Tunneling the Metro do Porto - Under Pressure in Porto Granite

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ABSTRACT: The tunnels of the Porto Metro Light Rail project form the heart of the new 70km transport system for the Metropolitan area of Oporto, Portugal. Linking the historic central Trindade district with Vila Nova de Gaia to the South and Póvoa do Varzim and Maia to the North and to the east Gondomar, this ambitious project got off to a rocky start. Following a tragic incident which resulted in the death of a member of the public and linked to the TBM excavation, the works were halted. The client, construction manager and contractor were forced to take a fresh look at their respective roles and then to take the necessary actions imposed by a government appointed *Commission of Inquiry*. The *Commission* outlined the steps required by all concerned so that tunneling could recommence. This paper will provide a general overview of the project, discuss the events leading up to the fatal collapse, treat the steps that were required to recover from the tragic events and conclude with the various solutions adopted, including the controversial use of Earth Pressure Balance techniques in rock, finally resulting in the successful completion of tunneling in late 2003.

1 INTRODUCTION

The *Metro do Porto* project comprises 70 km of light railway; 20 km of new construction and 50 km utilised existing railway alignments. Approximately 6.5 km have been tunnelled by two tunnel boring machines (TBMs) using single-pass pre-cast concrete segments with either a 7.8 or 8.0m internal diameter. These single twin-track running tunnels are large enough to accommodate circulation of the trains running in either direction. The system comprises 64 stations of which 12 have been constructed underground. Of the remaining 52 stations, 41 are new construction and 11 have been renovated. The construction of the underground stations was carried out using various techniques Including Diaphragm walls, tangent piles and NATM methods.

The bored tunnels were separated into 3 separate drives; Line C or the Blue Line was 2.4 km in length, Line S or the Yellow line was 2.7 km and the Line S1 the continuation of the Yellow line a further1 km of tunnelling to the south of the Trindade station. The S1 tunnel broke into a cut and cover section adjacent to the historic Don Luis Bridge. A separate NATM tunnel of 300 m was constructed in order to permit trains to be shunted between the Yellow and Blue lines at the Trindade station, hub of the new light rail system.

Figure 1: Bored Tunnels and stations on the Blue and Yellow lines of the *Metro do Porto*.

2 GEOLOGICAL SETTING

The entire underground system was excavated through Porto Granite. The Porto granite is a two mica igneous rock characterised by its heterogeneity caused by the weathering processes. This part of the Iberian Peninsula was once located within the tropics and suffered tectonic movements leading to the penetration of the weathering fronts deep into the system of fractures. This has left very deep weathering profiles similar to other tropical granites such that completely decomposed granite can be encountered next to fresh material in any possible depth and location.

The hydro-geological regime encountered was also extremely complex and defined by sharp changes in permeability. In weathered granites and residual soils water circulation took place through the pores whereas in fresh granites the water flow was through the fractures. Water levels were generally close to the ground surface and therefore represented the biggest challenge during tunnelling. Man-made “minas” or water mines and deep wells were also found frequently both intersecting and above the tunnel alignment.

3 PROJECT ORGANIZATION

The metro system has been constructed on a Design, Build and Operate Transfer (DBOT) basis by the consortium *Normetro*. The consortium has responsibilities for the operation of the Metro system during a 5 year period after which the concession will return to the owner of the project; *Metro Do Porto*.

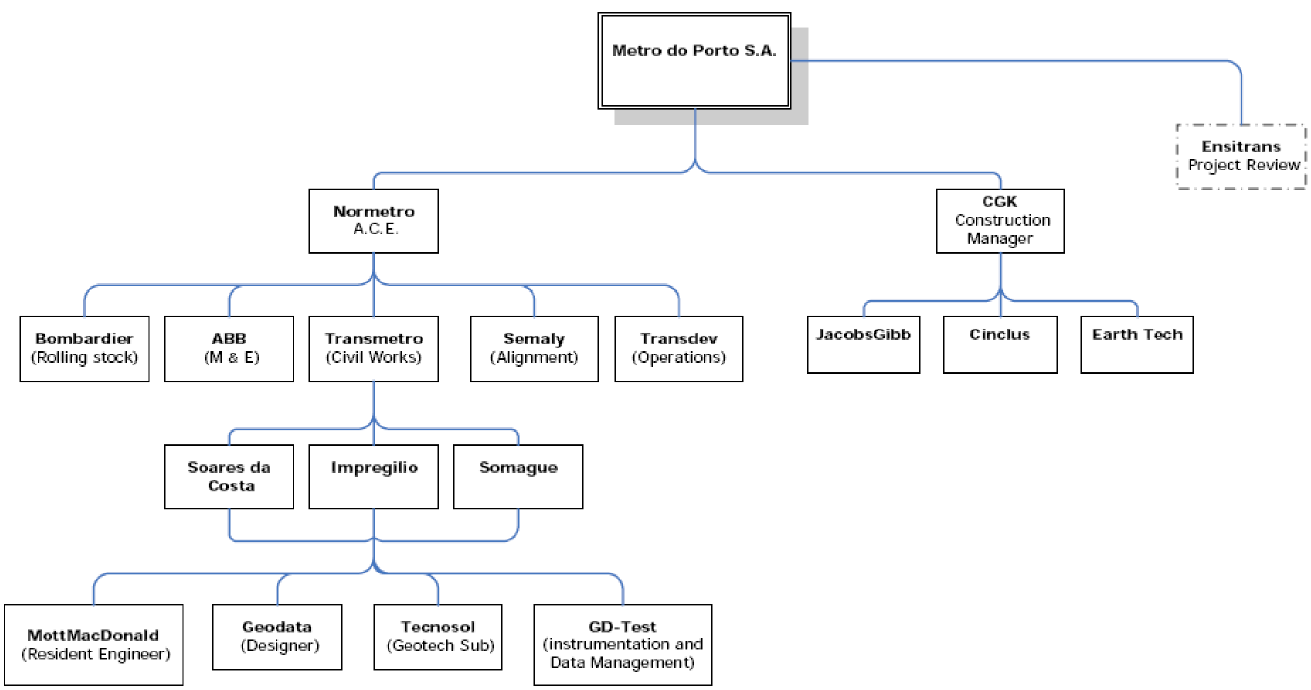

Figure. 2: General project organization chart during construction of the *Metro do Porto* light rail tunnels

The *Normetro* consortium supervised the construction of the various facilities including the tunnels through their civil construction group collectively know as Transmetro. The principal contractors making up the group were Impregilio, Soares da Costa and Somague, the latter two companies of Portuguese origin. Following the restructuring that took place following the accident both Geodata of Italy and Mott-MacDonald became responsible for design with the Mott team taking on the resident engineering duties for the Consortium during construction.

The “Fiscalização” or Construction management team (CM) was responsible for the management of Safety, Quality, Schedule and Costs and made up of a consortium of Cinclus, Jacobs (Gibb) and Earth Tech (Kaiser Engineers) known as CGK. Ensitrans, a group comprised of engineers with experience from the Metro do Lisboa, carried out the project review on behalf of the *Metro do Porto*.

4 PROGRAMME

4.1. Line C

The 8.7 m diameter S-160 Herrenknecht earth pressure balance (EPB) TBM began excavating line C on June 12th 2000. However due to a major set-back caused by the sudden collapse of a home and the death of one of the occupants, the TBM was stopped after less than 25 % of the drive had been completed.

A *Commission of Inquiry* set up by the government to investigate the accident mandated change at all levels of the project including an overhaul of the equipment, personnel, geological model and working methods. A considerable delay was inevitable since all of these items had to be completed including the hiring of new personnel prior to restarting the TBM tunneling. The

Metro do Porto took a further step by engaging an international Panel of Experts, POE, which also added further recommendations to be implemented.

Following the restarting of the TBM drives no major problems were encountered and the TBM passed through the three underground stations along the alignment finally holing through into Trindade station on October 21, 2002.

The planned progress rate was 25 rings (35 m) per week. As can be noted in figure 3 the planned rate was regularly achieved through all soil types encountered along the alignment despite the heavy maintenance required on the cutterhead carried out almost exclusively under hyperbaric conditions.

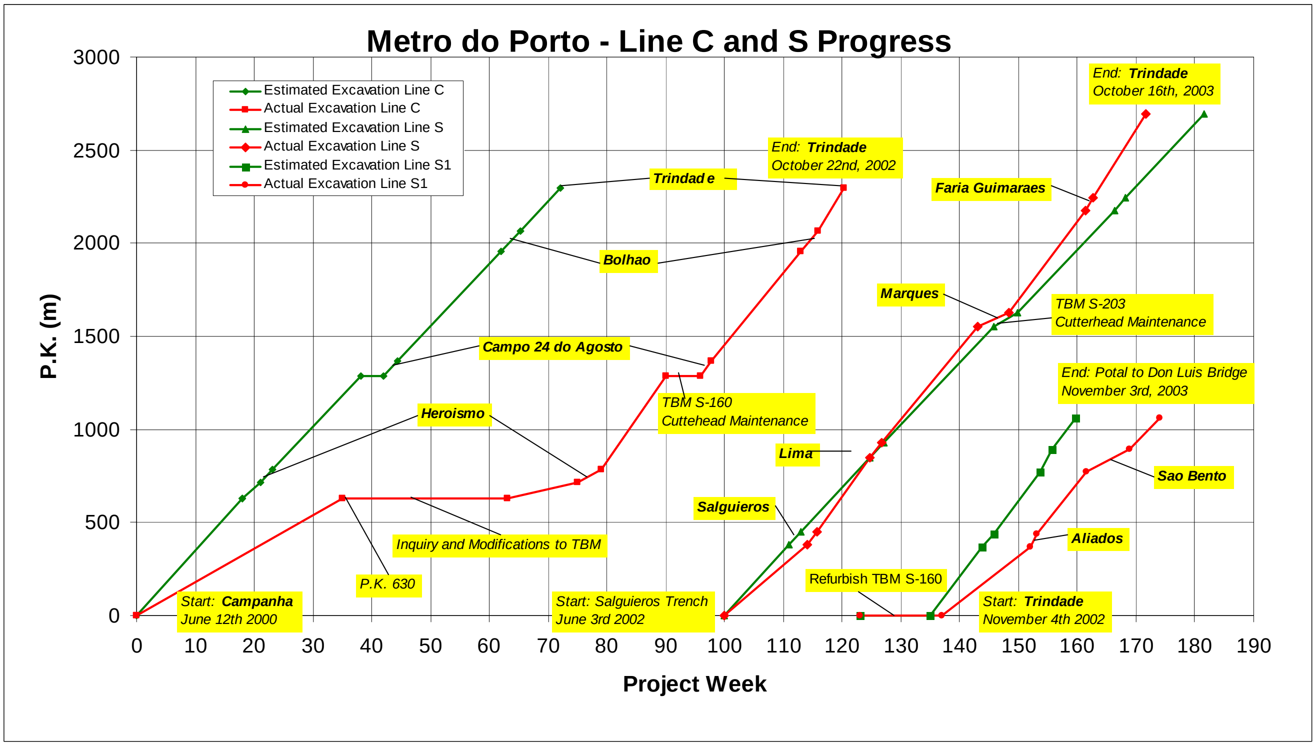

Figure 3: Sloping line diagram showing the progress of major TBM activities for line C and S.

4.2. Line S

Delay to the works caused by the accident required the purchase of a second machine. The S-203 TBM for the northern extension of the S line was designed to be 200 mm larger in diameter to better accommodate the dynamic envelope of the single twin track running tunnels. It was launched from a cut and cover portal adjacent to the Salgueiros site in June of 2002. The TBM traversed the alignment without mishap passing below a major highway, through the Salgueiros, Lima, Marques and Faria Guimaraes stations to its final breakthrough into the Trindade station hub at the end of October 2003 several weeks ahead of schedule.

The southern extension of the S line was excavated using the refurbished S-160 TBM following the completion of the C-line. After a successful re-launch in February 2003 it excavated through the Aliados and Sao Bento stations finally breaking through on November 3, 2003 into the cut and cover portal adjacent the historic Don Luis Bridge. This bridge has now been refurbished to be used as a dedicated link to the southern side of the Douro River and completes the link with the city of Vila Nova de Gaia.

The programme for payments on the contract was set out according to agreed milestones being reached. In the case of the tunnel a schedule was created with specific chainages identified as milestones for payment.

The original budget for the tunneling works was 55 million euros not including the tunnel lining, an estimate of the final costs range to 110 million euros.

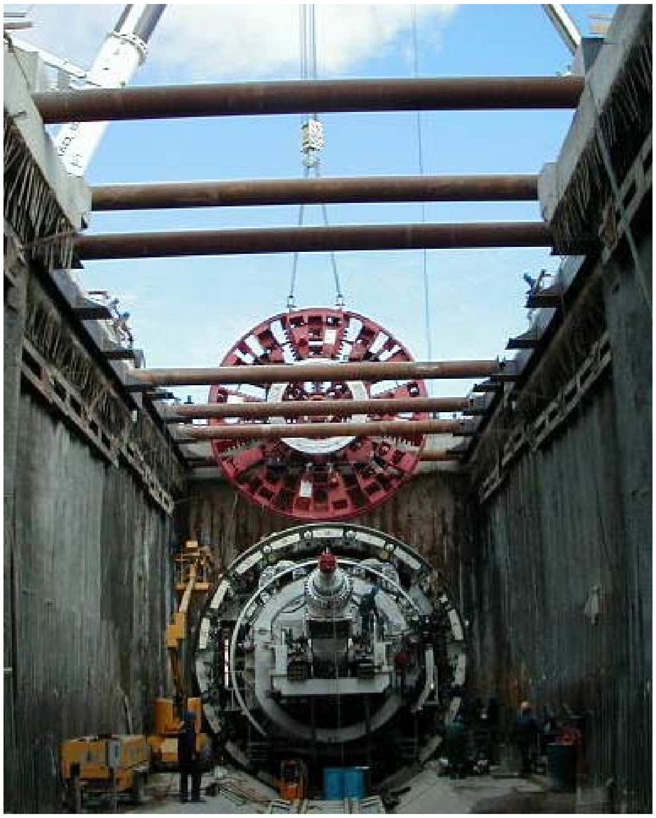

Figure 4: Lowering the cutterhead of the Herrenknecht S-203 8,9m Ø EPB-TBM into the Salgueiros cut and cover portal.

5 COMMISSION OF INQUIRY

An inquiry into the causes of the fatality which occurred following the collapse was commissioned by the various government ministries involved in the works. This report had essentially the force of law and was binding for all the involved parties.

A list of 16 recommendations was generated which gave rise to a complete re-organization of the contractor and construction manager, CGK, including the presence of TBM and Geotechnical expertise.

The list is summarized as follows:

- Improve the knowledge of the geology along the proposed tunnel route.
- Improve the soil where indicated to avoid collapses.
- Revise the system of surface and deep monitoring on a permanent basis particularly in suspect areas.
- Revise the Normetro management team and ensure that they have the correct experience for the job. Revise the required procedures for safe execution of the works.
- Safety first. Production second.
- Operation of the TBM in closed mode only except where the situations warrants.
- Reinforce the teams with additional competent personnel in the geotechnical area.
- Provide real-time access to the information from the TBM and settlement monitoring
- Revise the project geological model.
- Improve the prediction of material densities in order to improve the excavated volume measurements.
- Improve the primary grouting and prove it by taking cores and by making secondary "proof" injections.
- Probe ahead of the TBM to verify predicted conditions.
- Uncover all possible pre-existing underground structures along the alignment which could affect the safety of TBM operations.
- Implement the PAT (Tunnel Advance Plan) system bringing together all the information existing along the route of the tunnel to assist in the proper execution of the works.
- The first PAT should redefine the investigation, consolidation and monitoring that must be carried out or had been carried out in the accident areas.
- It is fundamental that the supervision follows the works both inside the tunnel and on the surface. The safety of the project can not depend upon mere contractual penalties which could be imposed.

These recommendations formed the skeleton of a specification under which the construction management could operate and compel the contractor to perform the work in a controlled systematic manner. Daily meetings were held during tunneling with the construction manager, designer and contractor so that information could be exchanged easily and any issues could be dealt with promptly by the team. Analyses of the tunneling and TBM activity were also made on a daily basis so that any anomalies in the operation of the TBM and its impact particularly on the deep instruments could be reviewed. Although a formal "Partnering" process was not implemented the value of these daily meetings in creating a collegial atmosphere open to dialogue among all the parties cannot be overstated.

6 A BRIEF HISTORY

Since the start of the line C tunneling in June 2000 there had been three ground collapses. The most serious incident occurred on 12 January 2001 when a crater formed at the surface leading to the sudden collapse of a home resulting in one fatality. At the time of the collapse the TBM was approximately 60m ahead of the collapse zone and was halted after driving 470 m of tunnel.

Following this unfortunate incident and the removal of the wreckage of the house, the cavity was measured and the resulting volume was estimated to be 250 m^3. The TBM had passed below the property during the previous 16 to 18 of December, i.e. 25 to 28 days before the accident. The collapse and resulting cavity did not damage the tunnel lining which had remained remarkably stable.

It is uncertain in what mode the TBM was driven over the initial stretch due to the fact that these records were incomplete. The construction management team did not have access to the records from the TBM data logger system nor was the conveyor belt scale thought to be working correctly. At that time, the construction management team of engineers and inspectors were performing a more passive role of record keeping and measurement in accordance with their contract, rather than the proactive role which they would later embrace.

At the outset, the tunneling activities were carried out by Transmetro on site with the design support from Geodata who were located off-site. Prior to the accident there had been no real construction supervision as it is normally understood. The fatality resulted in the reorganization of the whole construction team following the mandate of the *Commission of Inquiry*. The new structure led to the employment of Mott-Macdonald who was subcontracted by Transmetro to assist the original designers and undertake the design and construction supervision.

The new team worked on the recovery works and prepared all the documents, specifications and required steps to recommence the tunneling. Finally after months of preparation including the introduction of many new specialists and full analysis of the means and methods proposed, excavation began anew on 18 September 2001.

7 PANEL OF EXPERTS

A panel of experts or POE was commissioned by the *Metro do Porto*. The panel was composed of a group of internationally known experts in tunneling and underground engineering including: Dr. Ing. Siegmund Babendererde, Prof. Antonio Silva Cardoso, Dr. Evert Hoek, and Prof. Paul Marinos.

Their first report proved to be the most significant. Two major modifications to the TBM were proposed.

- Automatic bentonite injection system in order to maintain a minimum EPB pressure in any situation.
- Addition of a double piston pump permanently attached to the screw conveyor in order to handle material not manageable with the screw conveyor.

The contractor added his own modifications including:

- 10 independent foam generators.
- A new rotary fluid joint which permitted the passage of ground conditioning, high pressure water and hydraulic fluids.
- A new twin belt weighing system
- A laser scanner to detect the volume of material passing over the belt.
- Various improvements in the PLC system were developed so that alerts and alarms could be given to the operator immediately in the event that the any of the levels were reached. For example, a warning for minimum apparent density within the chamber measured by the pressure acting on EPB cells located on the bulkhead of the TBM. This indicated to the driver in the form of a message and light.

The POE met every four or five months in order to deal with any developments or technical issues including proposed modifications to the tunneling approach agreed upon.

For example in their second report they did not permit the use of foam for soil conditioning due to the unreliable foam generating plant and the systems for control. They instead encouraged the use of bentonite for ground conditioning. The CM team encouraged the use of polymer as the most useful compromise.

In their third report they gave the approval for foam trials satisfied that the problems with the plant had been corrected. However they raised the question of compressed air interventions and the need for having a proper bentonite membrane on the face in order to avoid sudden collapses of the face due to the use of compressed air.

Subsequent reports began to deal more with the pressing problem of station construction as it was clear by this time that the major problems with the TBM drives had been overcome and that the tunnel drives were being managed very well by the contractor and construction management team.

8 INNOVATIVE DEVELOPMENTS

As a result of the accident many new developments were recommended or introduced by the Commission of Inquiry, the Panel of Experts and the Contractor.

8.1. Granite under pressure

The first major development to be universally implemented was the exclusive use of closed mode TBM operation. This strategy meant the operation of

DADOS DE AVANÇO DA TUNELADORA - 1A - Posição da frente entre Pk 0+000 e Pk0+361 (Aneis instalados 1-258)

ANEL MONTADO		1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64				
Pk CABEÇA		1.4 2.8 4.2 5.6 7.0 8.4 9.8 11.2 12.6 14.0 15.4 16.8 18.2 19.6 21.0 22.4 23.8 25.2 26.6 28.0 29.4 30.8 32.2 33.6 35.0 36.4 37.8 39.2 40.6 42.0 43.4 44.8 46.2 47.6 49.0 50.4 51.8 53.2 54.6 56.0 57.4 58.8 60.2 61.6 63.0 64.4 65.8 67.2 68.6 70.1 71.5 72.9 74.3 75.7 77.1 78.5 79.9 81.3 82.7 84.1 85.5 86.9 88.3 89.7				
Geologia prevista		Frente mista g3-g4-g5; cobertura em g5 e g7	Frente misto g3/g2/g5; cobertura em g5 e g7	Frente em rocha g3/g4 (raio do tunel) e		
Poços		NÃ				
Pressão de suporte da frente (P7)	[bar]	0,6 Atenção: >1.2P7 <0.9P7; Alarme: >1.3P7 <0.8P7				
Peso (W) do material escavado; med (min-max) Atenção: >1.1W< 0.9W Alarme: >1.2W <0.9W	[t]	**193** (184-201)	**198** (190-207)	**210** (202-218)	**2**	
Pressão de Injecção primária (P) ABÓBADA	[bar]	2,8 minimun				
Pressão de Injecção primária (P) EIXO	[bar]	3,1 minimun				
Pressão de Injecção primária (P) BASE	[bar]	3,5 minimun				
Injecção primária Vol./anel Atenção >1.2G < 0.9G Alarme: >1.5G < 0.7G	[m3]					
Prospecção em avanço						

Figure 5: Example of the TBM drive parameter table from P.A.T. document.

the TBM in EPB mode through areas where good quality granite was expected and proven by the probe holes drilled ahead of the TBM. In many cases a minimum face support pressure was adopted and used to excavate where competent rock was encountered.

The consequences of this approach were the rapid wearing of the cutting tools and the structure of the cutterhead. By the time the TBM had reached the 24 do Agosto station, much of the front and periphery of the cutterhead had to be rebuilt underground, stopping progress on the tunnel drive for an additional 6 weeks (note in Figure 3 above).

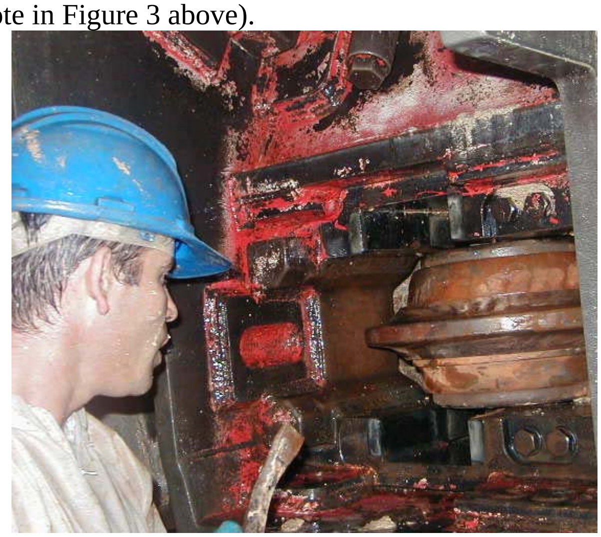

Figure 6: A worker changes a disk cutter tool.

Both the C line and S line TBM cutter heads required heavy maintenance throughout the respective drives as a result of strict adherence to closed-mode operation despite treatment with polymer ground conditioners added at the face. Both the client and their experts felt that no other alternative was considered to be 100% safe. The risks of another major collapse as a result of moving away from this strategy would have meant the permanent cessation of tunneling and serious blow to the Metro scheme.

Figure 7: View of the face of showing the Porto Granite

8.2. The PAT document

The contribution made by those who developed the PAT document should not be overlooked. In Figure 5 an extract of the summary table is shown. This document along with its supporting calculations, plans and tunnel sections permitted easy reference to any position along the tunnel alignment showing buildings and condition surveys, expected settlement and other information invaluable to all parties during the prosecution of the works. The fundamental parameters included by ring and chainage were; the expected geology, the required face support pressure, the weight of material excavated, the grouting pressures and total volume to be injected. Other information included a table of the required starting air pressure for the daily hyperbaric interventions which were needed to maintain the cutting tools. The PAT became an indispensable document for all of those involved in the daily management of the tunneling works

8.3. Apparent Density

Another development was the concept of "apparent density" which is an interpolated value of the pressure registered on the pressures sensors located within the plenum. The sensors were fitted to the main bulkhead which separates the pressurized soil from atmosphere. The uppermost three sensors were used to determine the apparent density. The uppermost sensor pressure was compared to that of the lower two sensors which were separated by a fixed height such that a differential in pressure could be noted. This differential in pressure was used to evaluate if the chamber was really filled with material and if the material had sufficient apparent density to provide effective pressure to balance any instability which may have been present at the tunnel face. A simple system was incorporated into the operators' display to warn the driver to slow the screw or modify the rate of ground conditioners added if the chamber density became too low. This concept worked very well and was the subject of continuous observation by the construction management team.

Further measures were implemented at the request of the Panel of Experts. These included the fitting of a double piston pump at the screw outlet and an Automatic Face Support system which permitted the injection of bentonite when the pressure in the chamber dropped below a predetermined level for a period of time. This system did not require input from the operator and proved to be useful when using foam as soil treatment. Figure 8 shows a graphic illustration of the AFS system in automatic mode injecting bentonite as needed to maintain the target face support pressure. The purpose of the double piston pump was to permit the handling of running sands in the event that these could not be controlled easily by the screw conveyor.

8.4. Belts Scales

Due to the fact that the contractor elected to use a continuous belt conveyor for removing muck from the tunnel, a positive method of volume measurement such as the counting of muck cars was not easily available. In light of the lost ground noted in the first 470 m of line C it was of special interest to all involved that careful and continuous monitoring of the muck weight and volume be carried out in order to determine if over-excavation was occurring. The contractor installed two belt scales on a level portion of the fixed conveyor fitted to the TBM trailing gear in order to measure the excavated weight of the muck.

Additionally, flow meters were installed in the ground conditioning lines capable of providing the total volume of liquids injected. Thus, a concise accounting of materials injected and extracted could be made readily indicating if over-excavation was occurring.

This system was reliable and worked very well in controlling the excavated weights and showing a very controlled excavation was possible using EPB methods. The scale readings were added to the operators' control screen and provided warnings of over-excavation based on instantaneous measurement of propulsion strokes relative to the total excavated weight.

8.5. Real Time Monitoring

Modern data loggers and computer networks made possible the rapid and reliable exchange of data such that real-time observation of all important TBM parameters, and instrumentation such as settlement points, piezometers and inclinometers were available on a continuous basis. This access to the data and the time to interpret and act appropriately was a powerful tool for demonstrating the contractor's control of his works and giving confidence back to a client and to the public at large.

9 THE FOUR FUNDAMENTALS OF EPB TUNNELING

During the course of the works some fundamental parameters which together contribute to the success of the EPB tunneling technique were identified:

- Maintenance of appropriate face support pressure
- maintenance of material density in an appropriate range
- Control of excavated weight and volume
- Control of primary grouting

10 FINAL OBSERVATIONS

The successful breakthrough into the Trindade station following the challenging low-cover under-passing of adjacent buildings was really the highlight of an almost two-year struggle for the *Metro do Porto* to once again feel confident that EPB-TBM tunnels could be safely driven through the unpredictable geology that lies below the city of Porto.

This was due in no small part to the dedicated tunneling team which Transmetro was able to assemble following the tragic accident and the willingness of the *Metro do Porto* together with their Construction Manager Cinclus Jacobs Gibb and Earth Tech to create a team which could work with contractor to tackle the issues placed before them.

The successful completion of the tunneling on the *Metro do Porto* is a reason for all parties to be proud and for which the fans of the recent 2004 European Cup Football held at the Porto's new Dragon Stadium had another reason to cheer as they stepped off the metro and into to a new era of transportation for Portugal's "working city".

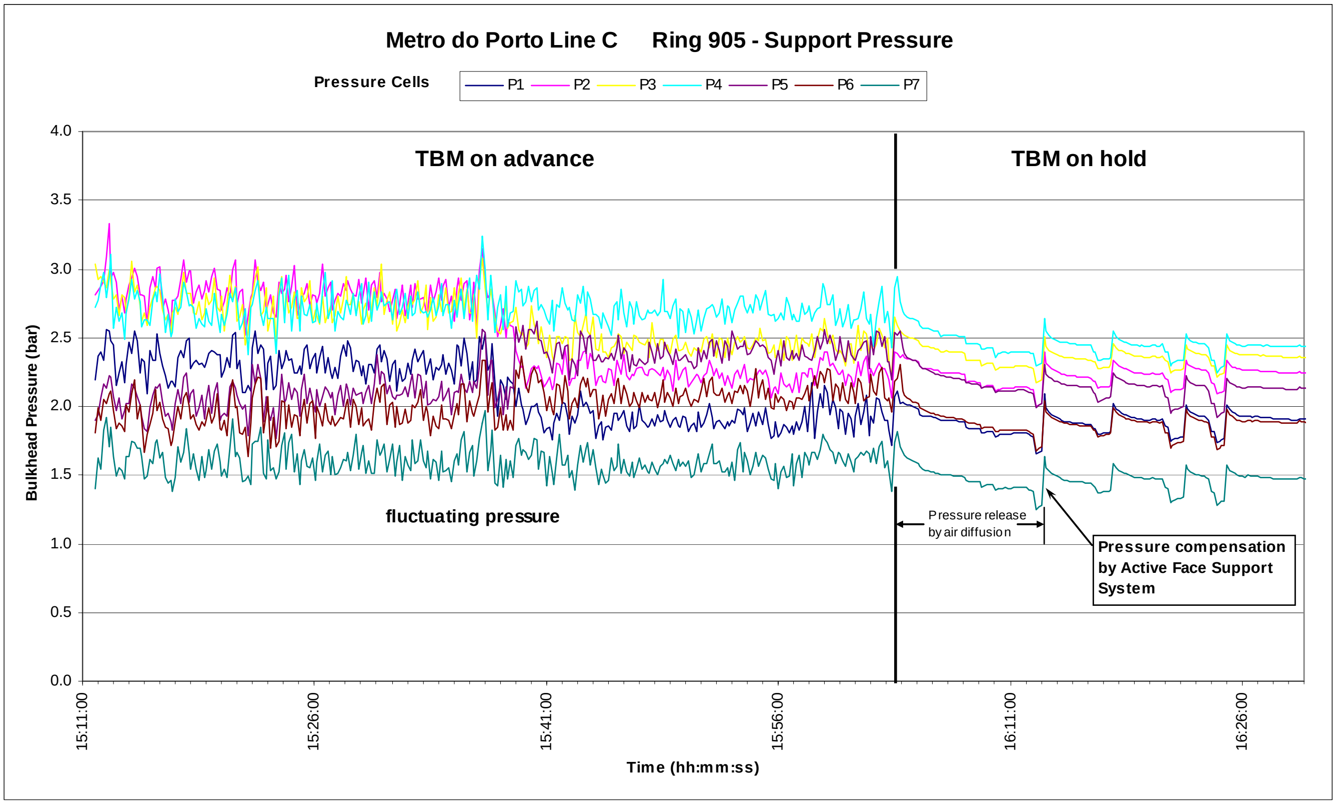

Figure 8: Variability of EPB pressures while using foam soil conditioning and the pressure compensation of the "Automatic Face Support" system at ring 905 of the *Metro do Porto*, Line C.