

SOIL CONDITIONING AND GROUND MONITORING FOR SHIELD TUNNELLING

Claudio OGGERI, Raffaele VINAI**

Abstract

Soil conditioning consists of mixing and remolding the natural material during the mechanical excavation of tunnels, generally at low depth, with additives, in order to obtain suitable properties of plasticity and consistency for the excavated material, so becoming able to apply a counterpressure against natural earth pressure and groundwater flow towards the excavation chamber. The assessment and the control of the soil parameters and of machine performance are fundamental for a regular and safe excavation, also with regards to surface stability. This paper mainly focus on testing approach aimed to the proper soil conditioning with EPB shields, whose results have been validated at real scale. The influence of the water content and the amount of conditioning foam has been studied by the Authors. A proper definition of conditioning parameters can allow to extend the application field of Earth Pressure Balance (EPB) tunnel machines to various grain soil distribution, even in weak rock formations (e.g. siltstone or flysch). Importance of conditioning is reflected also on the possibility of a proper spoil disposal or better for its reuse.

Keywords: *mechanized tunnelling, soil conditioning, EPB shield, spoil reuse*

1. Introduction

Tunnelling activities are always affected by local excavation conditions. When the face stability, the ground stability, the safety from collapses both underground and aboveground are threatened by such difficult conditions, or more simply the aboveground conditions impose restrictions (e.g. in urban area), the tunnel excavation method has to be carefully chosen and, when necessary, adapted. Excavation conditions the most critical, and very often encountered, are the followings:

- Tunnels under the water table;
- Tunnels in loose, cohesionless soils;
- Shallow tunnels;

- Big excavation sections;
- Surface settlement restrictions;
- Vibrations restrictions.

In order to overcome such critical conditions, the shield technology has been developed. In simple terms, shield tunnelling consists in protecting the excavation face area with an iron shield that allows to carry out the excavation operations and the lining installation avoiding void deformations (which can result in settlements or, in the worst case, collapses), and thus preventing from major criticisms. Close systems have then been developed for providing a face support by applying a confining counter-pressure, initially with pressurised air (nowadays abandoned but for maintenance activities on cutting face) and then with bentonite slurry circulation (Slurry Shields – SS), enhanced with a air-operated pressure control system (Hydro Shields – HS), and, eventually, with the excavated material pressurisation (Earth Pressure Balance Shields – EPBS). Such methods can also be coupled with specific intervention for risk mitigation, which are often referred as consolidation techniques (ahead, over and beside the tunnel excavation face).

2. Technology

Historically, slurry shields (SS) were adopted for coarse-grained soils and bigger diameters, whereas earth pressure balance shields (EPB) were utilized in soft, clayey and silty soils with lower diameters. The reasons for such a dichotomy were mainly:

- for EPB:

- fine soils are more able to create a plastic mass for the pressure transmission, whereas coarser soil are unlikely to become pulpy;
- the cutter-head rotates in a soil plastic mass therefore required power is quite high;

- for SS:

- fine soils are more difficult to separate in surface plants for the bentonite recovery;
- the cutter-head rotates into a mud with low to very low viscosity, therefore the required power is lower than in the EPB case.

The recent developments of the EPB technology allow to overcome both these constraints, since higher and higher mechanical powers are installed on the TBM and consequently

**DIATI, Politecnico di Torino, Italy*

giant machines have been lately delivered. Furthermore, a fundamental development is represented by the extensive and effective application of the technique usually referred as “soil conditioning”, i.e. the treatments executed during excavation that give to the soil the required features for the EPB tunnelling operations.

The EPB technique was developed in Japan. The first application dates from 1974 and involved boring a collector of 3.35 m in diameter and 1900 m long. This technique developed quickly and it is today the most widely used for many soils, excavation diameters and groundwater conditions.

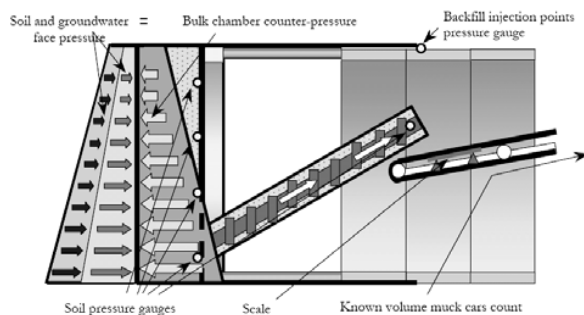


Fig. 1. Functional scheme of an EPB TBM

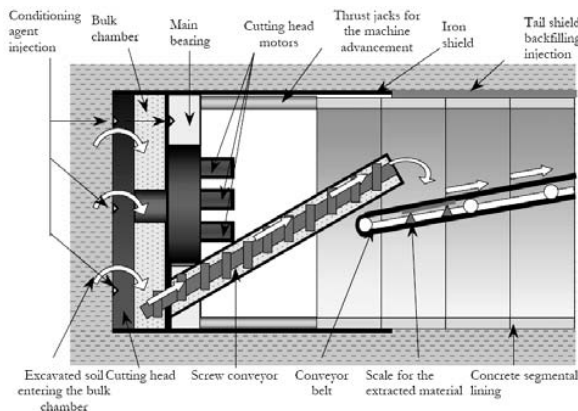


Fig. 2. Description of the main parts constituting the EPB TBM

In EPB technique, the ground excavated by the cutter head is mixed and accumulated under pressure in a chamber (the muck chamber, or excavation chamber, or bulk chamber) and is then extracted at atmospheric pressure by means of an Archimedes screw (the screw conveyor). The principle of earth confinement is based on the use of the excavated material itself which, when mixed and filled into the muck chamber, makes a mass of varying viscosity (depending on the fluidity and plasticity characteristics), maintained under controlled pressure to balance the pressure exerted by the ground, thereby ensuring face stability as the shield progresses. The pressure exerted on the cutting face, to balance the pressure of the ground and possibly the hydraulic load, varies as a function

of the force of the thrust exerted by the shield on the cutting face and also of the rate of muck extraction (screw speed).

As the tunnel machine advances, pressure is maintained on the front by having the screw extraction speed (variation in speed of rotation – rate of opening of the screw discharge gate) and the thrust controlled by pressure detectors mounted on the rear wall (bulk head) of the muck chamber. This system of regulating directly influences control of face stability. This means that the excavated material has to be kept under pressure in the muck chamber and consequently that the volumes of material excavated and discharged have to be kept equal at each instant; this is why the speed of rotation of the screw has to be controlled following the real advance rate of the shield, the pressure in muck chamber being kept greater by about 0.2 bar than the pressure exerted by the ground (earth pressure + the hydraulic load) (Peron & Marcheselli, 1994). The ideal soil behaviour for an EPB drive generally includes:

- good plastic deformation
- pulpy to soft consistency
- low inner friction
- low permeability

These characteristics are necessary in order to ensure that: 1) the soil as a fluid can transmit pressure from the bulkhead; 2) groundwater can be adequately sealed; 3) the drive torque can be minimized; 4) abrasive wear can be reduced (Feng, 2004). Ideal soils is therefore a clayey, soft soil with “toothpaste” consistency as presented in fig. 3.

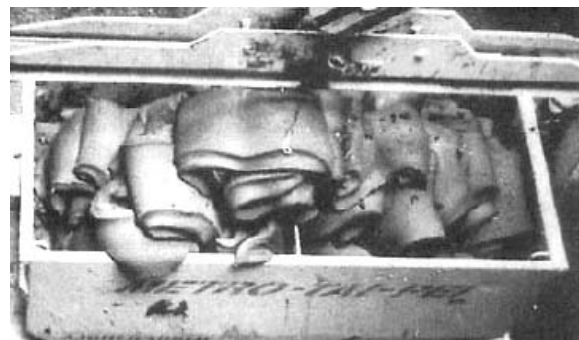
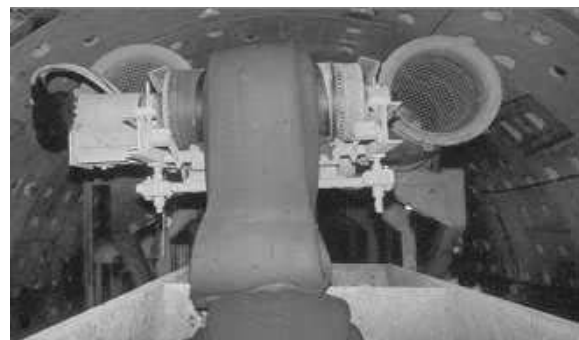


Fig. 3. Taipei Metro. Ideal soil consistency for EPB operations (“Tunnel”, STUVA)

Usual geotechnical characterisation tests (grain size distribution, Atterberg Limits, Consistency Index) are sufficient for identifying the type of natural soil encountered during the excavation.

The application of EPB in sand and gravel requires mainly that the excavated soil be rendered effectively impermeable and of a plastic consistency which can be remoulded in the machine head and extruded through the screw conveyor without allowing inflow of the groundwater. High wear is also to be expected with abrasive minerals.

The problems of EPB in stiff, over-consolidated clays are related to the interaction of water and soil: adding extra water, clays can become as soft as desired, but the plasticity range can be quite narrow: too little water and the material remains too stiff, too much and the material can flow out without proper control by the screw conveyor. With highly plastic clays the problem is that large quantities of water are needed to change the water content sufficiently and the clay is very impermeable. It is almost impossible to achieve a well-mixed soil of reasonably uniform consistency at the right shear strength. It may instead be possible to create a “rubble” of chunks of the intact clay sliding in a matrix of softened soil; however in this case there is a great danger of recompacting the material into a very sticky mass that clogs up the machine head and conveyor. Similar problems can occur in clays of intermediate plasticity, though to a lesser extent (Milligan, 2000).

In order to extend the original application field for EPB shields towards coarser soil, as well as towards hard and gluing clayey soils, the natural material can be treated by means of additives injection during the excavation step. Such additives can be of different nature and composition, and have changed deeply for the first applications to the more recent developments.

The conditioning additives are, mainly:

- foam;
- polymers;
- water;
- fillers, like bentonite or similar fine particle materials.

The properties of foam are related to the expansion ratio (Foam Expansion Ratio FER: the ratio of the foam volume to the original liquid volume), and also to the nature and concentration of the foaming agent in the liquid. In a typical application, the expansion ratio might be 10 to 20, so that 1000 litres of foam would contain 100 to 50 litres of liquid, the rest being air. The liquid in turn would typically contain 1 to 3% of concentrate, the remainder being water. Thus even if large quantities of foam are required, and the

concentrated agent is expensive, the cost of the foam may be quite modest (Milligan, 2000).

Foam with expansion ratios in the range 8 – 10 are usually referred as “wet” foams, whereas foams with expansion ratios in the range 10 – 20 are usually referred as “dry” foams. Dry foams are usually more stable than wet foam.

Foam should be stable during injection and mixing with the soil, but should become unstable as soon as possible after discharge from the screw conveyor. In the first case it is important to maintain pressure and a plug in the screw conveyor, in the second to reduce the volume of soil for transportation and land filling (Kupferroth et al., 2001).

The amount of foam that is added to the soil is measured through the so-called Foam Injection Ratio (FIR), that is the ratio of the injected foam volume over the volume of the excavated material.

Polymers act as dispersants by increasing the overall negative surface charge on solid particles to which they become attached, reducing the natural tendency of particles to flocculate as a result of the variable distribution of charge on particles, and hence maintaining a dispersed structure of lower viscosity.

Water-absorbing polymers merely absorb water and swell. Water-absorbing capacities of 500-600 times the weight of the polymer are possible with pure water, but 100 times is more realistic for water containing dissolved solids.

Water can complete the effectiveness of other conditioning agent, like foam, by lubricating and activating the finer grain size fraction, as well as alone, in case of soft clays near to the plastic limit (Bordachar & Nicolas, 1998).

3. Soil testing

The performance of the conditioned soil should be evaluated with tests that are able to describe its mass behaviour, but very little research has been carried out in this field. Often the choice of the conditioning agent set and its control during the excavation is made on a trial-and-error basis during the excavation process (Peila et al., 2009). These tests must be able to provide an easy comparison of the various additives available on the market, the definition of the correct amount of conditioning agents, and an easy control of the conditioning quality during excavation. The characterization of conditioned soil is usually obtained using tests derived from geotechnical or concrete measurement technologies; these tests include the mixing test, the cone penetration test, the permeability test, the compressibility test, the shear test, and the slump test.

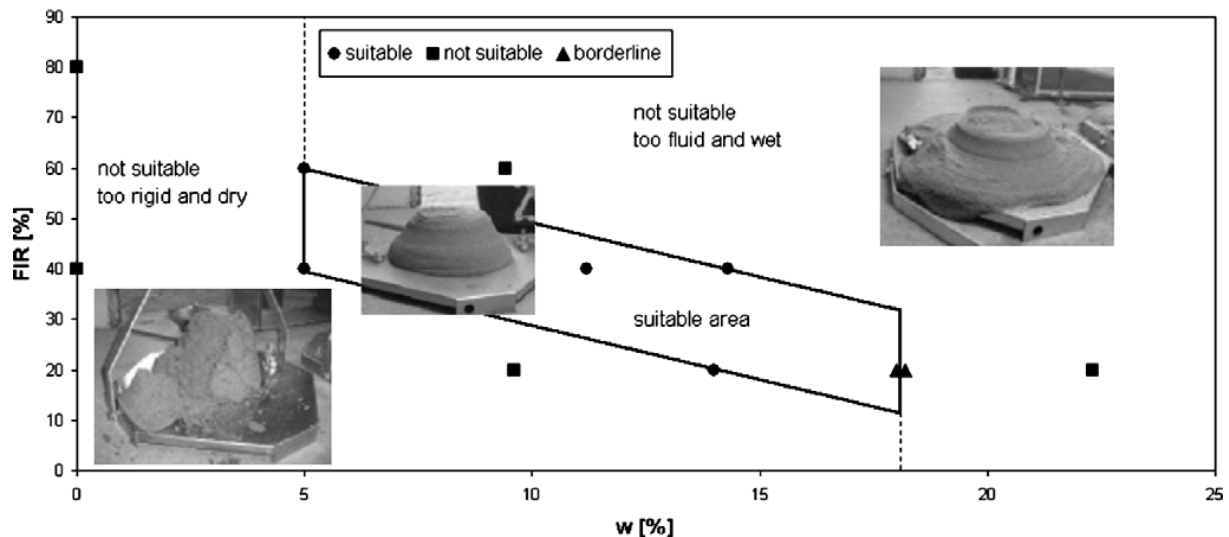


Fig.4. Parameter set area definition and optimum conditioning treatment choice

Some large-scale tests using a laboratory screw conveyor device have recently been proposed and they have proved feasible since they allow many parameters directly linked to the EPB excavation process to be measured (Mair et al., 2003; Merritt and Mair, 2006; Peila et al., 2007; Vinai et al., 2008, Borio et al (2009). At present, this type of test appears to be the best tool for conditioning design but it requires a large volume of soil to be handled and it is not suitable for carrying out a systematic comparison of various conditioning sets with various types of products.

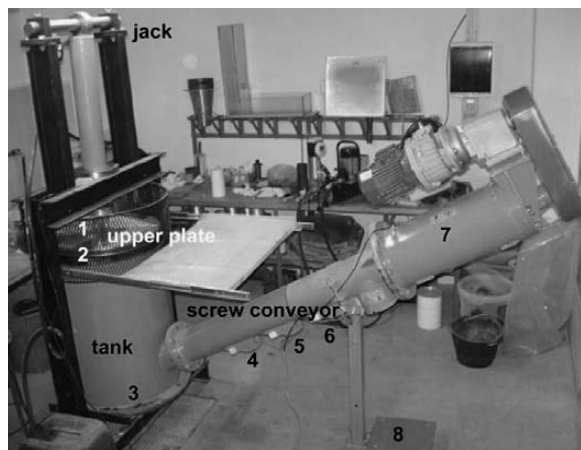


Fig. 5. The laboratory test cell developed by Vinai. Numbers refer to the installed sensors:

- (1) displacement wire transducer; (2) tank top pressure cell and (3) bottom pressure cell;
- (4) screw conveyor pressure cell 1, (5) cell 2 and (6) cell 3; (7) torque meter on the screw; (8) scale for spoil weight (Vinai and Oggeri, 2008)

With reference to optimum parameters for sand, Vinai (in Vinai et al. 2008) developed a series of tests using the laboratory screw conveyor device on the same soil and found that this mix, defined as

“optimum” using the slump test, also offers satisfactory results in terms of torque reduction on the screw conveyor and of pressure transmission and control, which are the key parameters for the management of an EPBS.

The slump cone test, which is usually performed on fresh concrete, has been widely used in the tunnelling industry and provides a simple, quick and low-cost procedure for quality control both in laboratory and on the job site (Peron and Marcheselli, 1994; Quebaud, 1996; Jancsecz et al., 1999; Williamson et al., 1999; Leinala et al., 2000; Peña, 2003; Hanamura et al., 2007; Vinai et al., 2008, Peila et al., 2009).

The slump can be performed following the Standard Test Method for Slump as suggested by ASTM 143C. Typical test procedure is as follows: the soil is mixed with the desired amount of foam and water in a concrete mixer, then it is poured inside 2 slump cones. After one minute, without stroking or mixing the soil, the cone is lifted. The fall value and the global behaviour of the mix is then observed. The shape and possible rupture of the soil cone and the drainage of water and foam can also be observed and taken into account in order to define the behaviour of the material.

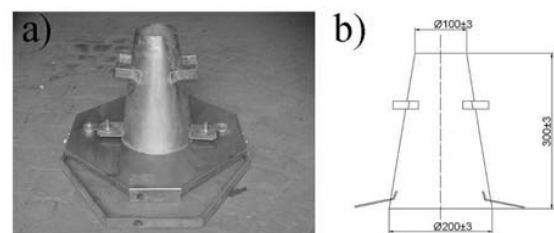


Fig. 6. Photo (a) and schematic drawing (b) with the main dimensions (mm) of the used slump test cone

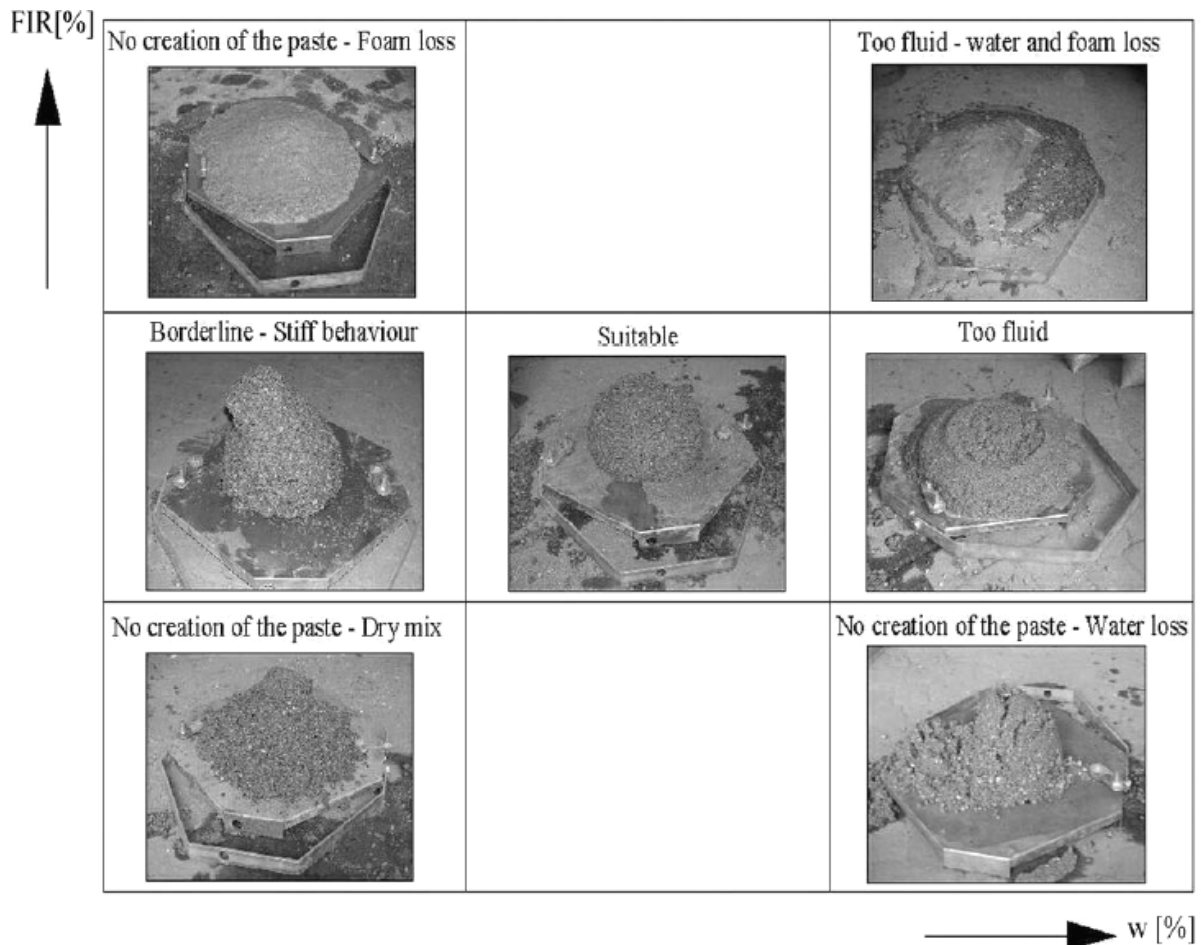


Fig. 7. Different behaviours that can be encountered and comparison related to water and foam contents

According to the observation of the conditioned soil undergoing the slump cone test, five behavioural categories can be described and can be grouped under three classes (suitable, borderline, non suitable):

- difficulty to form a plastic “paste”, as defined by irregular collapse of the cone (not suitable), due to insufficient water or foam content or both (dry mix) or too much foam but not enough water. A loss of foam is observed, the grain size distribution curve is not suitable for the creation of the paste (i.e., not enough sand, silt, or clay in the mix);
- a stiff behaviour with a reduced slump value but with the creation of a plastic paste (borderline behaviour), mainly due to an insufficient foam content;
- a too-fluid mix with a relevant loss of water and/or foam (not suitable behaviour) due to the presence of too much water and/or foam;
- a plastic behaviour with a reduced water loss from the soil (borderline behaviour);
- a correct behaviour of the mix (suitable behaviour) that consisted of a slump cone fall of 140–200 mm with a regular shape of the mass and little or no water loss.

Peron and Marcheselli (1994) described the application of an EPBS to excavate a twin tube tunnel in Milan (Italy) in an alluvium containing 75 percent sand, 20 percent gravel and cobbles, and less than 5 percent clay. They reported that, for a correct excavation procedure, it was necessary to maintain the slump between 50 mm and 100 mm. When tunnelling above the water table, a FIR (ratio between the volume of foam and the volume of conditioned soil) ranging from 50 percent to 80 percent and 5 percent water were added to the bulk chamber, while below the water table it was necessary to inject foam with a FIR of 50 percent.

Quebaud (1996) and Quebaud et al. (1998) carried out tests on a homogeneous fine sand with a grain size distribution curve ranging from 0.2 mm to 0.4 mm and on a sand with a grain size distribution curve ranging from 0.01 mm to 4 mm. Quebaud et al. stated that the optimal slump value was 120 mm and that, in order to obtain this result, when the water content varied between 6 percent and 23 percent, it was necessary to use a FIR ranging between 5 percent and 35 percent for both soil types. Peña (2003) compared the effects of different foaming agents to condition a reference

sand with a grain size distribution curve ranging from 0.002 mm to 2 mm. He observed that with a water content of 22 percent, a concentration of foaming agent ranging from 1.5 percent to 2.5 percent, and a FIR of 65 percent, the slump was 100–150 mm (which he considered the correct range for EBPS application), while with a FIR of 80 percent, the slump rose to 150–200 mm.

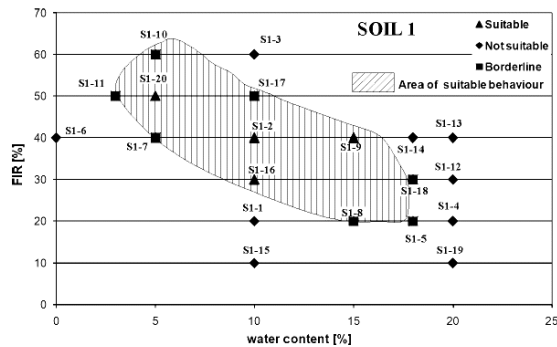


Fig. 8. Example of suitable conditioning area obtained for a sandy soil. X-axis: water content (%); Y-axis: FIR (%). Key: triangles = suitable behaviour values; diamonds = not suitable behaviour values; squares = borderline behaviour values (Oggeri et al., 2008).

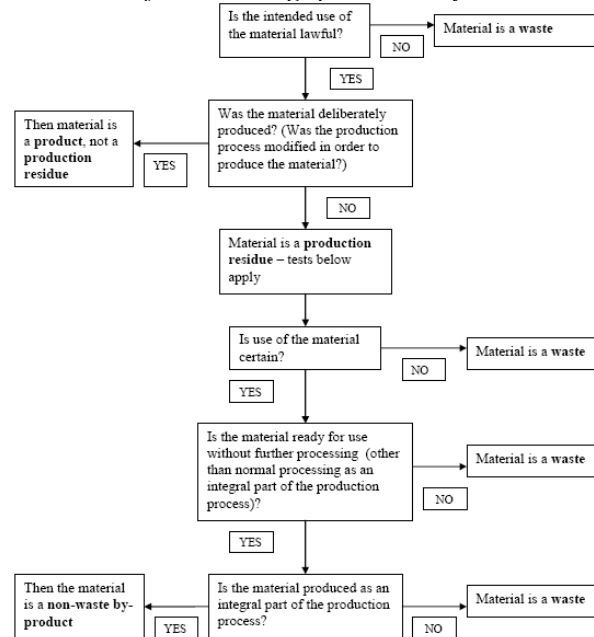
Similar results were obtained by Leinala et al. (2000), who carried out tests on the different types of soil encountered during excavation of the Toronto Sheppard Subway Project. For the studied silty sand with an initial water content from 8 percent to 11 percent, it was necessary to use a FIR of 50 percent to obtain a slump of 100 mm. Vinai et al. (2007), Oggeri et al (2008) and Peila et al. (2009) carried out tests on a homogeneous sand and on different coarse soils to obtain a workable mix, and they found that there is a close correlation between the water content and the FIR.

Spoil recovery

The conditioning of the soil is also important because it can influence the chemical and physical properties of the spoil after mucking out of the tunnel. The aspect of considering the possibility of a recovery of the spoil is today considered as one of the major constraint from the environmental point of view.

This fact involves the effective reduction in external area consumption for landfill disposal, the lower demand for aggregates for concrete for the tunnel lining, the availability of material for nearby use as filling of land irregularities, for reclamation of abandoned quarries, to provide material for embankments or cover strata.

Table 1. Flow chart for definition of by-product for tunnelling spoil recovery



Some aspects have to be taken into account:

1) obviously the properties of the natural geological formation represents the starting point for the preliminary evaluation of possible uses: so a granitic rock is more likely to be reused rather than a flisch formation, a clean coarse gravel is easier prepared rather than a silty sand (fig.9);

2) the excavation method is strongly acting on the grain size distribution after tunnelling, so drill and blast produce different materials if compared to mechanized tunnelling;

3) possible natural contaminants could lead to a low recovery (mineral fibres such as asbestos);

4) the additives for mechanical excavation need variable period for decay, and sometimes the residual chemical products could not be acceptable for high quality use (e.g. for concrete aggregates). It has been observed that, whereas foams alone show quite short decay times (minutes to hours), foam-soil mixes can maintain their plastic features for several days and, without good air exposition, even longer. A common technical procedure consists in creating thin layers of spoil on a yard that are periodically remoulded for ensuring the correct air exposition required for a complete aerobic foam degradation, kept over a period usually ranging from 30 to 60 days. Eventually, chemicals “re-activation” due to water comings should be considered when the material is used for land reclamation purposes (i.e. without proper material selection and washing), since friction parameters of bulk mass may dramatically vary if the foam lubrication effects are reactivated due to, for example, rainwater;

5) suitable areas or plants are requested to reduce the water content in the muck or to separate it from bentonite or clay particles.

6) in order to exhibit all the requirements for the final destination, the materials have to be tested, adopting practically the usual standard for natural raw material (deformability, strength, permeability, ice resistance, etc), because stability and compatibility should be assessed in any case.

National laws are fixing specific parameters for the acceptability and also a “muck use plan” has to be drawn by the Client or by the Contractor.

The recovery ratio can vary between extreme values. In the specific case of EPB tunnelling, is the soil is coarse, even 50% can be recovered for high quality uses and other partial reuse can be done as by products for reclamation.

Definitely, in terms of sustainability and construction control also the muck should be considered in the whole optimization process.

4. Special features: time and temperature

Due to excavation work the material excavated by the cutterhead, prior to be extracted from the bulk chamber by the screw drive, spends a variable amount of time inside the chamber. It should be considered that a stoppage time of the machine for the ring assembling is lasting for about one hour and if relevant excavation problems occur also for more than 2 hours. Furthermore, inside the bulk chamber the temperature of the materials ranges between 30 and 40 °C. Due to these factors, it is important to understand the influence of time and temperature on the initial properties of permeability and plasticity, also referred to clogging phenomenon.

In order to better understand the time dependent behaviour of the conditioned soil, a campaign of slump test, lifted after different interval of time and at different temperatures has been carried out on 2 reference soils and on a volcanic pozzolana coming from the tunnels of Rome Metro.

The results presented in Fig. 10 show that if the material is well conditioned, it could preserve its properties of plasticity also after 24h (soil 1), but generally, after a time ranging between two and four hours, the conditioned soil has lost about the 30% of the slump drop and therefore has reduced its plasticity.



a)



b)



c)

Fig. 9. Three examples for different conditions of the spoil:

- a) granular soil with very little conditioning
- b) rock chips after TBM tunnelling
- c) silty sand after conditioning

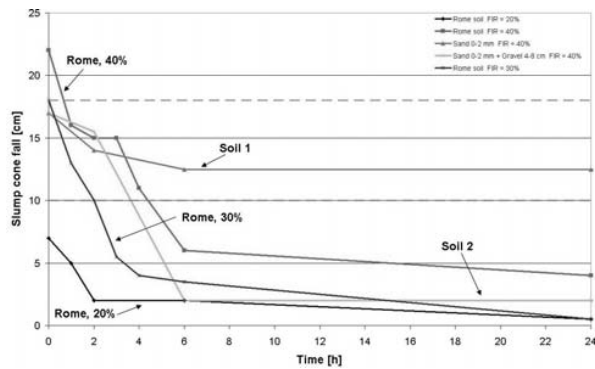


Fig. 10 –Values of the measured slump vs. time for the studied soils. X-axis: time (h); Y-axis: slump cone fall (cm).

In order to investigate the influence of the temperature on the conditioned soil, some tests have been carried out on Rome pozzolanic material at two different values of FIR (30% and 40%). The mix has been maintained at a constant temperature of 20 °C and 40 °C, respectively for one and two hours before lifting up the cone. It is observed that the heat speeds up the decline of the bubbles and therefore the global properties of the conditioned soil, with a significant reduction of the slump cone fall, as can be seen in Fig. 11 and 12.

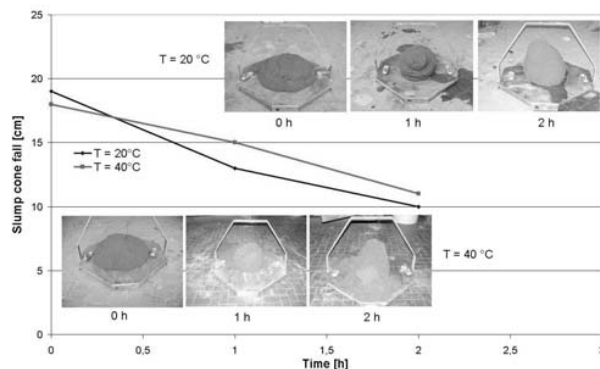


Fig.11. Values of the measured slump vs. temperature. FIR = 30%.

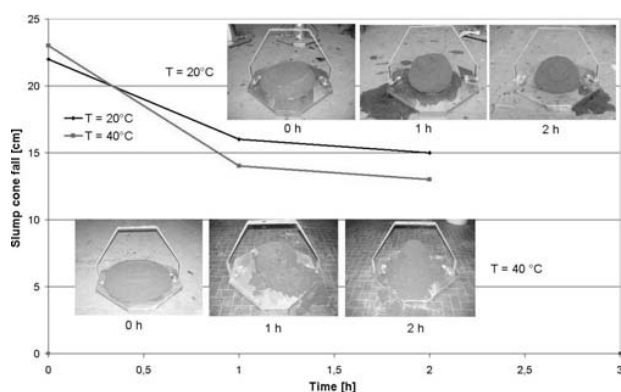


Fig.12. Values of the measured slump vs. temperature. FIR = 40%

5. Case history

An EPB shield machine was used in 2008 to excavate the Lot 2 of the Turin Metro, in Italy. The project has extended the already existing line towards the Southern part of the city, connecting Porta Nuova and Lingotto railway stations. For this new line a double track single tunnel of 6.8 m internal diameter, with a total length of approximately 2.9 km has been built. While the EPB machine was approaching Dante's station, a severe groundwater flow rushed into the previously excavated station, causing a stop of several weeks and the consequent need for countermeasures adoption for ground sealing.

Turin area extends in semi-flat plains formed by alluvial fans at the end of the Alpine valleys. These fans of fluvial-glacial deposits have been remodelled by the rivers that cross the area (Stura, Dora Riparia, Sangone). The prevailing units along the tunnel alignment are recent formations composed by sand, gravel and disperse pebbles in a silty matrix. These coarse formations present a high permeability ($10^{-3} - 10^{-4}$ m/s) and different degrees of cementation, as a result of a random sedimentation process (some lenses of natural conglomerates can exhibit UCS values of about 7-15 MPa). Tunnelling beneath urban areas in such geology is a challenging task, in particularly with an EPB shield machine.

In figure 13 the grain size distribution of the mentioned units together with the applicability limits for closed shield TBMs (according to BTS/ICE, 2005) are shown. The applicability of EPBMs is pushed to the limits in these conditions. Nevertheless, an extensive use of consolidated grout bodies and special ground conditioning techniques (namely with fines compensation injection and polymers to enhance stability and density) enabled the completion of the project successfully.

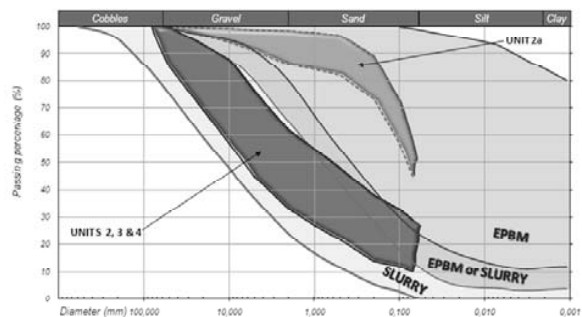


Fig. 13. Grain size distribution and applicability limits according to (BTS/ICE, 2005).

In urban environment the excavation control of an EPBM advance, together with surface and lining monitoring, are essential tools to manage the risks

inherent to this activity. It's essential that the management and reporting systems for all forms of monitoring are able to respond to unexpected results in a timescale that reflects the potential severity of the risk(s) being faced. Hence, trained and skilled personal, able to understand the consequences and to make decisions, together with real time data streaming are fundamental. Monitoring of EPBMs operation can be divided in six main groups: performance and production, boring parameters, muck extraction, earth pressure, backfill grouting and soil conditioning parameters (Camposinhos et al., 2009). Despite that, only performance and production, muck extraction and backfill grouting will be discussed in the following subsections.

An automatic system was used to monitor and follow the complete project. In addition it was possible to monitor the TBM data on a real time basis, allowing a quick identification of potential problems. The present case study reports the period between the start of the project (21-04-2008) and holidays break (06-08-2008). It is important to state that practically half of this period reports the initial testing area, where a continuous consolidation grouting canopy was performed along 100 m.

Performance and Production

Like in any other project, some problems and low production were experienced at the initial stage. During the above mention period a total of 213 m of tunnel was excavated, resulting in an average production of 2 m per day (20% of the estimated). The referred low production can be explained by the numerous stops and breakdowns during this period. In figure 14 (bottom) it is possible to see a pie-chart with the average time per ring for boring, ring erection and breakdowns. Two immediate conclusions can be drawn: the machine spent much of the time stopped (utilisation factor of 9.5%) and for long periods (more than 13 hours in average). The stops and breakdowns had different origins and reasons, namely: disassembly of the steel reaction frame; assembly of remaining backup cars (major stop); problems with the availability of muck disposal areas; several stops to partially empty the excavation chamber and clean the cutterhead; blockage of grouting lines; etc. In figure 14 (top) the progression of the EPBM is shown, where is noticeable the major stop due to the final backup assembly, and several minor stops marked by the small vertical lines. During the analysed period the average day production was very variable and it was clear that the so-called learning curve period was yet to be finished.

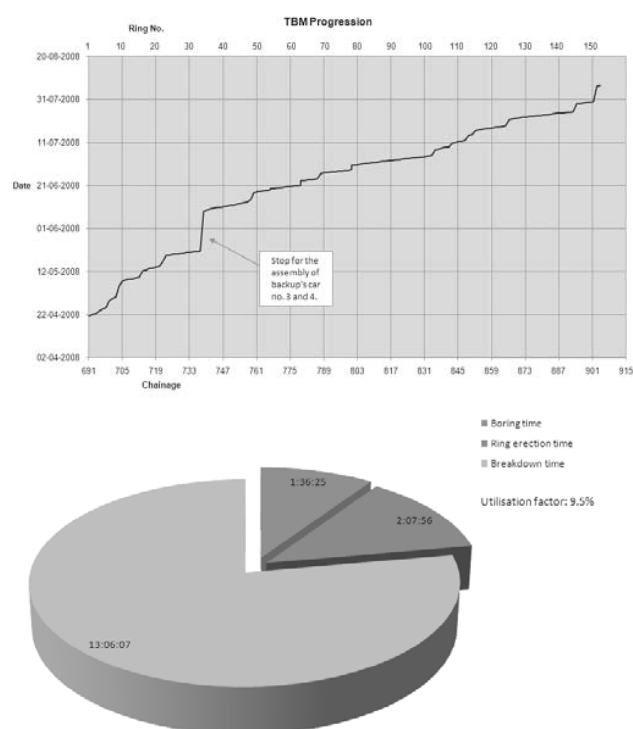


Fig.14. Average ring production (pie-chart) and TBM progression.

Muck extraction

The muck extracted weight (or volume) is one of the most important parameters to control. Modern TBMs are capable of extracting big quantities of material in a short period of time. If muck extraction control is not dealt with care, over-excavations can easily occur and cause surface subsidence or even sinkholes. The control of this parameter is very important for evaluating the soil in-situ unit weight, as well as for cross-checking the complete set of monitoring measurements. In the present project this control was done by means of only one conveyor belt scale.

In figure 15 the values of the total extracted weight per ring along the tunnel chainage are summarized. Two preliminary conclusions can be immediately drawn: the extreme variability of the results and the alarming registered values, often out of threshold limits. Another noticeable observation is the number of times that the excavation chamber was partially emptied, being such operations normally carried out under atmospheric pressure. However, these warning data were not properly considered due to the safety granted by the consolidated canopy and the zero settlements condition, and this results in lack of reactivity to unexpected conditions. Due to the lack of other warning signals, after ring No. 46 practically all excavation cycles registered an excess level of over-excavation. This fact was eventually a real warning and called for immediate action. During

data analysis, it was claimed that the conveyor belt scale was not properly calibrated and therefore the validity of results was uncertain. Despite all, the excavation continued and reached the end of the consolidated stretch without a proper calibration of the conveyor belt scale, together with other anomalies detected on face pressure, ground conditioning, as well as on tail grouting.

A closer exam on the cumulative extracted weight of some rings exhibits an alarming trend. In figure 16, considering the ring No. 86, the cumulative extracted weight trend quickly deviates from the theoretical reference reaching a final over-excavation of 41%; and an anomalous extraction during standstill (vertical trend near advance 0.80m), which can be a potential source of volume loss, even if compensated after by the screw conveyor shut down (following horizontal trend), can be observed. In the mean time, the EPBM was already well out of the consolidated stretch, and settlements were registered in the range of 9-16 mm, together with the evidence of over excavation problems. These facts raise the suspicion that voids could have been produced inside the volume of influence of the tunnel. Following this concern, some boreholes were made from the surface and important voids of around 20 m³ were found, determining the need for sudden countermeasures such as the immediate filling and supplementary grouting. All the found voids were probably related to the over-excavations between the rings 71 and 90 (out of the consolidated area). During the boreholes between rings 46 and 70 (just before the end of the consolidated area) no voids were found.

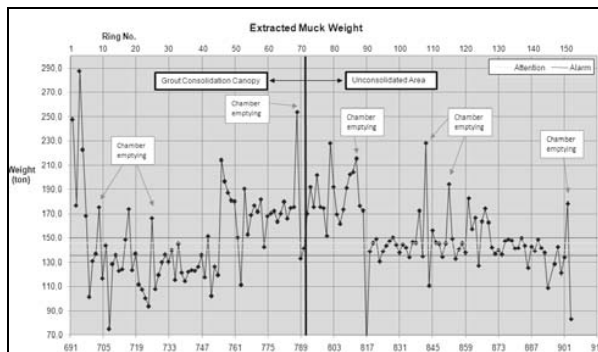


Fig.15. Total extracted weight per ring along the tunnel chainage. X-axis (top): ring number; bottom: tunnel chainage. Y-axis: extracted material weight (ton). Arrows indicate chamber emptying activities (which are in practice partial emptyings for maintenance and inspection). Yellow lines: attention thresholds. Red lines: alarm thresholds.

Due to these events, special procedure to correctly fill the voids was assessed, settlements attention and alarm thresholds were reduced, the

control of the extracted weight was duplicated (by means of two scales) and an emergency procedure was developed to guarantee a quicker intervention in the case of potentially similar events. The following rings (91 to 105) were excavated with a much better control of the muck extraction and main parameters. Despite these procedures, after some time the chamber was partially emptied again under atmospheric pressure and new over-excavations were registered. Again, boreholes from the surface were done and about 3 m³ of voids were found.

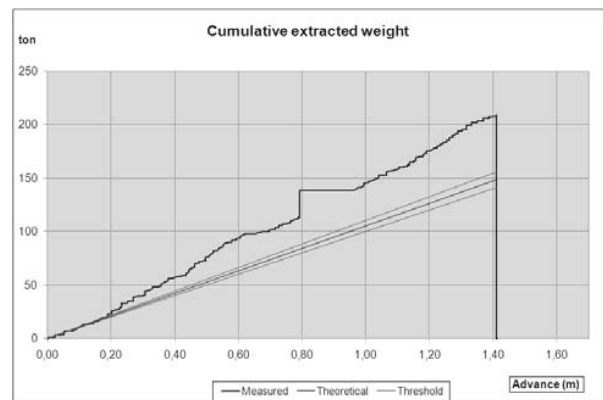


Fig.16. Cumulative extracted weight for Ring No. 86 (excavated during 02-07-08). X-axis: excavation advance (m). Y-axis: excavated material weight (ton). Blue line: measured data. Black line: theoretical trend. Red lines: threshold values.

Backfill grouting

Backfill grouting is essential to guarantee that the annular gap, between the excavation profile and the lining extrados, is completely filled. It has been recognized that the backfill grouting plays an important role on the magnitude of surface settlements. In that sense it is as important as face pressure in controlling surface subsidence. Hence, it should be controlled with the same care. It should be done directly from the tail of the shield and concurrently with the excavation cycle, using a reasonable number of lines to ensure a homogeneous filling. Control should be done both in terms of pressure and volume to ensure the complete filling of the gap. The pressure is normally set slightly higher (by around 0.5 bar) than the face pressure to guaranteed that the water and/or slurry inside the annular gap are repelled and substituted by grout.

In this case study, the above mentioned injection has been performed using a cementitious grout and via four injection lines; two on the upper part (lines 1 and 4) and two on the bottom (lines 2 and 3).

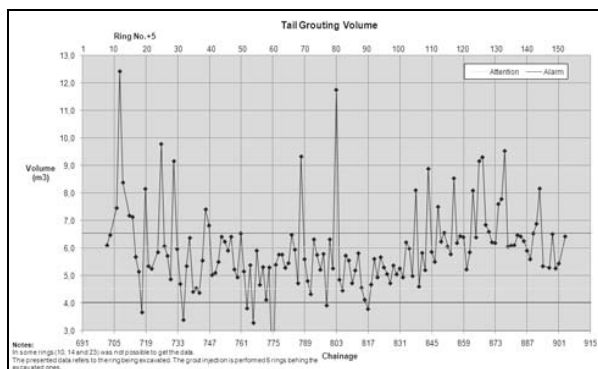


Fig.17. Total backfill grouting volume per ring. X-axis (top): ring number; bottom: tunnel chainage. Y-axis: injection volume (m^3). Yellow lines: attention thresholds. Red lines: alarm thresholds.

In figure 17 the total volume of backfill grout per ring is shown. The values are recorded for the rings that are being excavated, but they represent the injection being made at the tail shield, i.e. six rings behind. Values of grout filling volumes exceeding warning limits have been registered, but it seems more effective for real time control to focus not only on the lower value (nominal annular gap) but also on a percentage of extra grouting (about +30%) and also on the grouting pressure trend. For more accurate and illustrative analysis reference is made to ring 85 (within the region where several over-excavations were recorded and where the voids were found). On the upper part of figure 18 it is possible to see the cumulative grout injection made around ring 85 (boring of ring 91). This type of plot is useful to examine the trend of the measured values (blue line) compared to the theoretical one (pink line). In this example it can be seen that the injection was done in a discontinuous way (noticeable by the step-like trend), with several stretches where the advance proceeded without any injection.

This procedure cannot assure that no void is left at the rear of the lining. It can also be observed that the total injected volume was less than the theoretical one (-7%), although in this case within the attention threshold.

On the lower part of figure 18 four plots are shown, each one representing one injection line. In these plots it is possible to analyse the injection pressures (in blue) and the pump strokes (in pink) for each line separately. The first observation that can easily be done is that the bottom lines (No. 2 and 3) have not been used.

It is a good practice to inject as much lines as possible, and around the total periphery, to assure a good and homogeneous fill.

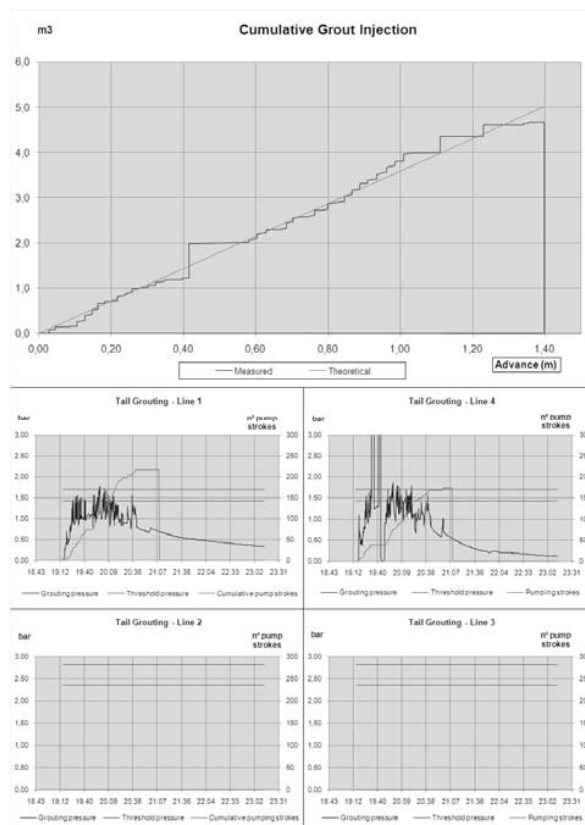


Fig.18. Detailed analysis of the backfill grouting done on a ring-by-ring basis. Record obtained during the boring of ring 91 and injection of ring 85. Top: Cumulative grout injection. X-axis: excavation advance (m). Y-axis: grouting volume (m^3). Blue line: measured data. Pink line: theoretical trend. Bottom: grouting line pressure and pump stroke for the four lines. X-axis: excavation time (hh.mm). Y-axis: (left) pressure (bar); (right): number of pump strokes.

It is also noticeable in line No. 4 a situation of blockage (pressure peak associate with no injection). Blockages were observed quite often and were probably caused by the low advance speed of the TBM and consequently by the hardening of the cementitious grout. Another important observation is that, in this case, the injection is not controlled in terms of pressure. The injection should be performed at the required pressure values (horizontal red lines) and should only stop when the following double condition is met: (1) the total theoretical volume is injected and (2) during the final part of the injection the pressure rises (indicating that there is no more space for grout to flow). When the injection is controlled only in terms of the theoretical volume, it is easy to understand that if an over-excavation occurs part of the annular gap is left unfilled.

Concerning soil conditioning, it is important to mention that a strong conditioning was carried out,

practically only with the use of dry foam (FIR=136% and FER=9, average values). As a result of that, some operational problems regarding muck extraction, conveyance and disposal took place. In addition, the face pressure was hard to maintain due to the muck segregation inside the chamber. The muck segregation originated the aggregation of the coarser fraction in the bottom part of the chamber generating high effective stresses, and consequently high torque and wear. On the upper part, due to its fluidity, the muck could easily infiltrate in the permeable ground, and therefore resulting in a difficult application of the required effective pressure.

6. Conclusions

In order to achieve a good result both in terms of advance rate and ground stability at the surface it is important that:

- soil conditions and stratigraphy are well defined before the excavation
- proper test for soil conditioning are carried out
- the machine is equipped with sensor for a quick and complete detection of the excavation parameters
- procedure for advancing, filling the voids and setting the lining are well established, to avoid over excavation and subsidence;
- surface monitoring systems are installed, in order to maintain a control on the buildings.

The paper focus some of these aspects after experiences obtained by the authors and practically observed also in a real case. Soil conditioning cover a variety of parameters, as it depends on the soil, on the additives, on the water content, on the time of the excavation process, on the temperature and finally on the skill of the personnel. As final remark it can be said that even if general rules for successful operations have been determined, it is mandatory that the specific described laboratory tests are carried for each geological unit along tunnel.

References

1. **Borio L., Peila D., Oggeri C., Pelizza S.**
Effects of foam on soil conditioned behaviour
Proc. 35rd Int. ITA-AITES World Tunnel Congress 2009 Safe tunnel for the city and for the environment, Budapest, 23-28 May. 2009.
2. **Bordachar F., Nicolas L.**
Fluides conditionneurs pour la pression de terre
Tunnels et ouvrages souterrains 169 - Janvier/Février 1998, AFTES, pp. 21 – 27 (in French), 1998.
3. **BTS/ICE**
Closed-face Tunnelling Machines and Ground Stability: A Guideline for Best Practice.
British Tunnelling Society with the Institution of Civil Engineers, Thomas Telford, 77 p, 2005
4. **Camposinhos R., Oggeri C., Beccaria G.**
Monitoring of EPBM tunnelling at lot 2 of Turin Metro
Proc. 35rd Int. ITA-AITES World Tunnel Congress 2009 Safe tunnel for the city and for the environment, Budapest, 23-28 May 2009
5. **Feng, Q., L.**
Soil conditioning for modern EPBM drives
Tunnels & Tunnelling International, December 2004, pp. 18-20.
6. **Hanamura T., Kurose J., Aono Y., Okubo H.**
Integral studies on mechanized functions of mudding agents and the properties of muddified soils in the EPB shield tunneling technology
In Bartak, J.; Hrdina, I.; Romancov, G.; and Zlamal, J. (Editors), 33rd ITA-AITES World Tunnel Congress: Underground Space. The 4th Dimension of Metropolises: Taylor & Francis Group, London, United Kingdom. 2007
7. **Jancsecz S., Krause R., Langmaack L.**
Advantages of soil conditioning in shield tunnelling: Experiences of LRTS Izmir
In Alten, T. and Broch, E. (Editors), ITA-AITES World Tunnel Congress '99: Challenges for the 21st Century: Balkema, Rotterdam, The Netherlands. 1999
8. **Kupferroth F.J., Ellenberger P., Kalin B.A.**
The use of foams and polymers in Earth Pressure Balanced TBMs
MBT –Degussa technical literature. 2001
9. **Leinala T., Grabinski M., Delmar R., Collins J. R.**
Effects of foam soil conditioning on EPBM performance
In Ozdemir, I. A. (Editor), North American Tunneling 2000: Balkema, Rotterdam, The Netherlands
10. **Mair R. J., Merritt A. S., Borghi F. X., Yamazaki H., Minami T.**
Soil conditioning for clay soils
Tunnels and Tunnelling International, Vol. 4, pp. 29–32. 2003.
11. **Merritt A., Mair R. J.**
Mechanics of tunnelling machine screw conveyor: Model tests
Geotechnique, Vol. 56, pp. 605–615. 2006.
12. **Milligan G.**
Lubrication and soil conditioning in tunnelling, pipe jacking and microtunnelling state of the art review
Geotechnical consulting group – London, 2000
13. **Oggeri C., Borio L., Peila D.**
Influence of granulometry, time and temperature on soil conditioning for EPBs applications
Proc. 34th ITA AITES World Tunnel Congress, Underground facilities for better environment and safety. Agra, India, 19-25 Sept.2008.

14. Peila D., Oggeri C., Vinai R.

Screw conveyor device for laboratory tests on conditioned soil for EPB tunnelling operations
Journal Geotechnical Geoenvironmental Engineering, Vol. 133, pp. 1622–1625, 2007

15. Peila D., Oggeri C., Borio L.

Using the Slump Test to Assess the Behaviour of Conditioned Soil for EPB Tunneling
Environmental & Engineering Geoscience, Vol. XV, No. 3, August 2009, pp. 167–174.

16. Peña M.

Soil conditioning for sands
Tunnels & Tunnelling International, July 2003, pp. 40 – 42

17. Peron J. Y., Marcheselli P.

Construction of the 'Passante Ferroviario' link in Milan. Italy. Lots 3P, 5P, and 6P: Excavation by large EPBS with chemical foam injection
Tunnelling '94: IMM, Chapman & Hall, London, United Kingdom, 1994.

18. Quebaud S.

Contribution a` l'Etude du Percement de Galeries par Boucliers a` Pression de Terre: Amélioration du Creusement par l'Utilisation des Produits Moussants
Ph.D. Thesis, Université des Sciences et Technologies de Lille, Lille, France [in French], 1996.

19. Quebaud S., Sibai M., Henry J. P.

Use of chemical foam for improvements in drilling by earth pressure balanced shields in granular soils
Tunnelling Underground Space Technology, Vol. 13, pp. 73–180, 1998.

20. Vinai R., Oggeri C., Peila D.

Soil conditioning of sand for EPB applications: A laboratory research
Tunnelling Underground Space Technology, Vol. 23, No. 3, pp. 308–317, 2008.

21. Williamson G. E., Traylor M. T., Higuchi M.

Soil conditioning for EPB shield tunneling on the South Bay Ocean Outfall
In Hilton, D. and Samuelson, K. (Editors), Rapid Excavation and Tunneling Conference 1999: SME, Littleton, CO, pp. 897–925.