The Turin metro alluvium soil is mainly made of large boulders, cobbles and gravel, few sand and almost no fines. This grain size curve is out of the range of application for EPB and Slurry TBMs. In order to bore 5 of the total 7.5 kms of Line 1 tunnel, two specially designed Lovat EPB TBMs were utilised in combination with a systematic non structural pre-grouting of a small volume rectangular slab just above the tunnel section. The same pre-grouting was not however applicable for lack of access on surface in some sections of the remaining 2.5 km of tunnel that had to be bored below important buildings/structures, with under ground water pressure up to 1.5 bar, with curves radius of 180 m only. For these more critical sections it was necessary to study and implement a new technical solution and improve the capacity of the TBM to work efficiently in EPB mode even in this unsuitable ground and overall conditions. After months of studies the selected and adopted solution has been to inject inside the cutterhead chamber, in addition to the almost standard foams & polymers additive mixes, a suspension of limestone powders. This with the scope of compensating the lack of fines of the natural ground with rock powders. The implementation of this so called “fines compensation injection” technique proved to be effective in producing an homogeneous, impervious “EPB suitable” ground mix in the cutterhead chamber. As a consequence it was possible to bore even the most critical tunnel sections without suffering instabilities, over-excavations as well to avoid ground water inflows through the screw conveyor of the TBM.
CHAPTER 1 – THE TURIN AUTOMATIC SUBWAY - LINE 1

The Turin Automatic Subway – Line 1 is composed by:

- 7500 m of tunnels bored by n.3 EPB TBMs (from Fermi up to Porta Nuova stations)
- 15 stations plus a deposit and workshop area for the Metro trains maintenance.
- 18 shafts ventilation and safety purposes (14) as well for the execution grouting works (4).
- A number of small tunnels to connect the main line to the shafts and to allow consolidation works constructed by conventional method.
- 910 m of surface line connecting the train deposit to the first underground station of Fermi.
- 80 m of tunnel line excavated by traditional methods (from Principi d’Acaja station toward XVIII December station)

The Client is GTT S.p.A., a company owned by Turin Municipality.

The works for the construction of the tunnel line and stations have been devised in n.3 lots, Lots 3-4&5, each one including almost 1/3 of the tunnel line and the relative stations.

The three lots have been awarded to different Joint Ventures in 2001.

Each Joint Venture was required to utilise a different TBM, for a total of n.3 TBM to be operated at the same time in the project.
The deadline for the completion of the three lots was linked to the necessity to put into operation the line for the winter Olympic to be held in Torino at the beginning of 2006.

SELI, as TBM specialist contractor, has been in charge of the study and of the operation of the n.3 TBM sites.

CHAPTER 2- PROJECT GEOLOGY AN ALIGNMENT OVERVIEW

The formation interested from the tunnel line is mainly constituted by river-glacial and river-Rissian deposit (Quaternary), of gravel sand and cobbles in silty matrix. Within this formation there are 4 units identified by specific granulometry and of different cementation:

- unit 1 – superficial ground
- unit 2 – gravel with sand from loose to slightly cemented
- unit 3 – gravel with sand from weak to medium cemented
- unit 4 - gravel with sand from medium to highly cemented.

The tunnel excavation of Lot 3 and 4 (from Collegno to Acaja ) interested unit 2 and 3 which were foreseen to have the following average granulometry..

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobles (%)</td>
<td>3.4</td>
</tr>
<tr>
<td>Gravel (%)</td>
<td>46.1</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>37.4</td>
</tr>
<tr>
<td>Filler (%)</td>
<td>13.2</td>
</tr>
<tr>
<td>WL</td>
<td>19.3</td>
</tr>
<tr>
<td>WP</td>
<td>16.3</td>
</tr>
<tr>
<td>IP</td>
<td>3.2</td>
</tr>
<tr>
<td>Cobles (%)</td>
<td>7.6</td>
</tr>
<tr>
<td>Gravel (%)</td>
<td>41.6</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>37.4</td>
</tr>
<tr>
<td>Filler (%)</td>
<td>20.0</td>
</tr>
<tr>
<td>WL</td>
<td>17.6</td>
</tr>
<tr>
<td>WP</td>
<td>11.8</td>
</tr>
<tr>
<td>IP</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Figure 2 table resume the average size distribution of the soil as indicated in the project design.
The permeability of the soil of unit 2 and 3 was foreseen to range from $10^{-3}$ to $10^{-8}$ m/sec. Furthermore local pockets of pure un-cemented sand were foreseen locally along the drives. Especially in the area interested by Lot 3 tunnel it was furthermore foreseen the random presence of large and very hard boulders.

Figure 3 represents the tunnel profile along the line below the city.

The ground water level is below the tunnel invert in Lot 3 and 4 tunnel sections while in Lot 5 for 90% of the length the water level is above the tunnel invert with a maximum pressure of 1.5 bars in the most critical sections.

As far as the tunnel alignment the following are the main aspects to be considered:

- A first section of the tunnel in Lot 3 is interested by a shallow cover ranging from 6.00 to 12.00 m.
- For the remaining stretch the overburden range from 11.5 m to 13 m except for two sections in Lot 5 where the tunnel underpass buildings and railways where the cover has been increased by the design up to 24.5 m.
- In these sections at deeper elevation the ground water table has the maximum pressure above the tunnel.
- To follow the vertical and horizontal alignment of the tunnel the vertical gradient is ranging from 0.5 to 5.96% and the minimum tunnel radius is 180 m.

CHAPTER 3- THE PRESENCE OF THE CITY AND OD CITY SERVICES
In every tunnel project in urban area the presence of the city, with its buildings, foundations, services, shafts and other old/unknown objects that might be encountered by the tunnel or around the tunnel shall be carefully considered.
In this regard a city like Torino, with ancient buildings and man made tunnelling systems excavated since centuries, can present several surprises when bored at shallow cover.

For this reason the design located the tunnel at deeper level than most city services and possible surprises, with the exception of an initial shallow cover section in Lot 3 and a section in Lot 5 that underpasses building foundations as well in an area interested by an old tunnelling network (Pietro Micca Tunnels)

CHAPTER 4- THE SELECTED TUNNELING METHODS AND TBMS

The project design was indicating two tunnelling methods as suitable for the construction without indicating any specific preference.

The two methods were:

a) EPB TBM technique
b) Slurry Shield TBM technique

All Joint Venture contractors, after having received the advise of expert consultants and on the base of other specific considerations, decided since the tender stage to select the EPB TBM technique.

While knowing that the tunnelling conditions would have been in any case at the critical limits also for the EPB technology, this method was preferred to the Slurry Shield TBM method for the following reasons:

- The good recent experience in utilisation of EPB technique in similar critical ground conditions
- The too high permeability for Slurry application
- The presence of large boulders that would have required a crusher in the Slurry shield excavation chamber with all consequent problems
- The presence of tunnels and other cavities underground surrounding the tunnel that could induce the sudden loss of the Slurry mud
Figure 4 confirm by comparison that the foreseen ground of Torino was within the range of the latest successful application of the technology in similar ground.

Nevertheless, in consideration of the criticalities and peculiarities of the expected ground conditions, the n.2 TBMs ordered to Lovat for the utilisation in lot 3 and 4 were designed and equipped with several special features; and in particular:

Cutterhead design
Since the presence of the boulders and the unknown behaviour of the Torino ground when bored by a TBM the cutterhead was designed for the maximum flexibility in order to be able to adapt its configuration to the actual circumstances as they may vary along the tunnel drive.
- The Cutterhead was therefore fitted with double cutter housings to be able to have two cuts in every grow and achieve a better penetration for revolution without destroying the cutting parure
- The housing were able to accept either picks, single disc cutters and twin disc cutters, for the maximum flexibility.
- The center of the cutterhead had bolted plates to modify the opening ratio and an two bolted different center noses.
Figures 5a and 5b show the two possible cutterhead center configurations
- The cutterhead openings were equipped with bolted grill bars to avoid blocks larger than the screw capacity to enter the excavation chamber
- The axial length of the cutterhead was kept to a minimum to reduce the risk of instabilities
- The whole cutterhead was protected against wear by special Trimay (Chromium-carbide) plates applied to the structure

The initial idea was to equip the cutterhead with twin disc cutters in order to break the boulders as much as possible when they are confined into the face.

**Ground Conditioning**

Always with the aim to be more flexible and be able to face different tunnelling conditions, the foam generating system of the TBM was designed for the maximum capacity in terms of flows and number of injection lines.

- The Maximum flow capacity of the system is 5,000 lt/min
- The number of separate lines to the cutterhead is 6, with 8 injection points
- The number of lines to the TBM bulkhead is 2, with 4 injection points
- The number of lines to the screw conveyor is 1, with 2 injection points

Each line could be supplied with foams or with water or with bentonite mud depending on the needs and the circumstances.

**Screw Conveyor**

The diameter of the screw conveyor was dimensioned in 950 mm, the maximum size in the given TBM diameter, in order to evacuate the maximum size of boulders.

**Main bearing**

In consideration of possible future diameter enlargements of the TBMs for utilization in other projects, the main bearing of the TBM has been dimensioned to resist to higher loads than the one expected in Torino.

**Torque capacity**

According to the known formula:

\[
\text{Torque} = 24 \times D^3
\]

that is used in the industry to determine the maximum torque an EPB TBM shall be designed for a given diameter, the EPB TBMs for Torino should have been designed for a Torque of 11,000 kN*m.

Always in consideration of possible enlargements of the same TBMs in future projects, the Torque of the TBMs was raised to 20,000 kN*m.
Main Thrust
Also the main thrust of the TBMs was increased above the standard levels for this diameter and the maximum design thrust have been fixed in 7600 tons.
This also in consideration of the narrow curves of the tunnel.

Excavated muck weight and volume control system
One of the most important problems in EPB tunnelling is to monitor continuously that the quantity of evacuated muck through the screw conveyor does not exceed the theoretical quantity corresponding to the TBM advance.
An excess of evacuated muck indicate either a lower level of the muck in the excavating chamber either an over excavation at the face; both circumstances being critical for the stability and safety of the tunnel and of the surface structures/services.
For this reason the TBM system have been equipped with a triple weight control systems: two on the back-up conveyor and one on the crane that lift the muck cars at the station.
The data given by these units were also compared with the volume of muck in the muck cars at the end of each stroke.

Mucking out system
A rail bound mucking out system, using a multi-traction hydraulic driven locomotive and muck car system manufactured by SEMAFOR (France), has been selected to transport the muck and the other construction materials.
This system has been preferred to a conveyor system for the following reasons:
- The deep and narrow stations and shafts from were the TBM are operated do not allow the use of inclined conveyors but only of vertical conveyors. These type conveyors would have been unsuitable to transport large boulders as well in general heavily conditioned ground
- The narrow curve along the tunnel would have created difficulties to the conveyor functioning
- It would have been more difficult with a conveyor muck out system to have a control of the volume excavated
- The short distances of the mucking out shafts and stations from the TBM face allow the utilisation of single truck rail system without limiting the TBM productions
Figure 6 shows the first Lovat TBM put into ground in the Fermi station in Lot 3 in October 2002.
Figures 7a and 7b shows the second Lovat TBM put into ground in the Principi di Acaia station in February 2002.

Figure 8 shows the muck cars when lifted by the gantry crane at the stations.
The two Lovat TBMs, identical in their design, have been operated in substantial different operating modes due to difference in the local geological conditions, as it will be described in detail in the following chapters of the present report.

The third TBM, to be utilised in Lot 5 is the NFM-Mitsubishi TBM previously utilised to bore the Milano Passante tunnel, in similar ground conditions that the ones foreseen in Torino.

As will be described with more details in the following chapters of the present report the TBM has been modified for the Torino Lot 5 tunnel in two phases:

- In a first phase the TBM was overhauled and modified to match the new Lovat TBM dimensioning criteria. In particular:
  - higher power hydraulic drives and reducers were installed to increase the cutterhead torque
  - an extended articulation and two copycutters were installed to accommodate the narrow radius of the curves

- In a second phase, after having experienced the difficulties to bore in the Torino ground with the first Lovat TBM in operation, it was decided to implement further experimental modifications to the NFM-Mitsubishi TBM in order to better face the even more critical ground conditions of Lot 5.

*Figure 9 shows the NFM-MITSUBISHI TBM*
CHAPTER 5- INITIAL SET UP OF EPB OPERATIONAL MODES IN THE TEST SECTION

In the first meters of tunnel excavated by the Lovat TBM in Lot 3 it came evident that:

- The percentage of fine materials was much less than foreseen in the project design
- The percentage of cobbles and boulders was very high and locally almost the complete tunnel section was interested by round blocks with very few sand and fines
- Due to the particular granulometry the cohesion of the ground was basically zero

In these ground conditions the TBM could not operate in an efficient EPB mode and frequent over-excavation occurred at the tunnel face and crown.

Considering the above the Contractor, the Client and the Engineer agreed to prepare a test section of 100 m in front of the TBM were to experiment different EPB operating procedures.

In order to secure the stability of the tunnel crown in this section a pre-grouting treatment of a rectangular shaped ground body was executed above the tunnel.

Figure 10 shows the ground consolidation scheme adopted under this test section.

Figure 10 shows a schematic drawing of the geometry of the consolidated slab
The aim was in this section to test different EPB operating mode and conditioning set up to find out the best compromise among stability, penetration, TBM operating torque and thrust.

As a conclusion two different “optimised” EPB operating mode and conditioning set up were determined:

✓ One named **EPB 06**, were the pressure in the top of the excavation chamber was kept between 0,6 and 0,7 being this the pressure necessary to assure the stability of the tunnel face. 
  With this operating mode: 
  o the segregation of muck in the chamber and the loss of foams and fluids phenomena were still important 
  o in order to reach an acceptable penetration rate (30 mm/rev) it was required an excessive amount of conditioning agents (FIR 50%) as well of water injection. The result was a conditioned muck of fluid-like consistency.

✓ The second one **named EPB 02** were the pressure in the top of the excavation chamber was kept between 0,1 and 0,3 despite this pressure was lower than the one required to assure the stability of the tunnel face 
  At this operating mode: 
  o The penetration rate achieved was more than acceptable (up to 50 mm/rev) and the quantity of conditioning agents (FIR 30%) and the consistency of the muck was more plastic-like as should be 
  o the segregation of muck in the chamber and the loss of foams and fluids phenomena were much less evident

The following table resume the main parameters of the EPB 02 operating mode: the operating pressure (average and in the top of the section), the ground conditioning parameters, the penetration rate, the operating torque and the total thrust.
### Table 1

<table>
<thead>
<tr>
<th>Average EPB pressure</th>
<th>Penetration</th>
<th>Total added liquids per stroke</th>
<th>TBM torque</th>
<th>TBM thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>mm/min</td>
<td>Ton</td>
<td>Ton m</td>
<td>Ton</td>
</tr>
<tr>
<td>0.2</td>
<td>37.2</td>
<td>8.0</td>
<td>1338</td>
<td>1642</td>
</tr>
</tbody>
</table>

Once out of the consolidated area the two above operating mode were experimented in a non consolidated area and the **EPB 06 mode** confirmed not to be suitable to stabilise the face, the large quantity of foams and liquids injected at high pressure actually contributed to the instability phenomena by: washing out the few fines in between the boulders, reducing both the cohesion and friction of the ground and with their pressure moving out the boulders.
Figures 11 and 12 shows the cavern that was created underground by operating at EPB 06 mode once out of the consolidated test section.

The EPB 02 mode confirmed to be more suitable both for the confinement of the face as well for the performance of the TBM and the consistency of the muck. However this operating pressure was not sufficient to stabilise the tunnel crown and the segregation of the ground in the excavation chamber was still occurring.

It was in other word evident the necessity to combine the EPB 02 mode with additional measures to allow a fast and safe execution of the tunnel.

CHAPTER 6- MODIFICATION TO CONSTRUCTION METHODS

In consideration of the outcomes of the test section it was therefore decided to associate to the EPB 02 operating mode a systematic consolidation of a slab over the tunnel section.

Professor Kovari as expert of the Contractor than determined two type of slabs
n.1- **light slab** “non structural” (to lightly consolidated and too small to be able to form a structure that can be taken into account in a structural calculation) having just the scope to increase the ground cohesion in the most critical crown area of the tunnel
n.2 - **structural slab** - having sufficient dimension and subject to heavier consolidation in order to assure a structural behaviour to be taken into account in the static verification of the tunnel stability

Following a risk evaluation and as proposed by the Contractor and Contractor Experts the Client finally decided to apply:

- The light slab associated to EPB 02 operating mode systematically all along the metro tunnel drive
- The structural slab associated to the EPB 02 operating mode in the most critical area nearby important buildings and under important subsurface and surface services

This new design and construction method was than extended to also to lot 4.
In lot 5 instead, having more time to study and implement additional measures, as will be better detailed in the following section of the report, several innovations were introduced to face the even more critical conditions of this lot.

CHAPTER 7- TBM PRODUCTIONS IN LOT 4 AND 5 AND OTHER OPERATING ASPECTS

With the modified construction and operating method the two Lovat TBMs outperformed in all tunnel drive and the light slab demonstrated to be sufficient, when combined with EPB 02 operating mode, to stabilise the tunnel face and crown in all encountered conditions.

The continuous control of the weight of the excavated muck furthermore allowed to detect in real time few local small over-excavations that were immediately filled by additional grouting.
Figures 15 and 16 compare the productions of the Lot 3 TBM (after the implementation of the new method) and of Lot 4 TBM.

The higher productions in average and in peak of Lot 4 TBM are due to:

- The substantially better ground conditions in this lot (less boulders and cobbles) that allowed higher penetration rates and less stability problems
- The advantage that, being this the second TBM in operation and by the same contractor, all small problems and operating tricks solved in Lot 3 (after having suffered the problem) were immediately transferred to Lot 4 that therefore found most of the problems solved before even to encounter such problems
- The steep gradient of the lot 3 tunnel (5.5%) which slowed down the train average speed

Despite the good productions, even with the new design and construction method, it was impossible to avoid some of the consequences of operating with an EPB TBM in a soil that for its nature and for the particular ground size distribution can not be conditioned for a decent EPB operation.

In particular:

a) The screw conveyor were severely damaged by having to transport large boulders and in general a very frictional not well conditioned ground

b) The operating torque of the TBM was in average 40 % higher in average that the maximum to be expected in this diameter range, with all negative consequence on the life of the TBM main components and on the integrity of the TBM itself
c) The wear of cutters and peaks on the cutterhead has been extraordinary high

d) The wear of the cutterhead structure, of the cutterhead antiwear protecting plates,
of the cutter and pick housings has been so dramatic that at every station and in
some occasion in between two station thy complete cutterhead had to be rebuilt.

CHAPTER 8- CUTTERHEADS CUTTING TOOLS
As mentioned above the Lovat TBMs cutterhead with the maximum capacity and flexibility in
term of number and types of cutting tools that is possible to install.

Initially in Lot 3 the cutterhead was equipped with all twin disc cutters with the scope of cutting
the blocks when still into the face.
Furthermore all grill bars were in place to avoid larger boulders to pass into the excavation
chamber

Figure 17 shows the cutterhead of lot 3 in its initial configuration
In field it was found that:

1. peaks were working better than discs in the central positions of the cutterhead and in general in the looser ground sections
2. cutters were working better on the peripheral sections of the cutterhead and in the hardest (naturally cemented or consolidated) sections of the tunnel
3. the noose of the TBM in the central part was helping in avoiding clogging of the material in this area

Along the TBM drives the cutterhead configuration was therefore modified several times to suit the ground characteristics.

As mentioned above, however, independently from the configuration, the operation of the cutterhead in the Torino ground resulted in rapid wear not only of picks and cutters but also of the cutterhead structure and the tools housings, with frequent necessity to stop the boring operation and rebuild the complete cutterhead.

In addition it was necessary to eliminate part of the grill bars to avoid the tendency of the blocks to accumulate in front of the cutterhead and stop the machine advance.

The elimination of part of the grill bars, forced the screw conveyor to operate with boulders having larger dimensions than the maximum size the screw was designed for. As a result both screws were subject to extraordinary wear and shocks.

**CHAPTER 9 - LOT 5 ALIGNMENT AND GEOLOGY**

Natural soil, as for lots 3&4, is basically composed of river’s and glacial deposits: cobbles gravel and minor sand with variable grade of cementation passing from loose up to solid with presence of boulders and sandy lenses.

Boulders might have dimensions ranging from 0.20 m to 1.2 m and have metamorphic origin with high grade of quartz contain.

The tests and experiences made during the excavation of tunnels for lots 3 and 4 demonstrated that the absence of fine grained materials in the natural soil, was even more marked than predicted in the design stage (less than 5% to be compared with 17 – 20% foreseen in the design studies).

Tunnelling conditions for lot 5 were expected to be even more difficult in respect of the tunnel sections included in lots 3 and 4. The already critical characteristics of the Turin subsoil are in fact combined in Lot 5 with additional difficulties as:
o Presence of underground water up to a level of 15 m above the tunnel invert
o Underpassing of important infrastructures, historical buildings and underground constructions.
o Presence of important traffic nodes along which vehicle circulation could not be interrupted.
o Dense presence of city’s main underground service lines and main sewerage ducts.
o Presence of narrow curves with only 180 meters radius.
o Presence of vertical gradients up to 5,6 % (first down-word and than up-word) and horizontal curves having a radius of 180 m combined with vertical curves

CHAPTER 10 – SPECIAL MEASURES TO BOOST EPB TBM TECHNOLOGY APPLICATION

The experiences, monitoring and investigations activities performed during the execution of the tunnels for lots 3 and 4, were at the base of the studies and risks analysis made in preparation of lot’s 5 tunnel construction.

From the outcome of these studies both the Designer and the Contractor agreed that neither a traditional EPB TBM neither a Slurry Shield could have guarantee to excavate in the Turin fine-less ground and moreover in such difficult conditions (narrow curves under buildings and under water pressure)

Due to the lack of fines the implementation of an effective EPB would have been impossible even through a massive utilization of foams and polymer conditioning.

From the observation of the Turin ground grain size curves it appears evident that they are out of the range of application of standard EPB TBMs.

![Comparison between Turin soil curves and standard EPB application limit](chart.png)
Figure 18 and 19 table resume the compare the actual average size distribution of the soils in Turin with the standard EPB limits.

On the other side the utilization of an Hydro Shield would have encountered possible problems due to:

- The very high permeability of the ground, locally greater than $10^{-3}$
- The large presence of cobbles and boulders
- The possible presence of voids and ancient services were the Slurry mud could be suddenly lost
- The environmental and disposal problems created by the residual bentonite mud in the treated muck

In consideration of the above the Designer and the Contractor agreed to utilise an EPB TBM modified and implemented by three major measures:

- **Improved soil conditioning system**: i.e. to install on the TBM a conditioning system able to mix and inject in the excavation chamber foams reinforced with polymers.
  This to improve the quality and control of the foam utilised for the conditioning of the excavated muck in the cutterhead chamber
• **Fines compensation** – i.e. to inject in the excavation chamber of a fluid mix of fines and polymers. This to compensate the lack of fine materials in the in situ soil and allow the TBM to advance in an efficient EPB mode

• **Structural grouting of soil bodies in critical area** – i.e. to execute from surface and specific access tunnels cement grouting injections. This to form grouted structural soil bodies to secure the stability and avoid settlements in the area interested by important buildings

Having implemented the above additional measures the design philosophy became:

- To stabilize the tunnel face and control ground water inflows by operating the TBM in EPB mode (thanks to the special conditioning and fines compensation)
- To stabilize the tunnel crown by creating structural grouted soil bodies above the tunnel in the most critical tunnel section under important buildings

The EPB confinement operating pressure was calculated by Dr. Kovari (SELI consultant) taking into considerations a safety factor ranging from 1,5 to 2 depending from: the importance of the buildings above the tunnel, geotechnical characteristics of the excavated units, the shape/dimension of the grouted bodies.

The values of the confinement pressure calculated at the front face resulted in a range varying between 0,2 ÷ 0,5 bar at the tunnel crown.

In the following sub-chapters are described in detail the special measures implemented.

### 10.a IMPROVED SOIL CONDITIONING SYSTEM

One of the key factors for EPB mode excavation is a good conditioning of the soil. The addition of foams and/or other products contributes dramatically to reduce frictions, decrease the specific weight of the excavated material, increase volume filling inside the chamber, reduce eventual filtration and in general to form the optimum EPB paste optimising therefore the both the face stabilization and the TBM penetration rate.

What is important for a successful application is anyhow to select the best possible foam/additive for each specific application and to correctly set up the foam plant on the TBM in order to reach a good quality foam and obtain the desired FER and FIR.

After an accurate laboratory and market investigation, taking also into consideration the environmental restrictions, it was decided to adopt a foam obtained by mixing compressed air and water with the foaming agent Foamex by Lamberti, stabilised by the polymer agent Drillam MV. This mixture was able to form a
dense and long term stable foam that did migrate even through the very permeable soils of Turin. Stability and strength of the foam bubbles could be eventually increased by adding a percentage of Drillam MV. Stability and density of foam are controlled by varying:

- the concentration of foaming agent between (between 1% and 5%) in the water mix
- and
- the F.E.R., Foam expansion ratio, (between 5 and 15) which represent the increase of volume of the foam formed by mixing compressed air with the water/foaming agent mix

Another important parameter to take into consideration in soil conditioning in EPB operation is represented by F.I.R (foam injection ratio) which represent the volume of injected foam per cubic meter of excavated soil.

Approximately, F.I.R. can vary from:

- 20%, for clay – cohesive soils
- 30% for sandy – silty soils.
- > 40% for gravel and sandy soils

In lot 5 tunnels the mean values utilised in soil conditioning have been:

- Concentration of foaming agent: 1.5 %
- F.E.R : 8
- F.I.R 46%

Table below shows the FIR real values utilised in the most critical section of tunnel excavated in Lot 5.

![Figure 20](image-url)
Another important aspect to be considered when operating an EPB TBM is the quality and capacity of the foaming plant installed on the machine. Due to the difficult ground to be conditioned, for the NFM TBM utilised in Lot 5 it was decided to substitute the original plant installed on the TBM by a new plant supplied by SPOILMASTER (England) specifically designed for the application.

The main features of this plant are:
- The capacity of mixing foam and polymer to form a thicker and more stable foam
- The automatic control of all conditioning parameters through several PLC’s while the TBM operator can check all its working data.
- The automatic adjustment of the quantity of foams injected according to the TBM penetration and the EPB working pressures

Inverters adjust speed for the pumps to add the three component (polymer, foaming agent and water). The foam is injected at approx 4 – 5 bars (inside the screw conveyer, at the cutterhead, in the working chamber) through proper nozzles which position was accurately studied to give a correct and homogeneous distribution.

10.b Structural grouting of soil bodies

In order to secure the stability of the more critical historical buildings located above the tunnel route it was decided to study, design and implement a special grouting scheme.

Grouting design had to be extremely accurate since it had to take into consideration various aspects such as:
The presence of underground lines not to be hit by drillings works.

The presence of buildings, structures, underground constructions that were limiting the drilling possibility.

To limit the disturbance caused by the drilling and grouting operations on surface in

The presence and level of the underground water table

Four different shapes of injected body were finally designed.

All these shapes were designed to form a tri-dimensional structural bodies to avoid that any over-excavation and/or instability occurred at tunnel level could be transmitted to the surface buildings.

A certain number of full face injected body, associated with injection of special mixture to lower the soil permeability, were also executed to allow major cutterhead planned maintenances.

![Grouting bodies schemes](image)

**Figure 21b - Grouting bodies schemes.**

The execution of drillings for the grouting works in many cases was done utilising mini crawled drillers placed inside small tunnels (section approx. 9 sqm) and located between the surface and the subway level. Those tunnels were bored in traditional method through access shafts and/or through the same shafts foreseen for the permanent works for ventilation and safety purposes.
During grouting execution all injection parameters were recorded to increase the knowledge and behaviour of soil and to detect the local presence of fine lenses in case of low absorption of injected fluids.

Quality of injected mixture was controlled during operations both in terms of density and of compressive strength, in order to compare the designed values ($\rho = 1.25$ t/m$^3$ and $f = 10.0 – 12.0$ t/m$^2$).
SELI SPA – Ing. Remo Grandori –
RETC Difficult Ground - Construction of the Turin Metro Line 1 Tunnel by no. 3 EPB TBM s
10.c – Compensation of fines

SELI performed a test program in its laboratory to study the soil conditioning problems of the Turin soil. From the result of these tests it was clear that the injection of a combination of foam and polymers was not enough to produce a plastic no segregating muck. As a consequence it was decided to study the alternative to complement the foam and polymers conditioning with the injection of a fluid mix containing rock powders.
In order to produce a stable mix, the following main aspects were considered:

- A filler having a fineness modulus and size for “closing” of the curve of the natural alluvial material.
- A polymer able to stabilize the mix and satisfy the environmental aspects at the disposal area
- A viscosity of the mix suitable to be pumped through the small conduits of the cutterhead rotary joints

**Filler characteristics**

Many fillers were tested such as coal, rise, fly ash, perlite, bentonite, fine sand 0 – 2 mm but all of them have been rejected for the impact on environment, economic and availability aspects.

After several tests limestone rock flour was chosen.

Two different fillers grain size were mixed in order to “adjust” the original alluvial percentage distribution:

- 50% of 40 size named VNT
- 50% of 20 size named M20

The blend was chosen according to the average of several sieve analysis performed on in situ soil samples taken under the water table in order to fill the grain size gap.

**Polymer**

The polymer has a double effect:

- stabilize the slurry mix avoiding the components segregation and the consequently bleeding
- penetrate through the soil at the tunnel face for few centimetre helping in the face support and in ground water control

However the polymer alone cannot replace the lack of fines in the ground since the polymer does increase the viscosity of the mix but not the mix specific gravity, which remain 1 Kg/l if no fines are added. SELI tested many polymers available from the market having different chemical composition and all environmentally acceptable.

After having selected the most suitable polymer for the application additional tests were performed to individuate the best dosage to improve the hauling time and the mixing condition.

Different dosages have been tested taking in account:

- filler grain size
- filler/water ratio
- hauling time
- mixer type
Figure 27: sand with polymer

Figure 28: sand without polymer

Figure 29: injected mix of fines and polymer
Mix Slump
in order to measure the plasticity/workability of the treated muck slump cone tests were performed until the target 140 – 160 mm value was reached. The slump tests provide a simple workability index for the conditioned muck.

Viscosity
The mixes viscosity have been determined according to the Brookfield RV 20 rpm method
The viscosity of the mix tested vary according to:
• filler/water ratio
• filler grain size
• polymer chemical composition and structure
• polymer dosage
The measured viscosity of the mixes tested vary between 545 cp and 19000 cp
The correct choice of the filler grading, polymer and filler/water ratio should take into consideration proper pumping of the mix from TBM back to the front face through to the rotary coupling and inside the working chamber, whenever necessary, without clogging.

Preparing the mix
The mix was prepared outside in a special plant designed by Seli. The plant was equipped with one high capacity mixer, balances for filler, water and polymer and two silos for the two fillers; all the mix preparation phases were controlled by a PLC system.

Transporting and injecting the mix
The slurry mix was pumped down inside a transport mixer that was part of the mucking train. Once reached the TBM back up the mixer was connected to a pump that directly injected the mix at the face through the cutterhead rotary joint.
A custom made PLC program controlled by the TBM operator supervises and monitors the injection of fines process.

The plastic, well-graded muck obtained by combining the special soil conditioning with the fine injection compensation allowed to achieve:
• more uniform pressures in the excavation chamber
• better control of groundwater inflow by reducing the permeability
• high compressibility
• reduced friction and heat build up in working chamber
CHAPTER 11 – MONITORING SYSTEM

The monitoring system was designed to record in real time:

1. the stresses, strains and displacements of the tunnel under construction
2. the settlements of the soil at surface and below the surface.
3. the displacements and rotations of existing buildings

Due to the importance this tunnel and its potential interference with the urban net, the monitoring points and the relevant instrumentation have been widely redundant.

1. Monitoring of the tunnel under construction

These measurements were taken by installing precasted rings equipped of embedded instruments such us: strain gages, pressure cells both along radial and longitudinal direction and four (4) 3d targets for convergence measurements.

Monitoring sections for lining placed along the tunnel are correlated to other measurements taken for the soil settlements and the external buildings.

2. Settlements of the soil at grade and below the surface.

Checking of superficial settlements produced by the TBM excavating action was conducted by reading of topographic level benchmarks placed both along axial and transversal directions.

Deep settlements were measured by multi-base extensometers and increx systems installed at various position in order to read eventual displacements at different deepness.

![Surface topographic monitoring](image-url)

*Figure 30- Transversal sections of surface settlement monitoring readings*
3. Displacements and rotations of existing constructions

Monitoring of existing buildings was performed by taking into consideration a general scale of risk for each of them. This evaluation, prepared on the base of the age of the building, its historic importance, the distance from the tunnel, its destination, gave a final rate of risk according to which a certain number of instruments were placed and a consequent frequency of readings was taken.

The placed instruments consisted on:

✓ level benchmarks
✓ micro deformation meters
✓ micro crack meters
✓ triaxial vibro-meters

All the instrumentation complied with rules indicated by UNI 9916 and DIN 4150.

11.1– UPPER LIMITS VALUES FOR MONITORING DATA

The real time readings of the monitoring instrumentation, gave the opportunity to detect at any moment eventual displacements values that were reaching the upper admissible limits.

Two (2) different limits were set:

- Attention limit: defined as a portion of the calculated deformation (30%). Its reaching determines a more frequent monitoring reading and much more controlled excavation process.
• **Alarm limit**: defined as a greater portion of calculated deformation (60%). Its reaching could bring to uncontrollable risky situation of collapses and caving. Excavation is immediately suspended and risk committee is timely informed to decide remedy measures.

### 11.2 – RESULTS AND DATA INTERPRETATION

All the data were recorded, elaborated by PCs and read by a team of engineers. The lower attention limit was never reached and all movements and displacements were very minimal.

### CHAPTER 12 – TBM CHARACTERISTICS AND PERFORMANCES

#### 12.1 – MAIN CHARACTERISTICS OF THE TBM

The excavation of the lot 5 tunnel section was performed by using an EPB TBM NFM model 8030. This machine was used before in other two projects.

SELI however performed several improvement and modifications before to deliver the TBM to the Turin sit, and basically.

- New cutterhead configuration.
- N.2 special Copy cutters installed on the cutterhead
- New extended stroke shields articulation system to cope with the 180 m curve
- New Hyperbaric chamber
- New twin weighting system of extracted muck.

**New configuration for the cutterhead.**

The cuttehead was designed to penetrate through alluvium deposits with different grade of cementation. It is equipped with:

- ✓ scrapers
- ✓ rippers
- ✓ cutters

The different cutting tools can be interchanged and replaced from any point inside or outside the working chamber.

**Copy cutter**

This system allowed to cope with the narrow curves foreseen for the tunnel of lot 5. It is composed of 2 external five blades cutters installed in symmetric position on the cutterhead.

Each copycutter extends up to 140 mm out of the standard cutting profile.
During the cutterhead rotation the two cutters are extended and retracted actuated by hydraulic cylinders and controlled by PLCs.
The elliptical shape of the excavated profile allows the excavation of the TBM in narrow curves and minimize the over excavations.
The system proved to work very efficiently

**Articulation system**
The Articulation system of the TBM was changed to allow openings of the shield joint up to 200 mm, improving therefore the capability of the TBM to follow tunnel alignment along short radius curves.

**Hyperbaric chamber**
Hyperbaric chamber was installed to allow the access to the cutterhead chamber under compressed air for maintenance and inspections.
This chamber has a double compartment.

**Weighting system and control of extracted muck.**
Control of the weight of the extracted muck is a fundamental aspect in EPB excavation. This measurement allows to evaluate the correspondence between the weight of the extracted soil and the theoretical weight related to the TBM advance.
Important differences between the two weights indicate the presence of over – excavations or variations in the level of muck in the cutterhead chamber.
On the NFM TBM used in lot 5 two weighting scales were installed on the back-up conveyor and the recorded values were displayed on the monitor installed inside the operator cabin and compared with the theoretical weight.

### 12.2 – TBM ACTUAL PERFORMANCES

The arrival on site of the TBM components was completed on November 15th 2003 and in about two months the assembling and testing was completed.
First boring was done on January 25th 2004.
Arrival at the first station called “XVIII Dicembre” was achieved on April 5th 2004 with a general advance rate of 8.15 meters per day.

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1 Not considering season holidays for Christmas
During the TBM translation inside the station, special maintenance was performed to the cutterhead and the screw conveyor.

The following tables summarize the TBM performances and cutting tools wear data in this first tunnel stretch:

<table>
<thead>
<tr>
<th>length (m)</th>
<th>Daily adv.</th>
<th>Mean trust</th>
<th>Mean torq.</th>
<th>ROP aver.</th>
<th>Confin EPB press</th>
<th>Mean FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m/gg)</td>
<td>(ton)</td>
<td>(ton*m)</td>
<td>(mm/min)</td>
<td>(bar)</td>
<td>(%)</td>
</tr>
<tr>
<td>318</td>
<td>8.15</td>
<td>1360</td>
<td>590</td>
<td>22.4</td>
<td>0.30</td>
<td>45.7</td>
</tr>
</tbody>
</table>

Cutting tools replaced

Cutters 15
Rippers 240
Scrapers 52
Copy Cutter 2
Total: 309

Table 2

The excavation of the second section was resumed on April 22nd and completed on June 17th 2004. The average advance rate for the whole second stretch resulted 10.57 m/day with a peak value of 18 m/day.

The following tables summarize the TBM performances and cutting tools wear data in this second tunnel stretch between XVIII Dicembre station and Principi di Acaia Shaft.

<table>
<thead>
<tr>
<th>length (m)</th>
<th>Daily advance</th>
<th>Mean trust</th>
<th>Mean torque</th>
<th>ROP average</th>
<th>Confin EPB pressure</th>
<th>Mean FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m/gg)</td>
<td>(ton)</td>
<td>(ton*m)</td>
<td>(mm/min)</td>
<td>(bar)</td>
<td>(%)</td>
</tr>
<tr>
<td>497</td>
<td>10.57</td>
<td>1350</td>
<td>630</td>
<td>25.7</td>
<td>0.30</td>
<td>46.2</td>
</tr>
</tbody>
</table>

Cutting tools replaced

Cutters 89
Rippers 72
Scrapers 427
Copy Cutter 2
Total: 590

Table 3

The graph below visualize the TBM production during the excavation period.
12.3 – COMMENTS ON TBM PERFORMANCES

- The structural grouting of soil bodies secured the stabilities of the critical buildings avoiding settlements.
- The twin copy cutter worked very efficiently and the 180 m curves were driven by the TBM with very accurate steering.
- The compensation of fines proved to be essential to form a suitable EPB paste and to control the ground water, avoiding free inflows through the screw conveyor.
- The combination of special soil conditioning and compensation of fines allowed an efficient EPB operation of the TBM.
- No face instabilities and over-excavations were observed.
- This success of the fine compensation technique have been so convincing in the field that the Client and the Designer decided to excavate all the last section of the Lot 5 tunnel without any grouted body above the tunnel, except that for few short critical passages.
CHAPTER 13 – TBM SPECIAL LIFTING AND TRANSFER SYSTEM

The urgency of completing the works for the winter Olympic games pushed the decision to speed up the TBM removal from the shaft and transfer the same TBM to the next starting station. SELI studied a special lifting of the TBM in a single piece (except cutterhead).

The TBM was lifted by hydraulic hoist equipped with 4 hydraulic jack having a capacity of 180 ton each and carried on special multiple wheels modular car.

The TBM transfer was anticipated by a careful study of all interferences, aerial lines, traffic, underground services, structures and load capacity of bridges.
Figures 33, 34, 35 & 36 shows the TBM lifting and transport operations
Conclusions

Lot 5 of the Turin metro line 1 gave the opportunity to experiment new technologies in the EPB tunnelling field.

The compensation of fines technique allowed to extend the application of EPB technique well behind the standard limits and proved to be very efficient and safe.

The metro line, thanks to the effort of all the participants and to the innovations implemented, will be in operation on schedule for the Turin 2006 winter Olympic Games.