planned within the Madrid General Town Development Plan.

Cuatro Vientos

Cuatro Vientos station is located on the left-hand side of the N-V road, in the triangle left between that road and the platform of the C5 RENFE suburban railway line, facing the Dehesa del Principe Park. The station allows for passenger transfer to the RENFE line and inter-city buses running to and from Madrid. This will be a significant improvement for those users in the Alcorcón and Móstoles areas, who lack a Metrosur station nearby, but will be able to ride any of the buses running to and from Madrid. Meanwhile, the C5 Line users have a new, fast and direct connection to Madrid inner city.

For easier transfer, the station has two accesses, one on each side of the N-V, and an interchange concourse linking to the C5 Line. The right-hand side access, Dehesa del Principe, consists of a 50 m-long tunnel, that branches off to the N-V access, and runs to the square at the junction of Paseo de Húsares and Paseo de Lanceros. Two escalators and a lift bring users to a street-level pavilion. The gallery is equipped with two travelators.

The connection with the RENFE suburban station is through a gallery, driven by the traditional Madrid Method, which opens onto a concourse, located under the C5 Line. This was built by sinking a 14 m-wide caisson, extended at the ends to allow sufficient space for stairways under the platforms. There are one fixed stairway and two escalators, and an enclosure on the north side for technical rooms and ticketing booths. When RENFE refurbishes the Cuatro Vientos Suburban Railway Station, this new concourse will be the only access to the station.

The space over the platforms up to the station roof, at the south-western end, has been used to house an electrical substation for traction power, on two levels: the cabling vault; and the substation proper. A special feature is that the middle slab braces the sidewalls, allowing for a clear-through cables vault, since columns to carry the top slab load are not necessary.

Tunnel Boring

An EPB-type TBM with an inner diameter of 8.43 m drove the tunnel. The lining is of reinforced-concrete segment rings made up of seven units, 1.5 m in length and 320 mm thick.

Tunnel boring began on 2nd November, 2000, from Colonia Jardín Station to Cuatro Vientos, which was reached on 21st March, 2001. The tunnel comprises 1,846 rings, covering 2,769 m between the launch shaft and exit. Boring lasted 140

Colonia Jardín station.

TBM removal point outside Cuatro Vientos station.

calendar days, representing an average progress of 20 m/day, including the days set aside for scheduled stops to set up services extensions, track laying, and Christmas and New Year's Day. This left 123 working days, and hence the average progress per working day was 24 m/day. The longest distance bored on a single day was 42 m, on 18th January, 2001, and the monthly longest distance was 939 m, bored in the period from 15th January to 14th February, 2001. At the time, this was a world record for that class of TBM.

Ground Treatment

Prior to the TBM going through specific locations that were critical due to possible damage to nearby buildings, the ground was treated in different ways. There was compensation grouting at 340 m, under a residential block, and jet grouting at other points, including 870 m and 1,540 m.

The jet grouting was intended to protect buildings near the tunnel alignment from any subsidence risk. The results were highly satisfactory, since no movements larger than planned were experienced, and the buildings were not structurally affected. This is illustrated by the following case.

The building is situated at Calle Sanchidrián No. 2, under which the tunnel runs. This building was treated by compensation grouting in two phases. The preliminary phase was intended for stress induction in the soft ground, while the compensation phase proper was performed as the tunnel was bored.

In order to monitor movements in the building, 15 levelling bolts were placed on the facade walls. An initial reading was taken and all the bolts were levelled during the first phase of the ground conditioning. Initial stability was achieved when the bolts were raised 2-3 mm.

As the TBM went by, during the night of 27-28th November, 2000, building movements were monitored. It was decided not to perform further compensation grouting, as the measured movements were within allowed values. All monitoring points remained at all times above their original position prior to the soil treatment start with elevation, in all cases, ranging from 0.6 to 4.7 mm.

At a later stage, during grouting of the TBM annulus at the tail shield, and on subsequent days, no abnormal movements were detected, and the building has remained stable ever since.

Imposing entrance to Colonia Jardín station.

Line 10 Depot

Contractor: Sacyr Corsán-Corviam

Cuatro Vientos Depot and Access

The depot of Line 10 of the Madrid Metro comprises several buildings, facilities, and associated infrastructure, the aim of which is the proper maintenance and storage of the series 7000 trains that serve Line 10. These facilities are joined to line 10 itself by a number of one- and two-way tunnels, constructed using two different methods: between piled screen-walls where it crosses the M-40; and the traditional Madrid Method for the remaining branch lines.

The 305,441 sq m depot complex is divided in several modules: three modules are designated for the parking of trains, one for maintenance, and one module for inspection pits. The blowing, washing, go-devil and dock bays have been placed separately.

There are a total of 40 tracks in the Depot, and an additional test track. Next to the main bay there is an auxiliary building for offices, lockers, and training facilities, and an electric substation building.

Concept

The increase in capacity of Line 10 means a corresponding increase in the support facilities, so a new depot had to be built in the Cuatro Vientos area. This incorporates technological advances that will optimize the operation of the new 7000 and 8000 series trains.

The stations and the metro tunnel provide the transport network, but we must not forget all the other backup facilities needed to make their operation possible. The rolling stock needs a depot from which to start each day to reach the routes, and where they can receive the care and attention necessary for a good service. The construction of the new Cuatro Vientos depot completes the extension of Line 10 of the Madrid Metro.

The contract for the depot construction was awarded in December, 2000 to a joint venture of contractors Sacyr and Corsán-Corviam. The value of the award was €38,747,036, and this was increased with a complementary project of €5,761,442. The total construction time of the main project plus the complementary project was 20 months, but the work was carried out in a little more than a year. The depot is located within the city limits of Madrid, in the district of Latina, and next to the aerodrome of Cuatro Vientos. It is the tenth

Aerial view of the Cuatro Vientos depot under construction.

depot on the network of the Madrid Metro, and is thus called Depot 10, as well as serving Line 10.

Depot Access

The construction of the depot access from Line 10 required connecting tunnels. Just north of the Las Mimbreras complex, three one-way branch line tunnels were built to converge in a 'telescope' to a 2-way tunnel with a length of 677 m. The tunnels were built with the cut-and-cover method, using 800 mm-diameter piles with an average depth of 14 m. The slab that covers the tunnel is of reinforced concrete with a thickness of 800 mm, and a width of 8.20 m in one-way tunnels, and a width of 5.20 m in the rest.

Once the pile screen was cleaned off, a mat was placed, and the surface shotcreted in three layers to reaching a final thickness of 150 mm. In order to excavate the tunnels, one of the one-way branch lines was used, with a dirt ramp for spoil removal.

The crossing under the M-40 began with a mined excavation. The limited ground cover was less than 4 m at some points of the longitudinal profile, so the potential risks of a mined tunnel under this important ring road led to the change of method. It was therefore decided to construct this section between piled screen-walls.

This system has a section made up of two rows of piles of reinforced concrete, executed from the surface, and a roof slab supported on the wall after the ground between them had been excavated up to the support mark of the slab. Then the surface was reinstated to the original level, and the ground between the screen walls excavated down to the lowest level of the invert slab.

The length of the tunnel under the M-40 is 70 m, of which 62 m involved the screen-wall system. The process was carried out in four phases, in order not to interrupt the vehicle flow at any time. Temporary lanes were set up to divert traffic, and the affected areas were posted with signs. Most of the construction work was done at night.

Rail Yard

In order to construct the railway yard at the tunnel exit, some 300,000 cu m of earth was moved. This ground was substituted with selected material, to form a drainage network. The railway yard is made up of a group of 33 tracks of 54 kg/m ULC54 rails, with monobloc sleepers of pre-stressed concrete with post-tensioned frames. The fastenings are of the Pandrol type. There are also 40 side-tracks of TO 0.125 rail set on Akoga sleepers and two concreted bretelies.

Access tunnel portal.

The tracks give access to both the main bay and the auxiliary bay, with areas for blowing, washing, go-devil and dock. Altogether, there are 6.5 km of tracks in the yard. A branch comes out of the main group of tracks and leads to a 1,200 m-long test track, which is designed for a test speed of up to 80 km/h.

Forty tracks run through the railway yard, of which 24 go to the three parking modules, six to the maintenance module, three tracks to the pits module, and seven to the bay with set facilities.

Vossloh HM fastenings were used over a 500 mm-thick form layer made up of QS3 type soil and 300 mm of ballast under the sleepers. Exceptions are in the areas that have side-tracks where rails are supported on wooden Akoga sleepers, and for the tracks in the tunnel where the rails was placed on elastic blocks.

View down the Rail Yard towards the access tunnel under the M-40.

Cuatro Vientos depot and test track.

Under the form layer, a drainage system was designed comprising a network of hip heads and valley channels, which was also connected to a series of drains and collectors, ensuring the perfect drainage of the platform.

In the sundry modules of the main bay, the tracks were laid in a different way. In the parking modules rigid block and embedded track were used. In the maintenance module there are metallic forms, and in the fixed facilities bay a combined system where five tracks are embedded, and two are on metallic shapes. There are also 15 m of embedded track in the front of the bay.

Depot Buildings

The facilities occupy a total surface area of 395,441 sq m, which includes the bays of the depot building at 19,152 sq m, auxiliary building at 2,100 sq m, the facilities building and the tracks.

8000-series train sets inside the maintenance section of the depot.

The depot structure comprises two buildings: the main depot bay, with the capacity to house up to 30 trains of the 7000 series; and another separate building with the necessary auxiliary facilities.

The structure of bay is of prefabricated concrete in posts, beams and ties, with 24 m and 34 m lights, according to the area. Due to the ground conditions, deep foundations with sets of 50 mm piles, 14 m-long were constructed. The roof is of ribbed and pre-coated, panelized plate, 50 mm thick, with translucent panels as skylights. The outer closing is also prefabricated concrete with a Macaél white arid finish.

Once the works were finished, the perimeter of the entire facility was enclosed with a Panzer-type fence to Metro standards, and the surrounding area was returned to its initial environmental state. Following the criteria of environmental standards previously established for actions at Casa de Campo, towards the City on Line 10, a small intervention was made on the area surrounding the Depot. The aim was to re-establish the original landscape, improving it as much as possible with revegetation and planting of trees. The slopes next to the M-40 were treated with special interest and care, as were the landscaped areas within the substation grounds.

Advanced Facilities

As mentioned above, the Cuatro Vientos depot includes certain technical advances that improve the service of the Metro System.

In the auxiliary building, there is an innovative simulator that reproduces virtually any incident that may arise in the use of the trains. It incorporates stations, tunnel and the rest of the Metro facilities, and allows for the application, with no risk whatsoever, of the solutions normally deployed. To this end, full-scale, high-resolution images are projected on a screen in real time, as they would be seen in normal journeys on the new 7000 and 8000 trains.

Among other features, replica trains have an AT and ATO driving system, and overhead projection mechanisms that allow the visualization of the real images. They, likewise, have emergency evacuation systems, a fire fighting system, communications, and different methods of operation and driving. Even real sounds can be perceived from the cab of the train, as well as the rest of environmental conditions.

This system of learning through simulations offers savings and improved services. As a result of not having to test drivers on real trains, the simulator releases more trains for normal service.

Line 10 Extension, Section 2

Contractor: Dragados

Cuatro Vientos to Alcorcón

Section 2 of the Madrid Metro Line 10 extension starts at Cuatro Vientos station with a twin single-track tunnel. After passing under the N-V motorway, it crosses under land occupied by military installations, and after crossing the M-40 highway it reaches the Mimbreras area. Beyond this point, it continues towards the Park of Las Presillas and, after crossing the M-406, it makes its way to the Alcade Joaquín Vilumbrales Avenue station. It ends with a 'telescope' and a shunting spur in a single twin-track tunnel, before the entrance to the Puerta del Sur station on the Metrosur.

TBM and other methods were used for the running tunnel, station, 'telescopes', and spur lines to workshops. Ground consolidation treatment was required in places in order to work under optimum safety conditions.

Spur line 3 seen from telescope 2.

Section 2 Contract

The section 2 contract was awarded to Dragados, Obras y Proyectos. The section begins at Cuatro Vientos station in a twin 'telescope' that allows transition to Section 1. Here Section 1 consists of a double-track tunnel passing into a twin single-track tunnel section. After that, the alignment smoothly turns southwards, approaching the N-V, which is under-crossed almost tangentially. Then it passes under military land, including the Regiment of Railway Sappers and the golf course of the Barberán Military Sports Club. Beyond the M-40 and Mimbreras there is a link section of three spur lines connecting with Line 10 workshops through 'telescopes' 1 and 2.

Beyond 'telescope' 2, the vertical alignment descends and enters the Arroyo de la Canaleja groundwater table. Then the alignment has a vertical curve to cross under the stream bed, and rise afterwards. In the Park of Las Presillas, the track turns westwards and, after crossing under the M-406 Alcorcón ring road, and a residential housing development, it makes its way to the Alcalde Joaquín Vilumbrales Ave. After crossing Los Castillos Ave, it reaches Joaquín Vilumbrales station, the first station in the municipality of Alcorcón.

Beyond the station, there is a 'telescope' to bring the tracks closer, with the next section consisting of a double-track tunnel. At the end of the section, and before

entering Puerta del Sur station, which is part of the adjoining section, there is a shunting spur with switches to facilitate operations between the two stations.

Construction of Junctions

The elements of 'telescopes', spur lines and shunting spurs, although having different functions in the operation of the line, have a common execution method. The 'telescopes', in 'box' construction, respond both to the need for vertical shafts to assemble and disassemble the TBM, and for transition of the tunnel width changes. The spur lines are the connection tunnels from main lines to train parking areas in the Mimbreras Depot. The shunting spur is a double-track tunnel, which connects the section with the Puerta del Sur Station.

The construction sequence is basically as follows: excavation and preparation of the working site; construction of piled walls for the perimeter enclosure, trimming the heads of the piles, and formation of pile wall capping beams; open-cut excavation within the walls until reaching the lowest excavation level for free-standing pile walls; formation of bracing for the capping beams; continued excavation and installation of bracing spreader beams at the intermediate level; excavation until the working clearance is obtained under the intermediate bracing level; construction of the intermediate bracing level; excavation continued until the lower level of the bottom slab is reached and the slab cast; and construction of the roof, waterproofing and re-covering with earth from the enclosure.

As a variation of this general method, when space is needed, anchorages temporarily substitute for bracing. As soon as space limitations are removed, the specified bracing is installed, and the anchorages dismantled.

Because of general presence of earth with a granular matrix, piles have been drilled with a piling machine, reinforcement inserted, and concrete poured in situ. From July to November 2000, some 1,536 off 1 m-diameter piles were installed at Mimbreras, with lengths in the range 18-23 m. Additionally, some 38 off 2 m-diameter special piles, 30 m-long, without intermediate bracing, were built. The total excavation reached 24,692 cu m.

At the 'telescope' and the shunting spur, situated in the Alcalde Joaquín Vilumbrales Ave, seven months were needed to install 797 off, 800 mm-diameter, 19.5 m-long piles.

Joaquín Vilumbrales Station

The ground plan of the station takes up a rectangular shape 146.5 m-long x 26 m-wide. There are two levels. The top level, or vestibule, has a length of 58 m, including the area reserved for services, technical rooms and installations. The bottom level is provided with a central platform, 112 m-long and 16 m-wide, with 14 m-high central columns 10 m apart. Side passages are reserved for the rail tracks, and a platform end reserved for technical rooms and installations. The architectural result is a very spacious, open-plan station.

The station was built in open-cut, using diaphragm walls in an 'ascending-descending' system, similar to that for the Metrosur stations. This consists of: construction of the 'box' enclosure with reinforced-concrete diaphragm walls executed alternately to maintain the stability of the whole; construction of piled piers in the central area; excavation between diaphragm walls down to the depth of the roof slab; construction of the slab, connected to the diaphragm walls and piled piers with reinforcement; excavation under the roof slab, between diaphragm walls and columns,

Telescope 1 with provisional anchorages.

Excavation beneath the roof slab of Joaquin Vilumbrales station.

TBM assembly at telescope 2.

within the required structural strength and until the bottom level of the vestibule slab has been reached; construction of the vestibule slab, which also connects with the diaphragm walls and piers; after required structural strength has been reached, excavation is continued under the vestibule and roof slabs, in the free-standing vestibule area, until the lower elevation of the basal slab has been reached; construction of the bottom slab with the functions of bottom closure, platform foundation, and bracing for the diaphragm wall and columns; and construction of the central platform with prestressed, forged beams, and an independent concrete slab.

The data for the diaphragm walls are: 211 m-length of 1 m-thick wall, 24 m-high; 112 m-length, 800 mm-thick wall, 20 m-high; and 60 m-length of 600 mm-thick wall, 11 m-high. The 23 piled piers which form the central pillars and their foundations, comprise a bottom pile, 1.50 m-diameter and with an average depth of 18 m, with an upper shaft wrapped in a metal tube, 1 m-diameter and with a visible height of 14 m.

TBM breakthrough at Cuatro Vientos shaft.

Construction of the diaphragm walls and piled piers was completed in five months, and required the excavation of 7,234 cu m for the walls. The roof slab is a metre deep, with 180 kg/cu m of steel reinforcement. The 4,247 cu m of concrete for the slab was poured in four stages. The vestibule slab, comprising 906 cu m of concrete, was executed in a single phase, so it was necessary to pour concrete continuously for 24 hours.

Running Tunnel

The section consists of twin single-track running tunnels of circular section, with an inside diameter of 6.7 m and a minimum distance between tunnel axes of 11 m.

The 'Cibeles' TBM, made by Lovat, was used. It installs non-universal segmental rings with a length of 1.208 m, 825 mm-thick, and with the key segment closing the ring. The EPB works to balance the ground pressures at the face to reduce the risk of soil collapse but, additionally, after assembling the ring, special grout is injected to the annular space. Subsidence is clearly reduced.

The Membreras telescope (2) was used as a vertical shaft to open intermediate faces and remove spoil from the four tunnel boring operations in the project: two between Cuatro Vientos and Mimbreras, and two between Mimbreras and Alcorcón.

The execution sequence was the following: assembly of TBM at Membreras and launch from the shaft to open intermediate faces and remove spoil at telescope 2; boring of tunnel 1, axis 2 in the north-east direction from Mimbreras, until the first Cuatro Vientos target shaft was reached; partial dismantling of the TBM, lifting and transportation to Mimbreras; assembly and second launch of the TBM in telescope 2; boring of tunnel 2, axis 1 in the north-east direction from Mimbreras, until the second Cuatro Vientos target shaft was reached; partial dismantling of the TBM, lifting and transportation to Mimbreras; assembly and third launch of the TBM machine in telescope 2; boring of tunnel 3, axis 1 in the southwest direction from Mimbreras, as far as the Joaquín Vislumbrares Station, which became the removal shaft; partial dismantling of the TBM, lifting and transportation to Mimbreras; assembly and fourth launch of the TBM in telescope 2; boring of tunnel 4, axis 2 in the south-west direction from Mimbreras, as far as the Joaquín Vislumbrares Station which again became the removal shaft; and partial dismantling, lifting, final dismantling and removal of the TBM at the end of its work.

This sequence was planned to take advantage of operating from Mimbreras, in the open country and well connected to the M-40. This allowed spoil removal, siting of a precast segment storage yard, and supply of other tunnel construction materials. The major Mimbreras telescope 2 dimensions needed four areas from where to launch the TBM, and to have a wide open space to park and lift the mucking out wagons.

Tunnel construction began on 18th October, 2000 and finished on 26th November, 2001. In just over 13 months, 6,087 m of single-line tunnels were bored, and the TBM was dismantled and assembled three times, along with necessary technical stoppages. Discounting these stops, the average performance was 750 m/month, with a maximum of 894 m in October, 2001. The daily progress record was set on 15th October, 2001 by placing 43 rings, the equivalent of excavating 52 m of tunnel.

Geology

All the strata passed through by the TBM belongs to the so-called Madrid facies, with occasional overlapping of more recent terrain of a similar origin. With the exception of artificial fill and some recent alluvial remnants, crumb-sized, clayey sands (with less than 15% fines), coarse sands (arenas tosquizas with 15-40% fines), sandy clays (tosco arenoso, 40-60% fines), and some remnant of tosco (i.e. silty, 60-80% fines) from the decomposition of granites and gneisses of the Guadarrama Sierra, come to the surface. These basically consist of feldspar-like sands (arcosas), with pebbles or blocks of metamorphic rock. The matrix of the whole is yellowish clays. In simple terms, it is possible to consider the ground as predominantly coarse materials on the surface, and finer materials at depth.

Crumb-sized sand, generally very consolidated, predominates at the beginning of the section, with water levels near in the Cuatro Vientos area. This predominance is maintained as far as the Arroyo de la Canaleja vicinity, with occasional coarser lenses, or tosquizas. After this small stream, towards Alcorcón, finer dentritics begin to appear, also over-consolidated.

Ground Treatment

Ground treatment action was necessitated by incidents during tunnel boring, requiring consolidation and reinforcement treatment so that the work could take place under conditions of maximum safety. The following incidents and actions stand out in chronological order.

During the driving of tunnel 1, axis 2 between telescope 2 and Cuatro Vientos, over-excavation took place with the formation of a chimney. This became visible on the surface, within the land of the Regiment of the Railway Sappers, near Cuatro Vientos. The treatment consisted of stabilizing the chimney, excavating and removing loose material, and later filling with 90 cu m of compacted earth. Before restarting the TBM, treatment with mortar walls and jet-grouting was executed around the TBM, in front and on both sides.

When the EPB TBM reached the Cuatro Vientos shaft, the thrust of the shield machine broke through the front of the reinforced pile wall, producing a small tilt of these piles around the upper capping beam. It was only necessary to shutter and pour concrete on the deteriorated structure.

During the execution of tunnel 2, axis 1 between telescope 2 and Cuatro Vientos, a small hollow occurred at the surface, under the hard shoulder of the M-40. This took the form of a dip in the right-hand lane.

Final dismantling of Lovat TBM.

View of telescope 2.

Zephir locomotives dwarf a conventional Schoema at Mimbreras.

Some 15 cu m of mortar was needed to fill it, and the road surface was milled and reinstated.

At the beginning of the Section, tunnels 1 and 2 pass under the N-V. As a guarantee that no hollow would be left on the highway when the TBM passed, a grout-hole drilling programme was carried out from the road surface, but the volume of mortar grout used in the filling was negligible.

At the start of tunnel 3, axis 1 between telescope 2 and Joaquín Vilumbrales Station, a small chimney was discovered close to the site entrance fence at Mimbreras. As it was of small volume, it was not necessary to stop tunnel driving. The treatment consisted in stabilizing and filling it with 60 cu m of mortar. When tunnel 3 was close to reaching the exit fence of the Mimbreras site, a ground collapse was detected. The first measure taken was to advance the TBM a few metres to put it under military land lying beyond the fence, and then boring was stopped. After that, the area was stabilized, and two detected hollows were filled with nearly 400 cu m of mortar. Before restarting the TBM, preventive treatment was applied as follows. A probing programme comprised drilling between telescope 2 and the area filled with mortar, and injecting mortar grout where hollows were detected. The only tunnel bore taking mortar was that closest to the area treated, and it took 150 cu m. Four mortar pile walls were formed in front of the tunnelling shield machine, extending those on the side of the shield. These mortar piled walls were designed so that no further hollows would be created when the advance began again. The wall of piles would not allow the shield to be filled with ground at the level of the head of the tunnelling machine. This earth would tend to fall, as it was not balanced by the closed face operation of the EPB TBM.

Jet grouting columns alongside M-40 motorway.

Stabilizing Chimneys

When the boring of tunnel 3 was continued, chimneys were detected between the treated area and the M-40, and it was decided to stop again. This occurred under unoccupied military land. Immediately afterwards, the area was stabilized and filled with 1,200 cu m of compacted earth. The following treatment was applied:

between telescope 2 and the M-40 (for tunnel 4 to pass afterwards), jet-grouted columns were installed in the whole area of the Mimbreras site. These were inclined bores from both sides of the tunnel so that, when crossing over the tunnel key, they would consolidate the top and lateral ground and form a protective 'umbrella' in case of formation of hollows. Small amounts of ground could be dragged below the 'umbrella', but without the possibility of further deterioration. They would be easily repairable with grout injection holes. In addition, the ground below the military area was treated with jet-grout columns, next to where the chimneys occurred when tunnel 3 passed jet-grouting from both sides of the route, with inclined columns crossing on the key of the tunnel to achieve the same as before; mortar pile walls parallel to the highway, and therefore almost at right angles to the rail-track on both hard shoulders, and in the middle of the highway. Its objective was that to prevent excessive ground being dragged into the excavation; a by-pass parallel to the M-40 was constructed so that the lanes situated over the excavation area were never open to and used by traffic; systematic grout-hole drilling in the closed section over the passing TBM and behind it, before restoring the traffic flow. Any hollows were refilled with mortar; and passage under the M-40 was carried out only on weekends to take advantage of the decreased traffic.

When the treatments had been finished, the boring of tunnel 3 continued with satisfactory results. 20 grout holes were drilled, requiring a total of 340 cu m of mortar, equivalent to a little more than 4 cu m per tunnel metre.

When tunnel 3 reached under the bank of the Arroyo de la Canaleja stream bed, the ground level showed a collapse with sudden settlement by 5 m. Thus, it was foreseeable that chimneys would form when the shield machine passed through ground with little consolidation. In fact, a chimney was formed at this slope, and was dragged along under the slab built to secure the tunnel on passing under the ground-water table of the Arroyo de la Canaleja. As always, the restorative action consisted of stabilizing and filling the chimney with compacted earth from the surface. To refill under the slab, boring was carried out, and mortar was poured into the hollow. 11 drill holes were completed, and 48 cu m of mortar required.

In tunnel 3, in the bend formed by the Alcalde Joaquín Vilumbrales Ave, at its beginning and a little before it crosses Los Lirios St, an over-excavation took place which caused the formation of a great hollow under the paving. The most likely reason was that, when coming across fill used during the construction of a deep sewer running along the axis of the Avenue, the balance of the pressures at the TBM face was lost. The area, situated under the municipal road, was widely stabilized by using a total of 486 cu m of mortar.

Over Excavation

On the route of tunnel 3 along the Alcalde Joaquín Vilumbrales Ave, there was an excess of over-excavation without producing chimneys. After probe drilling, hollows were detected 2-3 m above the tunnelling shield. On top there was a layer of arenas tosquizas, which prevented the upward progression of the hollow. It was decided to continue with tunnelling, and to start a grout-hole drilling programme at a distance of 6-8 m, filling the detected hollows. For tunnel 4 to pass, mortar piled walls were built perpendicularly to the railtrack, at 20-30 m spacing, to stop the advance of any generated hollows.

In tunnel 4, axis 2 between telescope 2 and the Joaquín Vilumbrales Station, there was a single chimney. This occurred at the same level as in tunnel 3 and, when the same treatment was applied, 11 grout holes were drilled requiring 88 cu m of mortar. At the passage under the M-40, which was carried out following the same procedure as with tunnel 3, 10 grout holes were drilled requiring 246 cu m of mortar. At the crossing of the Alcalde Joaquín Vilumbrales Ave, the same boring was carried out as for tunnel 3, to fill the hollows with mortar.

Finally, and in order to avoid the possibility that small hollows produced by the TBM may not have been noticed, it was decided to carry out a full grout-hole programme on both axes, between telescope 2 and the Joaquín Vilumbrales Station. This programme consisted of boring along axes 1 and 2 as follows: areas that had remained untreated between the M-40 and the Arroyo de la Canaleja. These borings produced no hollows; and completing the systematic boring carried out after passage of the TBM in the Park of Las Presillas and the Alcalde Joaquin Vilumbrales Ave. The criterion adopted was that, when a boring had required mortar of equal to, or more than, 20 cu m, grout holes would be executed on both sides of the tunnel in a staggered pattern, to ensure that the already treated hollows would be filled. Some 68 holes were bored for tunnel 3, requiring 159 cu m of mortar, and 33 drill holes in tunnel 4 required 27 cu m of mortar.

Railtrack Assembly

16,245 m of track were laid, distributed between the running tunnels, telescopes, shunting spurs, spur lines and stations.

The work began on 1st June, 2001 and was finished on 2nd June, 2002. The year included several interruptions. The assembly production was relatively low at an average of 1,400 line m/month, working on the track-laying by day and pouring concrete at night. The horizontal tunnel clearance prevented manoeuvring of, and passing, the concrete skips, and this produced a delay in concrete pouring. Passage of the skips within the tunnel had to take place in reverse gear, in or out of the tunnel. Concrete pouring at night made it possible to supply concrete more continuously, due to less traffic.

Pouring concrete on the line in tunnel 1.

Mar de Cristal to Nuevos Ministerios

Contractor: necso ACS ferrovial AGROMAN

The extension Madrid Metro line 8 joins the station of Mar de Cristal with the zone of Nuevos Ministerios, by means of a 5.4 km-long tunnel, of which the 3.4 km section from Mar de Cristal to the new station of Colombia and has been driven by EPB TBM. An interchange with Line 9 has been constructed as part of Colombia station.

The remaining section, of almost 2 km, from Colombia to Nuevos Ministerios in the centre of Madrid, has been mined using the traditional Madrid Method.

At Nuevos Ministerios, a new interchange has been constructed, with connections to Metro lines 6 and 10, and the RENFE commuter railway network. Line 8 connects this interchange with Barajas international airport, to which the journey time will be just 12 minutes. It will be possible to check in luggage at Nuevos Ministerios, and modifications have been made to the existing airport station, where the Automatic Luggage Transport System SATE has been installed.

Final stages of construction of Nuevos Ministerios arcade, following successful underpinning.

Nuevos Ministerios Interchange

Nuevos Ministerios interchange is located beneath the Paseo de la Castellana between the junctions with Raimundo Fernández Villaverde and the Plaza de San Juan de la Cruz, and the interior patio of the Nuevos Ministerios. The new interchange provides a fast connection with the two most important Metro lines: Line 6, which is circular; and Line 10, the principal north-southeast axis, which will shortly connect with the circular line of Metrosur. Likewise, the RENFE connection, on the Atocha-Chamartín axis, crosses several of their most important lines.

The interchange consists of a large common vestibule beneath the pavement on the western side of the Paseo de la Castellana and the interior patio of the Nuevos Ministerios. It is located above the new station of Line 8, to permit the vertical interchange of Lines 8 and 10 with the platforms of the commuter rail station. The lower level of this vestibule, conceived as a large open space within which it is possible to visualize the circulation of all trains and the access routes to the different platforms, also has a connection gallery for Line 6, equipped with travelators to decrease interchange times.

The interchange also includes a siding area, which reaches the vicinity of Plaza de San Juan de la Cruz, which allows the change of direction and the parking of trains. Within the siding area has been incorporated a connecting branch between Lines 8 and 10, which permits the circulation of trains between both lines, giving access to maintenance and repair depots.

Adjoining the sidings area, there are two large underground electrical substations, one to serve the Metro, and the other for future expansion of supply.

Finally, a vestibule with 34 check-in counters has been constructed to the south of the Line 8 station, communicating with the central vestibule. Points of information, ticket sales desks, and a luggage collection room are included.

Voids for the passage of support and tying beams at Nuevos Ministerios arcade.

The check-in vestibule is complemented with an underground car park with four access ramps from the street level of the Paseo de la Castellana, with a capacity of 180 spaces, destined for taxis, private vehicles, and service traffic for the interchange.

Paseo de la Castellana

The new interchange at Nuevos Ministerios has reformed the old accesses to the existing stations and has added some new ones. The accesses to the even numbers of the Paseo de la Castellana, the access in front of the Nuevos Ministerios guard house, and the accesses from the vestibule of RENFE all remain, but with updated facades.

Accesses have been added, from the Castellana shopping precinct, the shopping precinct carpark, and from the Nuevos Ministerios arcade, which now functions as an additional access to the whole interchange complex.

For the construction of the perimeter diaphragm walls and the street level slabs of the interchange station it was necessary to undertake various traffic diversions.

In a first phase, two central northbound lanes of the Paseo de la Castellana were closed to traffic between the Plaza de San Juan de la Cruz and the junction with

Transverse cuts for the introduction of steel framework over RENFE line tunnels.

Supporting beams for the carpark slab.

Raimundo Fernández de Villaverde, diverting the traffic to two lateral lanes with the same direction, conserving the flow of traffic in a southerly direction.

Once this phase was completed a reversal of the circulation of traffic was undertaken, in which the two southbound lanes of the Paseo de la Castellana were closed to traffic over the same stretch as in the first phase, for which the ascending flow in the lateral lane was preserved, and the descending traffic was channelled through the completed work zone of the first phase. In a third phase, the traffic flow was restored to its original positions, except for the bus lane in a descending direction that was maintained closed until the end of the works.

Underpinning the Arcade

It was necessary to demolish part of the diaphragm walls that formed the foundation of the Nuevos Ministerios arcade to provide space for the metro station vestibule. It was not possible to demolish, stockpile and subsequently reconstruct the arcade, given that it was composed of exposed brickwork with a granite facing. Hence, it was underpinned, and a slab was constructed beneath it to support the arcade.

The phases of construction were as follows: excavation at the side of the arcade to uncover the diaphragm walls on which the arcade is founded; discontinuous perforation of voids through the diaphragm walls to allow the passage of reinforcement to act as ties, at a level slightly below the natural ground; construction of the supporting beams and their connection to the arcade, such that they form an integral part of the upper slab, with the wall embedded in it; and demolition by diamond cutting the blocks of the wall which now lie beneath the upper slab, to form an uninterrupted void. At this point, an exhaustive control of the movements of the arcade was required.

Assembling TBM for launch from shaft near Mar de Cristal station.

Cutting the RENFE Station Vaults

One of the problems posed by extensions of existing works, is the adaptation of these to the new characteristics and criteria required for the construction of the new works. To provide a large height clearance between the surface and vestibule levels of the Interchange required partial demolition the existing roof vaults of the RENFE commuter railway station. This had to be carried out whilst maintaining full train services, and without interfering with passenger access to the station.

The construction phases were as follows: support the weight of the existing vaults using transverse cuts through the vaults to allow installation of steel structure, during 3 h-long night time periods; installation of the 48 modules of the structure during nightshifts, and without the removal of the railway's catenary; waterproofing and soundproofing of the exterior of the structure to protect station users; and diamond cutting of the roof vaults into easily-handled blocks. The steel structure also provided the formwork for casting the vestibule slabs for the new station.

It took approximately 500 working days to construct the interchange. It has a surface area of 36,500 sq m with three levels serving vestibule, Line 8 and Line 10, with a depth of up to 17.5 m. The complex has 36 groups of escalators, 16 lifts, two of which offer panoramic views, 522 m of travelators in both directions, and 690 m of underground access galleries.

The works were completed in 26 months, compared to the 36 months estimated during the planning stage, and they have not significantly affected the heavily-trafficked Paseo de la Castellana.

Cutting line 9 roof vault at Colombia station.

Crossing Line 8 over Line 10

Line 8 crosses over the existing tunnel of the Line 10, beneath the Paseo de La Castellana.

Due to the proximity of the two alignments, it was necessary to adopt an alternative solution to the traditional Madrid Method, used in the construction of the tunnel between Colombia station and Nuevos Ministerios interchange.

Two galleries were excavated, one on either side of the proposed Line 8 tunnel, to act as sidewalls or buttresses to support the arch of the tunnel. These galleries were themselves supported by four columns, excavated in-situ, 2.5 m-diameter x 9 m-deep, on both sides of the crossing. The upper arch was then constructed using the traditional Madrid Method, and the invert arch was reinforced and concreted.

This distributed the loads induced by the Line 8 tunnel onto the columns, with the whole tunnel section acting as a bridge over the Line 10 tunnel. Extensive ground pre-treatment in the form of consolidation grouting was undertaken.

Traditional Madrid Method was used on Colombia to Nuevos Ministerios stretch.

Connecting Lines 8 and 10

A connecting branch between the new Line 8 and Line 10 has been constructed to allow trains to switch for access to the maintenance and repair depots. The slab of the existing car parking area had to be underpinned over Line 10 to permit demolition of the supporting columns on one side. Some of this work had to be undertaken during the live operation of Line 10, but most critical aspects, such as launch and anchoring of beams, and work directly above Line 10, were carried out during night time. The process employed was as follows: creation of voids in the new diaphragm wall, constructed as the sidewall of the depot and substation, for the introduction of the supporting beams for the car park slab; installation of the beams, prior lateral founding, construction of new underpinning columns, and subsequent anchoring to the lateral walls on the opposite side to which they were introduced; and drilling of holes from the upper part of the car park slab for the raising of the beams by means of hydraulic jacks, and subsequent anchoring to the walls and underpinning on the new columns.

Enabling works to allow construction to take place included the movement of a large sewer which passed beneath the Paseo de la Castellana and a service gallery.

Line 8 Tunnel

The tunnel of Line 8 was constructed with a total length of 5,153 m to connect the existing station of Mar de Cristal with the Interchange of Nuevos Ministerios. An EPB TBM was used between the stations of Mar de Cristal and Colombia, over a length of 3,360 m from the introduction shaft, passing beneath the streets of Gran Vía de

Airline check-in desks at Nuevos Ministerios station.

Hortaleza, López de Hoyos and Pablo Vidal, and traversing beneath the M-30 and a residential complex in the Avenidas Aster and Alfonso XII. The tunnel has an average depth of 15 m, which is 1.5 times the diameter of excavation, until it reaches the valley of the M-30, where the cover to the tunnel markedly reduces, to less than one tunnel diameter. The maximum gradient of the tunnel is 3%, located at the introduction shaft.

For the 1,778 m distance between Colombia and Nuevos Ministerios, the traditional Madrid Method was used. This section passes beneath C/Potosí, subsequently turning to align with the Paseo de la Habana, and terminating by traversing the Paseo de la Castellana to enter, from the north, into Nuevos Ministerios interchange. It has a maximum gradient of 3%, located at the exit from Colombia station, where the natural ground descends to the valley of the Castellana. The cover to the tunnel oscillates between 10 and 20 m, except over the final part in the alluvial zone of the Castellana, where cover of less than the diameter of the excavation occurs.

The radii of curvature and gradients of the alignment permit velocities of up to 120 km/h, with the exception of a 250 m-radius curve at the entrance to Nuevos Ministerios station.

Test train leaving Nuevos Ministerios for Barajas airport.

Colombia Station

Colombia station is located at the junction of Príncipe de Vergara and Colombia Streets. At this point, Line 8 crosses the existing Line 9, creating a new station with a large common vestibule, wide and homogeneous, which houses all of the accesses.

The station was constructed using diaphragm walls and piles, followed rapidly by the construction of the upper slab, to permit the re-establishment of vehicular and pedestrian traffic as soon as possible.

The station has access from each of the four sides, fitted with ascending escalators and descending stairs. Lifts are available for the physically disabled, both to the vestibule and to the four platform levels. Walking distances are short, and the platforms are easy to find.

The new station includes a connecting branch between Line 8 and Line 9, constructed using the traditional Madrid Method, and a section of tunnel of the Line 8 between diaphragm walls with two slabs, which constitute the platforms of Line 8.

Worthy of special mention is the demolition of the vaults of the old Line 9 station. This was undertaken during a scheduled closure using a single module of sliding formwork placed along the lower part of the zone to be cut, and using a diamond cutter in the same manner as for the RENFE station.

On the Expansion Theme

Contractors: NECSO Sacyr

The San Martín RENFE suburban railway connection is in response to rapid growth in the area south of Madrid, and requests for better connections between the new theme park, San Martín de la Vega, and other local urban centres. The Madrid Transport Infrastructure Agency awarded a construction contract in December, 2000 to a joint venture of NECSO and Sacyr. The agency is part of the Public Works, Urban Planning and Transport Department of the Madrid regional government.

The scheduled duration of the contract was 13 months and, in view of the extent of the works to be carried out and the services affected, this posed complications for the Contractor.

The typical section of the line consists of an electrified double-track formation with an alignment suitable for speeds of around 100 km/h. The total length is 15 km of double track starting at the RENFE suburban rail station at Pinto, and finishing at the new San Martín de la Vega station after passing through the land belonging to the theme park.

Project Elements

The rail section is UIC-54 laid in lengths of 144 m and 18 m, and the sleepers are of MR-93 concrete Monobloc type. There are two turnouts and four escape routes.

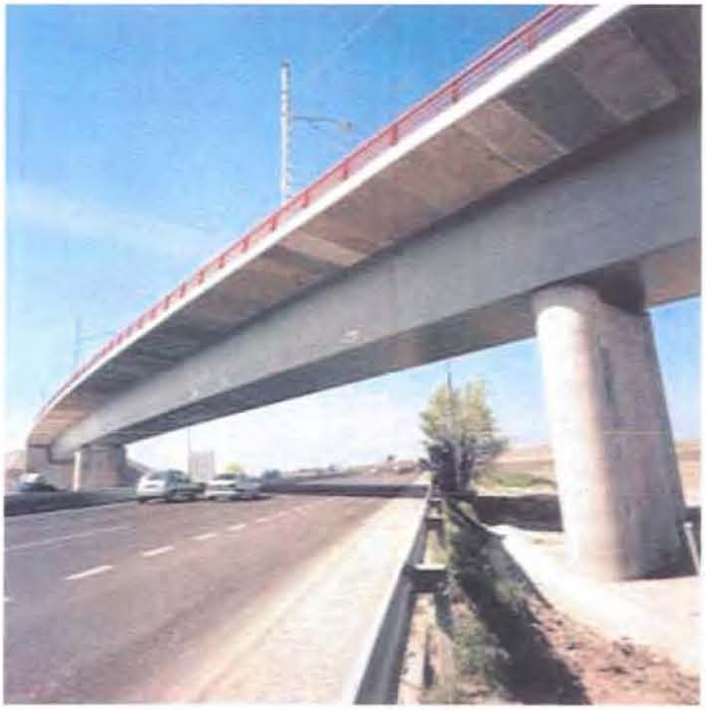
Two new stations are included: Parque de Ocio and San Martín de la Vega together with corresponding parking areas. The existing platform on the Pinto station was expanded to handle the additional passengers.

The connection with the Madrid-Aranjuez railway line consists of turnout 1, taking the form of a flying crossover with a minimum plan radius of 700 m and a maximum gradient of 2%. Turnout 2 provides the link between the existing Pinto station and the theme park on the San Martín de la Vega spur line. The points will not affect train speed on the Atocha-Aranjuez line, which is a maximum 200 km/h, and the turnouts themselves can be negotiated at 60 km/h.

National highway IV is crossed by a viaduct, which is curved in plan, and has a total length of 140 m. Lateral spans, 40 m-wide, cater for the service roads, and the 60 m-long central span crosses the six lanes of the motorway dual carriageway. The viaduct deck is a combination of steel beams and a reinforced concrete slab. It was constructed by launching the deck from one side, and pushing it into its final position. This meant that there was no

Embankments area.

Flyover with embankments.



Viaduct over the N-IV highway.

need to interrupt road traffic on the national highway, thus minimizing inconvenience to users.

A 600 m-radius curve brings the alignment into an easterly direction, and it continues to descend to the north of the El Corte Inglés department store. A section of 2 km with curves of 725 m and 700 m radius to the right and left, respectively, take the alignment between the above facilities and the M-506 by-pass. This brings the line into a north-easterly direction. The height of the embankment is not more than 9 m.

For the next 2 km, the line runs through the Los Majuelos district alongside the M-506 by-pass, using large radii curves.

After kilometre point 7.8, the alignment curves to the left, with a radius of 970 m. The longitudinal cross-section describes a vertical summit curve, until the downhill gradient reaches 2%. A second curve to the right, with a radius of 1,000 m, takes the alignment under the dual carriageway of the M-506 highway at kilometre point 9.62. At this point, there is a bridge deck formed with precast concrete beams, with a 15 m span supported on piled abutment walls.

The line now continues in a cutting with a maximum depth of less than 13 m, and maintains the same gradient up to kilometre point 11.52. It then describes a series of curves, and adopts an east-west direction at 220 m from the main entrance of the theme park.

After kilometre point 11.7, the line crosses over the theme park parking area, the bus parking area, and the park perimeter road, in an easterly direction. The viaduct that crosses the parking area is 500 m-long, and the deck consists of two V-beams, 2 m-deep, and a concrete slab. It has one span of 38 m and another two spans of 32 m on halved supports.

A 900 m-radius curve to the right brings the alignment into a southerly direction close to the foot of the escarpment, to minimize space required in the valley. Once the line drops into the valley, it has to face south in order to minimize occupation of the area reserved for future extension of the town. It therefore moves closer to the M-506 bypass, and then swings to the left in a 700 m-radius curve. The line terminates after crossing under the M-301 road on a straight of 412 m. This is the optimum position for the passenger station in view of its proximity to the centre of San Martín de la Vega.

Geology

Soil excavated on the line between Pinto and San Martín de la Vega can be divided into two types or subsections. At the beginning of the line, i.e. from Pinto to its passage under the M-506 highway (kilometre point 9.767), the excavated material consists predominantly of consolidated high-plasticity clay, of a sepiolite or montmorillonite nature, which is locally known as Peñuelas clay. Due to the conditions of deposition, the sulphur content is between zero and faint traces. It can therefore be classified as marginal, and be used for structure fill after treatment with lime.

On the other hand, the section from the M-506 to the San Martín de la Vega station is influenced by lower deposits of the Madrid facies, which are predominantly gypsum, although there are layers of grey and black clay. This material has also been

Project Data

Cost estimate of civil works	€67,247,682
Cost estimate of installed services	€17,963,202
Construction duration	13 months
Volume of excavation by mechanical means	1,082,648 cu m
Volume of excavation using explosives	432,842 cu m
Volume of embankment using material from excavation	1,179,707 cu m
Volume of concrete used	47,450 cu.m

used for fill, but it was contained in a packaged core, to prevent collapse in the event of a change in the water content.

Structures

Structures and building work in the project were as follows:

- two viaducts: 140 m-long over the N-IV highway and 500 m over the theme park parking area;
- three railway bridges with a deck consisting of precast V-beams on abutment walls;
- a railway bridge with a deck consisting of precast double I-beams on abutment walls;
- a bridge with double I-beams (flying crossover on the Madrid-Aranjuez line);
- a road bridge with double I-beams (where the M-506 road crosses the railway);
- three underpasses with portal frames where the railway crosses the theme park service road and right-of-way;
- two underpasses with closed structural frames to handle future intersections between the railway and roads in San Martín de la Vega;
- three 3-pin vaulting structures (right-of-way underpasses);
- two other bridges; one over the railway, and another over the M-506 highway.

Parque de Ocio Station

Located next to the Warner Bros Park public car park, the Parque de Ocio Station is 150 m from the park turnstiles, and consists of three separate buildings.

The main building has a square floor plan of 35 m x 35 m. It has an inset skylight for the vestibule, which forms the main hall. The building contains offices, the local control station, toilet facilities, personnel changing rooms, a cafeteria and the main vestibule. This is the most noteworthy building, due to its additional height. The concrete face of the underside of the waffle slab is exposed, and there are windows around the entire perimeter.

The other two large buildings are rectangular in plan 45 m x 7 m and 12 m-high, to house the stairs going up to the platforms. They contain a black granite flight of stairs and two escalators, as well as a large lift, which can be used for emergency evacuation. The equipment rooms needed for operation of the line are located under the stairs of one of these buildings. They include a room for the emergency generator for operation in case of power failure.

The platforms, which are 160 m-long, are located next to the above buildings. They are completely covered by a steel frame cantilever canopy of industrial appearance. The canopy houses a continuous light fitting provided with ducts, which carry the power cables and signal wires for security CCTV, loudspeakers and communications with the local control post. These platforms finish on the viaduct over the car park. For this reason, the platforms are situated 7.5 m above the main building to provide sufficient clearance over the car park area.

Parque de Ocio station.

The connection between the platforms runs under the first section of the viaduct between the abutment and the first set of columns. There is a glazed section in the center, to provide natural light to the underpass. Its roof is formed by the large V-beams of the viaduct.

The structure of the building consists of columns, flat slabs and reinforced concrete waffle floors. These elements are set on a continuous slab, which floats over a prepared surface to replace the existing soil with gypsum silt of alluvial origin.

San Martín de la Vega Station

This station is located on the outskirts of the San Martín de la Vega urban area, and

San Martín de la Vega station.

Theme park viaduct.

has a large car park and a bus stop. It is connected to the street by a pedestrian path, and links with a pedestrian bridge, which is a few metres from the main entrance to the station.

The buildings are located at different elevations, parallel to the embankment of the railway line, which is 6 m above the access level. There are three tracks, two of which use a common central platform, and the third serviced by a lateral platform. This arrangement entailed the use of a fairly large retaining wall at the back of the building, and for the underpasses. Most of the building is buried, but, due to the south-facing longitudinal wall, the interior has plenty of natural daylight.

The arrangement of the building is similar to the Parque de Ocio station. There is a double-height vestibule and, instead of an internal hall, the lineal arrangement of the building contains a garden, which is partially enclosed by the wall of the main elevation, which, in this case, is penetrated by two large rectangular openings.

Overpass at the M-301 road.

The platforms have the same 160 m length, and a canopy currently covers half of this. The access stairs from the ground floor are also covered. Due to the 10 m double width of the central platform, the canopy is supported on a portal frame, but the appearance matches the design of the canopy on the lateral platform.

Signalling and Communications

This is the first section of the RENFE C3 suburban line, and consists of double track with electronic interlocks at each end. Both of these are high-safety Westrace type, remotely controlled from RENFE's dispatching centre at Chamartin-Madrid. They are equipped with a local videographic control system at both interlocks.

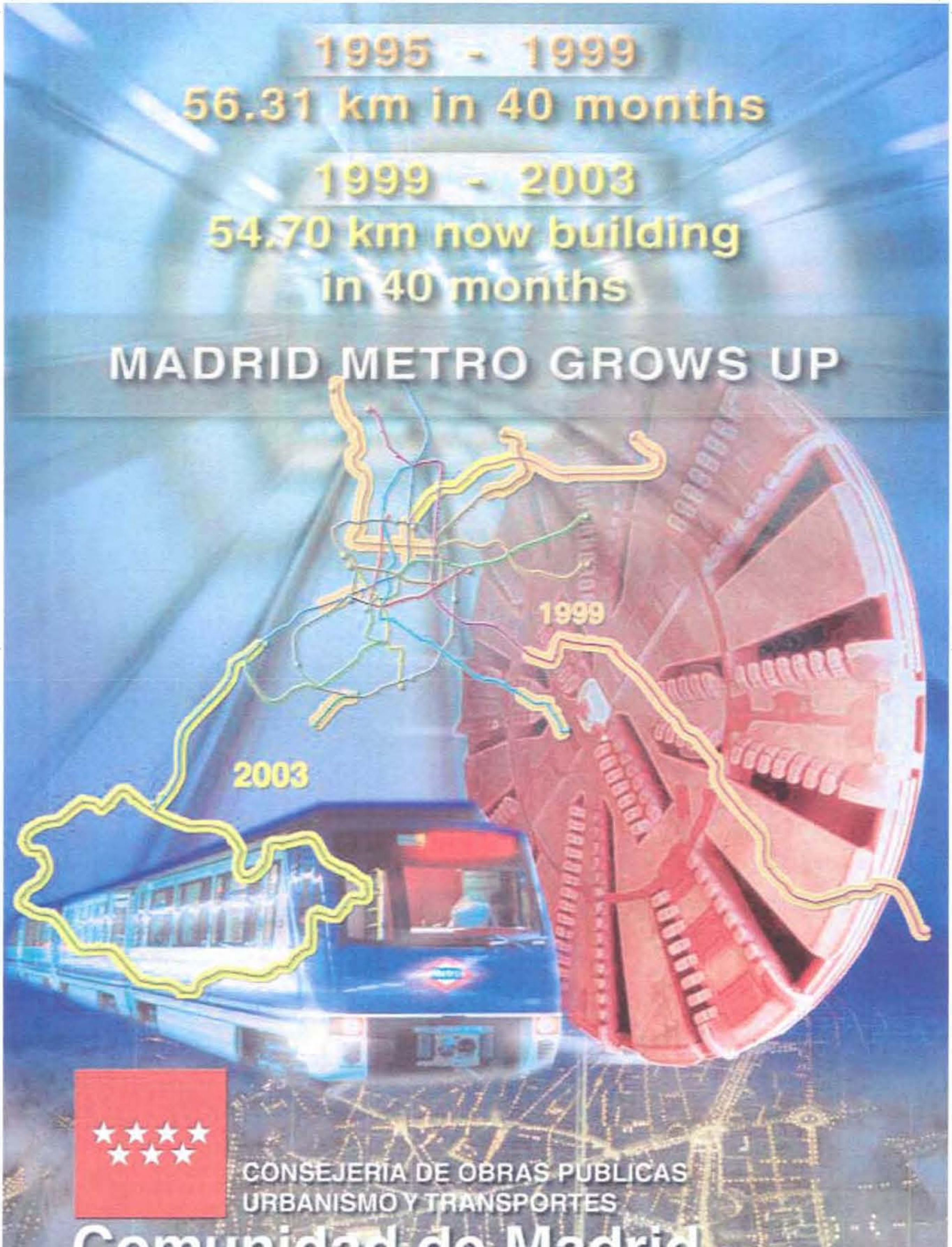
The Pinto–San Martín de la Vega section has automatic blocking control on bi-directional double track (Banalised Automatic Blocking). There are also communication systems, such as the train-ground system, that allow continuous communication between the driver and the traffic control centre.

The interlocks are provided with two sources of 2,000 V power, to RENFE's standards, and a local back-up line in the event of an outage or breakdown. Each set of points has an uninterruptable power supply (UPS), which ensures operation of the points for two hours or more in the event of a total outage. The points, and the line itself, are fitted with an automatic braking system (ABS) as normally installed by RENFE in Spain. This provides a high degree of safety under all conditions.

The train-ground communications system on the line consists of five antenna points, which use a channel reserved for RENFE for the electromagnetic signal between the train and the control centre. There is also a fibre-optic line for communication of all the signalling and building services with the various RENFE centres. There is an independent communications line using copper wire, which acts as a backup for the first.

The entire length of the line was electrified using a double row of elongated-type posts and 11.65 m posts at platforms and canopies. In addition, portal frames were erected at the Pinto and San Martín de la Vega stations.

Power for the engines is supplied at both ends of the rail link. One of these comes from the existing substation next to the Pinto station, where two new document composition feeders were installed, together with two corresponding return cables for the rail. The second source comes from a new motive power substation at the end of the line, next to San Martín de la Vega station.


1995 - 1999
56.31 km in 40 months
1999 - 2003
54.70 km now building
in 40 months
MADRID METRO GROWS UP
1999
2003
CONSEJERIA DE OBRAS PUBLICAS
URBANISMO Y TRANSPORTES
Comunidad de Madrid