
A. Sciotti¹, P. Lattanzi¹, G. Pacifici¹, G. Simonacci¹, A. Zechini¹
¹Roma Metropolitane Srl, Rome, Italy

1. Preface
In the next years the Municipality of Rome programs foresee the implementation of about 75 km of new Underground tunnels, with excavation diameters from 6.75 m to 10.50 m (single-track and double-track tunnels). The specific characteristics of the Rome’s subsoil requires necessarily the use of Tunnel Boring Machines to drive the tunnels safely. At the time this article was written there were six TBMs in operation in Rome; four of which on Line C and the other two on Line B1. Totally they had excavated about 10 km of tunnels. In the next six years (Figure 1) up to nine TBMs will be working in Rome, to realize more than 45 km of new tunnels.

![Figure 1 – The TBM program in Rome](image)

All this requires a correct and integrated approach to design and for subsequently construction phases, finalized to improve the knowledge of mechanized tunneling efficacy in specific contest such the ‘Eternal City’ presents.

2. Underground Metro lines development programs in Rome
The development of Rome’s subway network didn’t keep up with the growth of the city. At the moment we have two lines with an interchange point at “Stazione Termini” only 36.5 km and 49 stations.
The first underground line which has been realized in Rome was the B line. It was designed before the second world war and opened in 1955. 25 years later, in 1980, the second line (the A line) was opened. Construction works started in 1965. 10 years later, in 1990, the B line has been extended. The last section, from “Valle Aurelia” to “Battistini” on “Line A”, was opened in 2000.
Due to the increasing traffic and transportation demand and in order to preserve the historical city centre, the Municipality of Rome has established an important development program for public transport underground infrastructures: two more metro lines (Line C and Line D) and an extension of an existing one (called B1 line) are to be realized by 2015. Other extensions of Line B and Line A, until to the great road ring of Rome, will be completed within 2020. The new lines will double the existing metro line lengths and the number of stations inside the historical part of the city.

‘Roma Metropolitane’ Company carries out, on behalf of the Central Municipality of Rome (“Comune di Roma”), all the tasks connected with the accomplishment, extension and modernization of the underground railway lines of the city of Rome. At the moment Roma Metropolitane manages investments for a total of approximately 10 billion Euro.

Regarding these activities, the Agreement approved by Municipality of Rome allows Roma Metropolitane to execute the design of works, plant and systems, and to execute the duties and the functions of Sole Project manager and of Works Direction. Roma Metropolitane, in this way, is directly involved both in the design and in the construction stage.

3. The hard challenge of realizing Underground Metro lines in Rome

The constructing an underground infrastructure in a ‘city’ like Rome presents numerous problems connected with geological aspects, archaeological and monumental structures and existing buildings.

The soil of Rome is characterized by prevalent fluvial-lacustrine recent sedimentary formations with extreme vertical and lateral lithological variations and gradual or abrupt transitions from granular to cohesive mechanical behavior. In the design stage, poor characteristic of mechanical strength and deformability of the soil, as well as its very changeable permeability, have to be considered. The piezometric level is few meters below ground level.

The city was built on several piled up archaeological rich layers, each one connected with a specific historical age: they go from the imperial Roman age to the medieval street level, and then up to the existing situation today.

The new lines must be realized in heavily built-up areas (Figure 2), often with multi-storey buildings, both in masonry and in concrete. This complex situation may entail remarkable impacts of the works, both on the existing structures and the environment.

4. Current works in progress

At the moment two new Underground Lines are under construction.

Line C is one of the biggest underway European construction projects. The “Main Section” of Line C stretches over a distance of more than 25 Km (about 18 km underground) with 30 new planned stations. At the time this article was written about 10 km of twin single-track tunnels have been excavated by means of four TBMs. The excavation of tunnels passed under heavily built-up areas and under a lot of topic site as well: an important communication ring road (GRA), an urban railway, an hospital, public manufactures such as great sanitary sewer.

Line B1 is a branch line of the existing “Line B” and extends for about 7,5 km. The section currently under construction stretches entirely underground over a distance of about 5 Km with 4 new planned stations. Two TBMs started from The “Conca d’Oro Station” shaft and, at the
moment, both of them have excavated about 1 km of tunnel towards “Gondar Station”. In this stretch the TBMs underpasses with low overburden some critical “structures”: the Aniene River, High-Velocity and Local railways in operation, the Valley’s Bridge. Then, passing through “Annibaliano Station”, they will run until “Bologna Station” of the existing Line B (where they will be extracted).

In the planning process it was decided, both in Line C and Line B1, to set the twin single-track tunnels (5.8 m internal diameter) relatively deep (20-35 m below ground level) in order to mitigate interactions with pre-existing structures (building foundations, gas and water pipelines, etc.) or archaeological rich layers. Tunnels are excavated through recent alluvial soils, characterized by poor geotechnical properties, below groundwater table.

Two different macro areas of geological features can be distinguished along the route of Line C and Line B1. At the north and central part of the Line C route, and on the whole Line B1, the typical excavated soils consists of fluvial-lacustrine recent sedimentary formations. The geological sequence comprises a base deposit of stiff overconsolidated clay of Pliocene age (Monte Vaticano unit) overlain by a layer of fluvio-palustrine gravel of Pleistocene age, followed by either clayey silts and sandy silts, both of Pleistocene age. Frequent and relatively deep ancient ditches filled by alluvial silty-clayey and sandy deposits cut into the Pleistocene deposits. The south-east extension of the Line C route, from San Giovanni station until the suburb areas, the geological sequence is mainly characterized by pyroclastic deposits. Pliocene deposits become deeper and the Pleistocene deposits consist of alternate incoherent tuff or pozzolanic ash with tuffs cemented by pressure and action of infiltrating water, making rocks which, while not very hardy, are strong enough to be used for building purpose. A layer of made ground of varying thickness including relics of ancient structures covers everywhere the natural soil profile.

5. The design approach
The construction of infrastructures like Line C and Line B1 involves situations that requires “extreme engineering”, and very important technical challenges have to be faced. Roma Metropolitane needs of norms, instructions and rules for design and construction, to guarantee transparency of tender procedures, accuracy and definition of project, performance and functionality of the infrastructures.

Roma Metropolitane can refer to national Laws and international Norms (ISO, rather EN, rather UNI), but the specific legislative whole doesn’t cover all peculiar aspects of tunneling works. For this reason Roma Metropolitane draw up the “Special contract specifications for the design” (SCSD). This document identifies all the necessary conditions that the design must fulfill, in terms of: requirements, standards, level of definition and detail, analysis methods and verifying procedures, operational guidelines. This document is enclosed to contracts, as a point of reference for Contractors and Client. A special attention is paid to those aspects which are not ruled by national laws or norms, preparing some peculiar dispositions regarding tunneling, as:

– the evaluation of face stability pressure; it has to be performed considering different conditions (“earth pressure at rest”, “active earth pressure”) and analytical analyses (characteristic line method, Anagnostou and Kovari equations, finite difference numerical analyses on cross and longitudinal sections). In this way the upper and lower limits for the face pressure can be defined as well as possible in planning phase.

– the study of the tunneling-induced settlements; it has to be performed following different approaches, depending on the complexity and peculiar conditions along the route. In most cases the displacements fields induced by tunnel construction activities in greenfield conditions must be computed using well established empirical relationships based on the Gaussian settlement profiles (e.g. Peck 1969, Attewell e Farmer, 1974; Attewell, 1977; O’Really e New 1982; Shirlaw e Doran, 1988). Some specific cases, characterised by shallow cover or large predicted settlements, required a more detailed study, carry out by means of numerical analyses, which also allow to evaluate the effectiveness of remedial measures. The empirical predictions were performed considering the following input parameters range: a volume loss from 0.5% to 2%. The smaller values are the design values as well as the most likely value, considering the excavation techniques and the mechanical characteristics of the soil, the larger values was adopted as a worst scenario values.
Tunnel Advance Procedures: in the construction phase the Contractor must draw up a document that represents the design specifications considered reliable and acceptable in operational terms. They define, as best as possible, the limits within which the working parameters of the machine must be maintained. These procedures constitutes the connection and join up between the design and the construction stages, because they are furnished instruments which are continuously updated by the “on site design team” on the basis of data acquired in real time integrated monitoring during construction. This verification in the field may even lead to changes being made to procedures and to the principles applied in the design stage if particular anomalies are found by the monitoring and survey system. It may involve repeated iterations between design and construction operations in order to bring the procedures into line with the reality of the situation.


- **TBM choice**
  
  All the TBMs in operation are EPB type machines. The decision to use an Earth Pressure Balance (EPB) TBM rather than a Hydroshield was dictated by the greater flexibility afforded by the EPB TBM in terms of logistics and managing construction operations because of the capabilities offered today by the systems for conditioning the material to be excavated. The choice of TBM is related at two principal aspects: application field and pressure in the excavating chamber, the muck treatment. EPB can be efficiently applied even in grounds outside its theoretically applicable filed with the appropriate addition of fillers and/or additives. Its face-support pressure is more efficacy than other method such Hydroshield TBM. The environmental impact and the requirement of large area for muck treatment are reduced in case of choice of EPB.

- **TBM design and lining characteristics**
  
  The design of the TBMs themselves (Figure 3), performed by the manufacturer (Herrenknecht AG, Germany), resulted in the construction of machines (Line B1: S-387, S-388; Line C: S-409, S-410, S-479, S-480) with the following characteristics: excavation diameter 6,71 (Line C) - 6.79 m (Line B1), installed power 2.500 kW, maximum torque 7.000 kNm (9.000 kNm only for limited time application), total thrust 50.000 kN, working pressure 4,5-5,5 bar, epb sensors 5-6, erector with vacuum system, conditioning through 9-10 injection points, backfilling through 6 or more indipendent injection lines with a binary component system.

![Figure 3 - TBM S-409 (Line C) and S-387 (Line B1)](image)

The lining of the tunnels has been designed according to “universal ring” scheme, with the following characteristics: six elements plus key, inner diameter equals to 5.80 m, minimum radius of curvature equals to 120 (Line B1) and 150 m (Line C). The precast reinforced concrete segmental elements characteristics are: thickness equals to 0.30 m (Line C) and 0.35 m (Line B1), element length equals to 1.40 m, concrete resistance Rck 45 MPa, steel reinforcements about 100-110 kg/m³.
Tunnel Advance Procedures (TAP)

It was decided to carry out monitoring and survey procedures for 200-300 m sections at a time in order to work with calibrations based on the field data acquired in the previous tunnel section each time. The T.A.P. contains the design specifications for the pressure in the cutting head chamber both at the crown and the tunnel invert with the relative warning and alarm thresholds. The pressure must be nevertheless always maintained above the minimum level obtained from the Anagnostou-Kovari equations, to avoid the possibility of collapse situations. The table also contains the values for the following parameters: theoretical weight of the spoil for each thrust, the injection pressure for the backfill grout, the theoretical volume of backfill grout to be injected.

The values given for each of these parameters are based on considerations concerning the geometrical dimension of the TBM advance (thrust length, area of excavation), the unit weight of the ground in situ, the swelling index of the material excavated, the backfill injection pressure 0.5 bar higher than the pressure in the cuttinghead chamber and the theoretical geometry of the annular space behind the concrete segments.

It is nevertheless important to underline that all the values given in that table are theoretical and predictive, and that they can therefore be corrected and refined on the basis of the actual values encountered during excavation. To that end and for better knowledge and control of the relationship between the face pressure and movement, settling or raising, of the ground at the surface, it is extremely important to continuously monitor the "operating parameters" and the "excavation data" recorded automatically by the EPB TBM during the whole transit phase of the machine and also to continuously monitor surface subsidence by means of the monitoring network on the surface above the tunnel.

Line B1 – TBM performance

In November 2009 the two excavated tunnels were about 1000 m each. They crossed alluvial soils, characterized by poor geotechnical parameters and a very variable granulometry (from clayey silts and sandy silts to clean or silty gravel). The overburden changes from 15 to 33 m. The groundwater head on the tunnel goes from 12 to 30 m. The basic ground mass properties are summarized in the next table:

<table>
<thead>
<tr>
<th>soil type</th>
<th>Unit weight (kN/m³)</th>
<th>Cohesion (kPa)</th>
<th>Friction angle (°)</th>
<th>Drained Young mod. (MPa)</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;clay&quot;</td>
<td>18</td>
<td>5 - 45</td>
<td>19 - 27</td>
<td>60 - 150</td>
<td>10⁻⁶ – 10⁻⁸</td>
</tr>
<tr>
<td>&quot;gravel&quot;</td>
<td>20</td>
<td>0 - 10</td>
<td>32 - 41</td>
<td>100 - 300</td>
<td>10⁻³ – 10⁻⁵</td>
</tr>
</tbody>
</table>

The table in Figure 4 shows a summary of the principal data collected during the excavation. It has been considered that the two TBM didn’t exploit all their potentialities in daily advance. Until November 2009 they excavated at a slow pace and moreover, not simultaneously but alternatively, due to the delay in the preparation of the first station which TBMs have to cross through.

![Figure 4 – Line B1: machine data](image-url)
Generally the data collected show as the TBMs design has been corrected: the values of significant parameters are always inside the predicted working range. The good TBM performance experienced throughout the first stretch was also reflected in the results of the surface settlements monitoring system.

- **Line B1 – “learning curve” (TBM S-387, S-388)**

The start of a TBM is always the critical situation: the usual “learning curve” is to be affected by specific conditions of each site. In Line B1 it was possible to exploit the first stretch (250-300 m), which is a relatively safe section (no appreciable pre-existing structures), to perfect the TBM management because of the ‘best-practice’ and the soil response. Figure 5 shows the maximum settlements recorded at soil level in the ‘learning’ stretch, during excavation for each TBM.

The first TBM (S-387) registered the most considerable surface settlements due to some difficulties: back-filling injection lines fouling, difficult soil conditioning, lack of effective of sealing grease for the brushes. The results were an incomplete back-filling, with inadequate pressures (to avoid the return inside the shield of the back-filling grout), and an inconstant face pressure value during the TBM advance.

The above mentioned problems induced in surface settlements greater than planned. The analysis of registered data has identified some specific corrective actions, applied on both TBMs (on the second TBM before the start). These improvements were: definition of a specific procedure to cleaning of the injection lines, qualification of the bi-component backfilling grout, amendment of FIR (Foam Injection ratio) and FER (Foam Expansion Ratio) values, replacement of the sealing grease for the brushes.

The following performance confirmed the validity of the chooses adopted in the first stretch.

- **Line B1 - Face pressure - expected and actual values**

From a strictly design engineering viewpoint the most critical working conditions of importance in the design of the TBM translate into the maximum pressure that it must exert on the face. Predictions of the deformation behaviour of the ground and the height of the water table under
which the tunnel would be driven indicated a maximum pressure of 4.5-5.5 bar (which included an appropriate factor of safety). Figure 7 shows the ‘face pressure’ data registered during the S-387 excavation.

Figure 7 – Linea B1: face pressure

The experience acquired in the completed advance confirmed the validity of the methods adopted in the design phase to evaluate face pressure operational range. The Tunnel Advance Procedures enabled a more detailed evaluation of the face pressure range on the basis of monitoring data, with consequent optimization of TBM performance.

- **Linea C - TBM performance**

At November 2009, S-479 and S-480, have excavated tunnels present a total length each of about 1800 m. They crossed pyroclastic soils, as tuff and pozzolanic ash. The overburden changes from 12.5 to 27 m. The tunnels run below groundwater table. The basic ground mass properties are summarized in the next table:

<table>
<thead>
<tr>
<th>soil type</th>
<th>Unit weight (kN/m³)</th>
<th>Cohesion (kPa)</th>
<th>Friction angle (°)</th>
<th>Drained Young mod. (MPa)</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tuff</td>
<td>17</td>
<td>25 – 300</td>
<td>30 - 35</td>
<td>300 - 750</td>
<td>10⁻⁵ – 10⁻⁶</td>
</tr>
<tr>
<td>pozzolanic ash</td>
<td>18</td>
<td>5 - 25</td>
<td>25 - 35</td>
<td>150 - 500</td>
<td>10⁻⁴ – 10⁻⁵</td>
</tr>
</tbody>
</table>

The table in Figure 8 shows a summary of the principal data collected during the excavation.

<table>
<thead>
<tr>
<th></th>
<th>max daily advance</th>
<th>average daily advance</th>
<th>working time</th>
<th>thrust</th>
<th>torque</th>
<th>advance speed</th>
<th>face pressure</th>
<th>overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S-479</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sep-09 tuff</td>
<td>10</td>
<td>2.6</td>
<td>40-82</td>
<td>21-58</td>
<td>12-26</td>
<td>1.3-2.3</td>
<td>15-36</td>
<td>0.6-1.4</td>
</tr>
<tr>
<td>oct-09 pozzolanic ash</td>
<td>16</td>
<td>5.9</td>
<td>31-69</td>
<td>17-73</td>
<td>15-27</td>
<td>1.3-3.3</td>
<td>20-52</td>
<td>0.7-1.7</td>
</tr>
<tr>
<td><strong>S-480</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>jul-09 tuff</td>
<td>18</td>
<td>5.2</td>
<td>26-96</td>
<td>20-137</td>
<td>18-28</td>
<td>2.0-3.5</td>
<td>17-54</td>
<td>0.6-1.8</td>
</tr>
<tr>
<td>aug-09 tuff</td>
<td>14</td>
<td>1.5</td>
<td>22-56</td>
<td>24-73</td>
<td>21-24</td>
<td>3.0-3.7</td>
<td>24-52</td>
<td>1.4-1.6</td>
</tr>
<tr>
<td>sep-09 pozzolanic ash</td>
<td>20</td>
<td>8.3</td>
<td>23-47</td>
<td>16-74</td>
<td>13-21</td>
<td>1.9-3.5</td>
<td>29-62</td>
<td>0.4-1.6</td>
</tr>
<tr>
<td>oct-09 pozzolanic ash</td>
<td>21</td>
<td>8.9</td>
<td>29-47</td>
<td>19-71</td>
<td>17-29</td>
<td>2.0-4.2</td>
<td>30-49</td>
<td>0.6-2.2</td>
</tr>
</tbody>
</table>

**Figure 8 – Line C: machine data**

- **Line C - settlements and cavities**

Recently bored tunnel of the new Line C (the south-east part of about 10 km) are excavated through pyroclastic deposits with high mechanical features. Absent significant settlements are recorded by monitoring system: data are a lot of lower than predicted numerical values on the basis of standard design (loss volume 0.5%). On the other hand, there is a different problem for a safety excavation process because the quite superficial soil layers, where groundwater table is not present, are characterized by presence of
underground cavities along the line route (Figure 9). Part of excavated ground consists of pozzolanic ash and tuffs cemented and, in past years, they were mined because good to be used for building purpose.

![Figure 9 – Line C: cavities along the line route](image)

Regarding this type of risk, systematic geological and geotechnical investigations were carried out in advance along the tunnel axis, to study location and width of underground cavities. A complete knowledge of underground cavities was achieved and, consequently, a specific process was implemented to fill up the cavities closer at least of about one diameter to the tunnel. It consisted in, at first, introduction of concrete from geognostic bore holes to subdivide the underground cavities’ net in smaller parts. Subsequently every confined zones were filled with Geomix. As further mitigation risk measure, the TBM’s have been equipped with ‘BEAM system’. This non intrusive geophysical probing system and prediction method allows a permanent drivage-accompanying exploration of presence of cavities ahead of the face.

7. Conclusions

The specific nature of the problems of boring a tunnel in an urban environment, and the very high level technology embodied in the latest generation of TBM’s, require an integrated management between the design and the construction engineering teams. It is also quite clear right from the start that a proper design approach is indispensable. This must specify the tools to be used, modulated and adapted to the subsequent construction stage. Tunneling activity must be based on the conscientious application of scientific principles supported by assessments founded on practical experience, accompanied by rigorous monitoring of construction work. As Contracting Authority, Designer and Construction Management Office, Roma Metropolitane is working in this direction, as outlined in this article. The data collected by mechanized tunneling progressively carried out are used for the following tunneling activities, to improve the design forecasts, the operational procedures and the monitoring system. The challenge is a safe and progressively more efficient tunneling in a problematic environment as Rome.

Acknowledgements

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