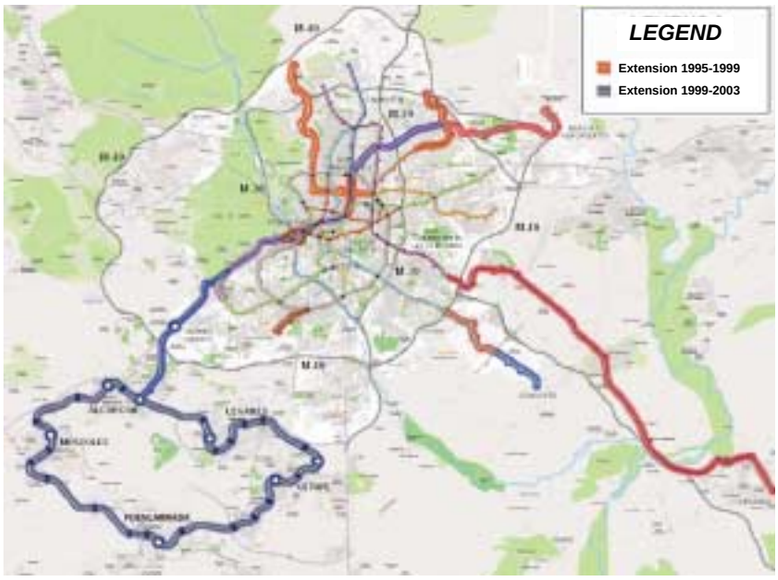
Introduction

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.

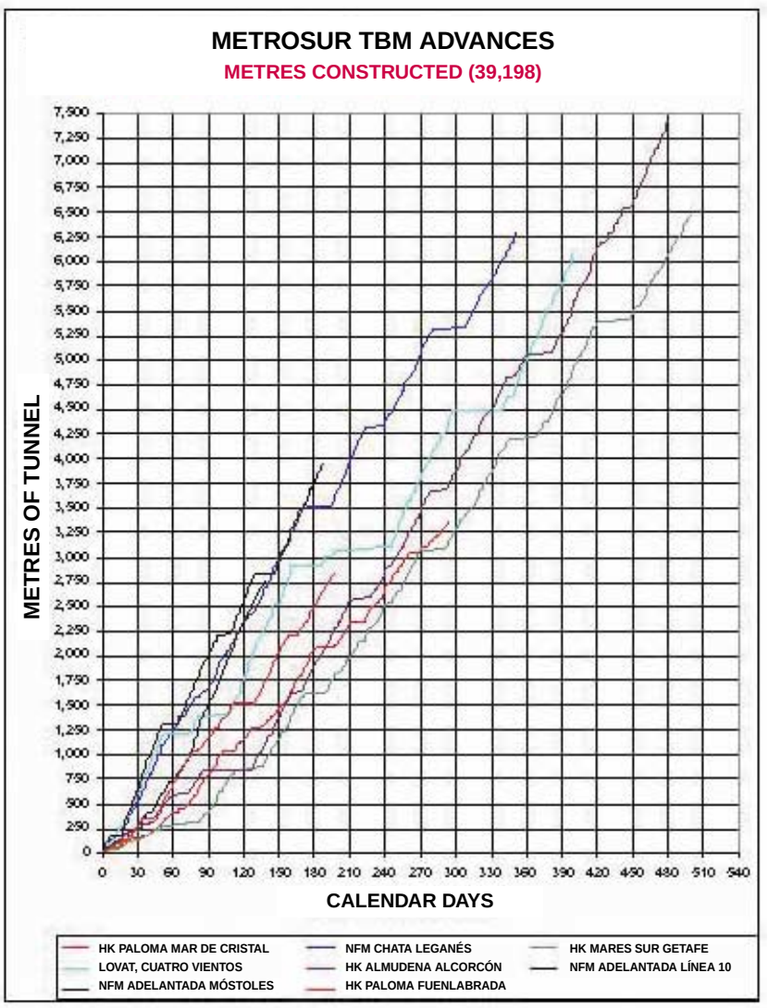
Construction Priorities

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**

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

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**