Toulouse Metro Lot 2: soil conditioning in difficult ground conditions

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ABSTRACT: The JV of Campenon Bernard TP (VINCI Group) & Eiffage TP was working on the Metro Line B, Lot 2 Project in Toulouse, together with BASF Constructions Chemicals for the soil conditioning and annulus grout admixtures. The machine used was the Herrenknecht S-208 7,75 m diameter EPB TBM. The TBM was driven under a housing area leaving the TBM launch shaft, continuing under a railway and houses with foundations lower than the tunnel alignment, coming then under the «Canal du Midi» and crossing old archaeological sites and sewers that were in a poor condition. Therefore the correct and stable face pressure was a prerequisite in order to prevent surface settlements and uncontrolled water & soil ingress. In addition, the clogging risk at the cutterhead and in the working chamber of the TBM caused by the tertiary molasses was fairly high, especially taking into account that the molasses were disturbed by sand lenses and large sections of the tunnel were below ground water level.

1 THE PROJECT

In June 1997, SMAT (Societé du Métro de l'Agglomération Toulousaine) got the task to construct the metro extension Line B from north to south through the city centre (Figure 1), a natural complement to Line A with the common station being Jean Jaurès.

Figure 1: Metro Plan Toulouse

Line B consists of 20 stations and a total length of 15.000m, where 2.000m represent cut and cover sections and 13.000m bored tunnel.

The main Lots were:

- Lot 2: Herrenknecht EPB TBM, 4.731m
- Lot 3: CSM Bessac compressed air TBM, 1.000m
- Lot 4: FCB Slurry TBM, 3.700m
- Lot 5: FCB EPB TBM, 3.400m

Campenon Bernard TP & Eiffage TP were responsible for Lot 2, using a Herrenknecht EPB TBM S-208 named «Carlos Gardel». The TBM had a shield length of 8,50m; a shield diameter of 7,750m and a cutterhead diameter of 7,785m. About 200 excavation tools were installed on the cutterhead and its rotation speed was adjustable from 1-3 RPM. The TBM speed was designed to reach 80 mm/minute with and EPB pressure of up to 3 bar. The installed power was 2.000 kW, resulting in a driving force of 55,75 kN and a jack force of 6.000 tons.

The tunnel inner diameter was designed reach 6,80m with a 5+1 Segment structure of 1,40m length and 340mm thickness. The total number of placed segments reached 26.000 and the muck excavation of 225.000m³ or 517.000 tons.

The tunnel alignment was placed under a housing area just leaving the launch shaft «Trois Cocus», continuing under a railway and houses with foundations lower than the tunnel, coming then under the «Canal du Midi» and crossing old archaeological sites and sewers in a poor condition. Therefore correct and stable face pressures were a must in order to prevent surface settlements and uncontrolled water & soil ingress. In addition, the cutterhead clogging risk of the tertiary molasses was fairly high, especially taking into account that large sections of the tunnel were below ground water level. Furthermore, sand strata were present at the TBM crown level.

2 SOIL CONDITIONING BACKGROUND

EPB tunnelling is used in homogeneous as well as heterogeneous ground conditions. Famous examples for EPB drives in very heterogeneous geological formation are BPNL Lyon with a 10,98m diameter NFM machine (Bentz et al 1997) and Barcelona Metro L9 with a 12,06m diameter Herrenknecht machine (Gabarró et al 2003). The soil distribution of these two projects is indicated in.

As a consequence of the soil heterogeneity, the TBMs cannot be designed for the optimum of a specific geology, but for the overall optimum (Rehm 2004). This implicates a compromise from the machine technology point of view which has to be optimized by using different soil conditioning agents. The 3 most important factors for soft ground tunnelling - apart from the hard rock geology - are the

- Soil permeability
- Ground water pressure
- Risk of clogging and adhesion

The soil permeability for EPB drives can reach values of up to $k=10^{-3}$ for the most porous soils (BPNL Lyon, Turin) and comes down to practically impermeable clay (Heathrow T5).

The TBM drives in clay soil – either full face or mixed face – often face clogging and adhesion problems. In porous soils, the faced problems are very instable tunnel face, uncontrolled soil and water income as well as loss of face pressure through the soil. These problems were lately described for the Milan Metro project (Grandori et al, 2003). Important for a successful TBM drive is the mechanical adaptation of the TBM itself including shield opening factor, number and choice of tools and finally the right soil conditioning with foams and polymers combined with a complete filled working chamber. The use of pure foams will not be successful.

Another important influence for the EPB drives in soft ground is the ground water pressure. The higher the water pressure, the more difficult to handle will be uncontrolled water ingress and subsequent settlement risk. From the machine technique point of view only few things can be done like very long screw conveyors, dual screws with intermediate water release or the installation of piston pumps after the screw conveyor. The most important and successful factor to control the water and the soil income is to fill the TBM working chamber completely with a homogeneous and impermeable soil paste by help of Foams and Polymers. Site examples are Botlek Tunnel and Aviles Sewage Tunnel as described in the literature (Fernandez et al 2002).

EPB drives in clay formations – either full face or mixed face – often run into clogging and adhesion problems: as it was the case in Toulouse. Even working in dry mode with compressed air in the working chamber resulted in huge problems.

Figure 2: clay clogging in Toulouse Line B Lot 2

Figure 2 shows how easily the cutterhead centre can be plugged, openings can be closed and cutterhead tools can be turned ineffective by clogging clay. The problem of clay clogging and adhesion will always lead to difficult TBM guiding, slow advance rates and extensive cleaning. From the machine technique point of view few things can be done like the design of an open cutterhead – especially in the centre – and well placed mixing devices in the working chamber. Again one of the most important factors to reduce successfully the clay clogging and adhesion is the use of highly effective Foams and / or special anti-clay Polymers. Site examples are Madrid MetroSur (MBT Online) and Roma 4 Venti (MBT Online) or Toulouse Metro as described in chapter 3.

2.1 *Foam*

The main demand of foam as a conditioning additive is to obtain the suitable rheology of the soil in order to build up and to maintain the necessary support pressure in the working chamber and to prevent high pressure variations. Foam incorporated in the earth paste has got the same effect as the big air bubble in slurry machines. The reduction of torque and abrasion are very important additional effects too. Foam is produced by turbulent mixing of a surfactant solution with air (Langmaack 2000).

The main surfactant properties are:

- fluidising effect on soils because of the decrease of surface tension. Soil particles are no longer bound to each other by linked water

- electrostatic repulsion effect which can separate two particles attracting each other by electrostatic forces.

Laboratory tests as well as the site experience show, that often each soil type, from stiff clay to sandy gravel, requires more or less an own type of foam to reach its best effectiveness. The reduction of the angle of internal friction as well as the cohesion is important. In clay soil, the reduction of cohesion is one of the main tasks of foam. The type of surfactant used for a specific site has to be determined by preliminary laboratory tests with the original in situ type of soil.

Generally, the use of only foam reaches its limits when it comes to clay containing soil as well as soil with high porosity and low cohesion. In these cases, the dual use of foam and polymers is necessary, as described in chapter 2.2 and 2.3.

2.2 *Polymer for clay soils*

As indicated already in chapter 2.1, soil conditioning additives shall decrease the clogging and adhesion characteristics of clay soil. Therefore anti-clay polymers have to adsorb on the clay particle surface. They have to carry a high charge density to separate the soil particles and they should furthermore be able to create a steric barrier in order to avoid re-agglomeration effects. These demands can be fulfilled by surfactants and anti-clay polymers, but anti-clay polymers are much more efficient.

Anti-clay agents are mainly used to support the destructuring properties of the foam, but they might be introduced without foam, too. Figure 3 illustrates the effect of those polymers in clay soil.

Figure 3: clay behaviour without and with anti-clay polymer

Using only foam and water, the clay particles agglomerate immediately and show extensive adhesion to metal surfaces (figure 3 left part or figure 2). Using a TBM in this mode, the cutterhead as well as the working chamber will get plugged. Only the additional use of anti-clay polymer results in separated clay lumps and decreases to a minimum their adhesion (figure 3 right part). A proper EPB mode with a reasonable TBM speed and regular maintenance work is only possible under these conditions.

2.3 *Polymer for porous soils*

In contrast to the anti-clay polymers, the polymers for porous soil have to create cohesion in order to obtain a pasty soil rheology. This was important for the partially existing sand strata at the TBM crown, preventing an uncontrolled inflow of sand or uncontrolled squeeze-out of foam.

Figure 4: comparison of original pure dry porous soil and as homogeneous paste after mixing with foam and polymer

A couple of polymers can be used in porous soils:

- water binding polymers
  to dry out (liquid) soils
- soil structuring polymers
  which are useful in loose, coarse soils to change the soil rheology and which prevent sedimentation.
- foam stabilising polymers

Some polymer developments are based on hydrocarbon chains and are produced by bacterial fermentation. These polymers are water soluble, biodegradable and compatible to the foam surfactants. Well designed, both of them are safe for the foaming generator and consequently they can be mixed with the foaming solution and pass through the foam generator. Polymers also induce a more stable support pressure in the working chamber during boring and when stopping the machine.

All polymers should preferably be in liquid form to avoid dosing problems and additional installation to get a solution or suspension out of the powder.

3 PROJECT TOULOUSE LINE B LOT 2

After the start on 5th August 2002, the TBM advanced slowly in the initial face. With in average 10 m of cover, the TBM had no general problems in zones of pure (full face) stiff & dry clay, but the numerous encountered sand lenses with pressurized water made the machine advance quite difficult. Despite the air pressurized working chamber, water and fine soil came into the TBM in an uncontrolled way, causing clogging & adhesion problems on the cutterhead (see figure 5), huge cleaning problems and last but not least causing doubts on abrasion, face stability and surface settlements.

Figure 5: problems working in dry compressed air mode

The only way to successfully counterbalance the soil and water pressure on the tunnel face is a completely filled and pressurized TBM working chamber (Herrenknecht et al 2003, Steiner et al 1994). Therefore the soil must be treated during excavation with soil conditioning agents either separately or in combination:

- Foams
- Polymers for porous soil
- Polymers for clay soil

Their use enables filling of the TBM working chamber with excavated soil and reducing simultaneously the TBM torque and abrasion. No other modes of advance are suitable for instable, water bearing ground and sensitive surface areas as Babendererde 2003 has shown in figure 6.

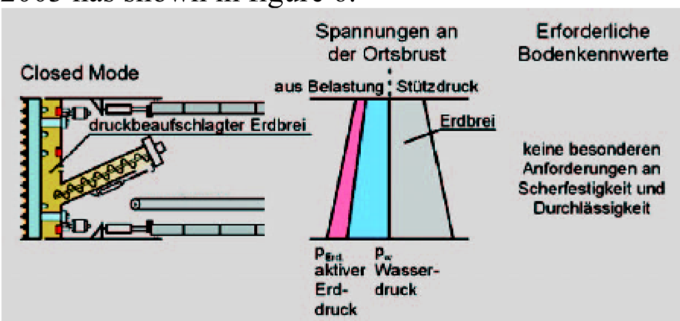

Figure 6: EPB mode (Babendererde 2003)

In order to advance the TBM quickly and safely, the in-situ soil must be transformed into a non-adhesive and non-clogging soil paste in order to completely fill the working chamber and work in EPB mode.

This soil transformation called «soil conditioning» has to be pre-tested in laboratory scale in order to determine suitable products and their quantity.

3.1 *Laboratory tests*

The first step in the laboratory is to reproduce the difficulties encountered on site. Therefore, original soil was used together with the soil conditioning systems originally used. The result is shown in figure 7, indicating quite well the difficulties encountered on site.

Figure 7: clogging soil in the laboratory

Scientifically, the clogging and adhesion capacity of the Toulouse molasses can be explained by their atterberg limits, showing a wide plasticity index between 15-55 combined with a high consistency index of >1 as indicated in figure 8 after Thewes 2004.

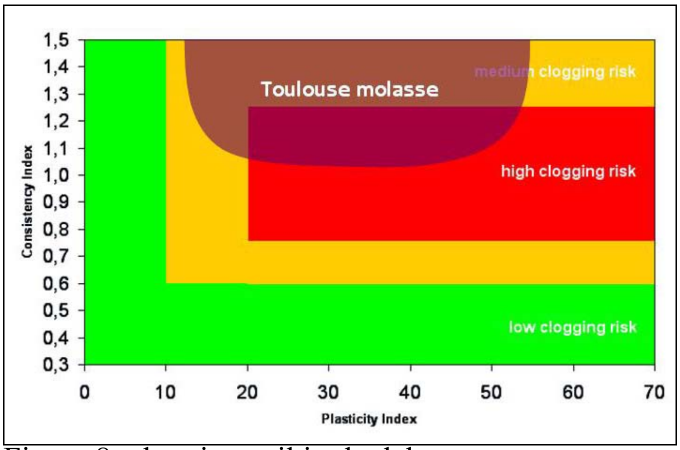

Figure 8: clogging soil in the laboratory

In order to achieve the desired pasty and non-clogging soil rheology, numerous trials had been carried out. The best results were achieved with simultaneous addition of water, foam and Rheosoil® anti-clay agent. The result is shown in figure 9.

Figure 9: correct EPB conditioning in the laboratory

3.2 *EPB mode using SLF30 and Rheosoil®*

The soil conditioning concept determined in the laboratory had to be translated into the site system with a 6 line foam generator, serving 5 injection points on the cutterhead, 2 in the working chamber and 2 into the screw conveyor. An example of the TBM setting is shown in figure 10, demonstrating full EPB advance with 54mm per minute and 2,6 bar medium earth pressure.

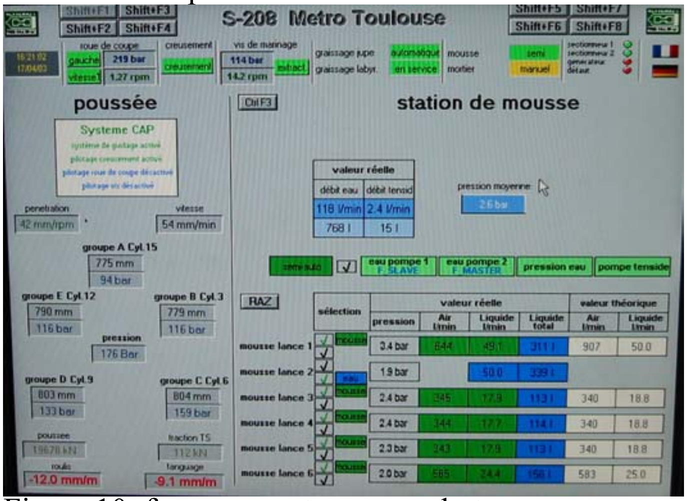

Figure 10: foam generator screenshot

The setting details were the following:

- Foam concentration SLF 30: 2-3%
- Expansion Ratio FER: 8
- Foam Injection Ratio FIR: 70% (+30% for the chamber)
- Rheosoil® 211: 0,8-1,0 kg/m³ soil in situ
- Water (in case of dry soil): 5-20m³/ring

This soil conditioning system could be handled in a very flexible way:

- advancing with low torque and low abrasion values in compressed air mode, in case of homogeneous dry soil
- quick change to EPB advance with completely filled working chamber within minutes, in case of geology change

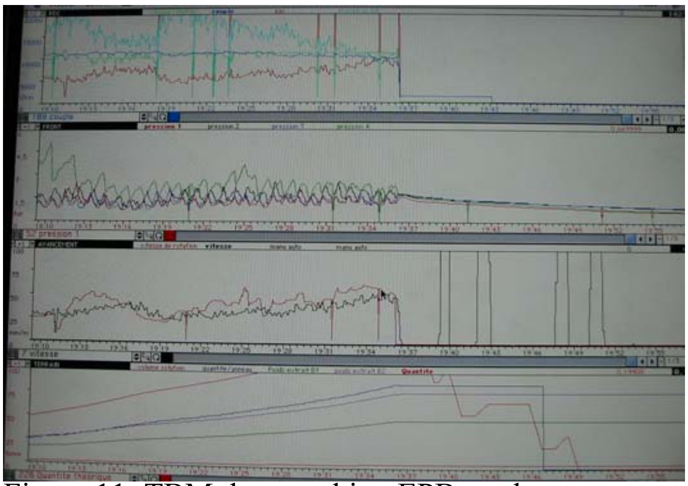
Figure 11: TBM data working EPB mode

Figure 11 indicates the TBM parameters just after switching from air to earth pressure, mainly decreasing the pressure of the cutterhead centre (reducing the clogging risk). Graphs show also an increasing TBM speed with simultaneous decrease of torque values, indicating a highly efficient soil treatment. Figure 12 illustrates the soil conditioning quality, creating a plastic and non-clogging earth paste.


Figure 12: plastic & non clogging excavated soil

Once this soil conditioning concept was established, the TBM showed reasonable advance rates of 40-50mm/min also in the EPB mode, no water ingress occurred any more and the face support could be secured. Figure 13 shows the clean cutterhead after the TBM breakthrough.


Figure 13: clean cutterhead after breakthrough

3.3 *Sand strata above TBM*

From ring number 2758 onwards, a sand strata was located in the crown of the TBM and on top of it. In order to avoid uncontrolled sand flow-in, a polymer (MEYCO Fix SLF P2) enriched foam with structuring effects was injected into the TBM crown. This system turned out to be quite effective, but due to increasing sand strata and collapse risk it was decided to undertake surface injection with cement and silica gel in order to stabilize this geology (ring 3095-3120)

3.4 *Ecotoxicology*

In the beginning of the project, also ecotoxicological questions were raised concerning the landfill of the excavated soil (see figure 14).

Figure 14: landfill of conditioned soil

After switching to the BASF soil conditioning concept, all additives used including the anti-clay polymer passed a strict risk assessment study to ensure minimum impact on the workers and the environment. Neither during construction nor on the disposal sites negative influence of the soil conditioning additives could be observed.
The lixiviation data (1 x 24h, DIN 38-414 4) and following acute toxicity tests on Daphnids (NF EN ISO 6341) showed no dangerous potential of the treated soil from day 1 on. This enabled the contractor to avoid costly pre-stocking of the soil and to achieve a low general cost level for the landfill disposal.

4 CONCLUSION

As demonstrated by various site examples including Toulouse Metro Lot 2, it is possible to drive a TBM successfully and quickly through difficult geologies. In addition to the choice of a well adapted TBM machine, the use of the right soil conditioning additives is vital - for very permeable soil under ground water table as well as for clay rich soils with high clogging and adhesion potentials.
With an average daily TBM speed of 16,20 m and a significant best day advance of 37,80 m, the tunnel Lot 2 in Toulouse was finished within the foreseen time schedule with the final breakthrough on the 30th August 2004, 25 months after the start.

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