

Soil Conditioning for EPB Machines: Balance of Functional and Ecological Properties

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ABSTRACT: Earth Pressure Balancing (EPB) tunnel boring machines using soil conditioning additives become more and more frequent in the world of tunnelling. Their ability to produce & secure the earth pressure equilibrium together with consideration on their ecological and toxicological aspects belongs to the most important factors of a successful TBM drive.

1 GENERAL

The correct and effective use of soil conditioning additives is not always obvious.

The success of EPB machines – especially in non-homogeneous, highly porous or adhesive ground conditions depend on good mechanical engineering combined with highly effective soil conditioning additives. Examples of these successful combinations are Madrid MetroSur, Toulouse Metro and Rome Railway.

An additional important point for the choice of soil conditioning additives is also their possible impact on the surrounding environment. Risk assessments concerning the emission into ground water during application, the working place concentrations and emissions from the land filling of the treated soil are necessary.

2 TBM DESIGN VS GEOLOGY

EPB tunneling 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 Figure 1.

EPB-drives in very inhomogeneous geology
examples of Lyon (1996) and Barcelona (2004)

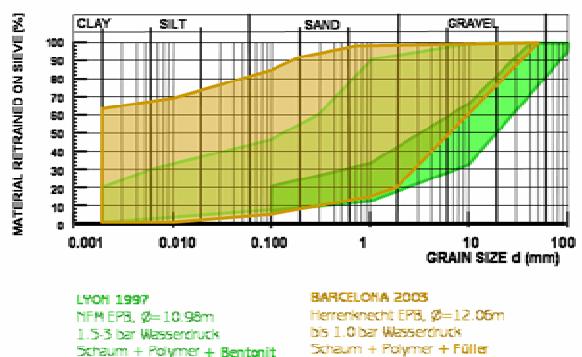


Figure 1: soil distribution of Lyon and Barcelona (Langmaack 2004)

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 tunneling - apart from the hard rock geology - are the

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

2.1 Soil Permeability

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 as described in 2.3.

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 – details see in chapter 3.2.

2.2 *Ground water*

An important influence for the EPB drives in soft ground is the ground water level respectively the ground water pressure. The higher the water pressure, the more difficult uncontrolled water income and settlement risks can be avoided. From the machine technique point of view only few things can be done like long screw conveyors to decrease the pressure gradient, installation of piston pumps after the screw conveyor ... The most important factor to control successfully the water is to fill the TBM working chamber completely with a homogeneous and impermeable soil paste by help of Foams and Polymers. Site examples therefore are Botlek Tunnel and Alives Sewage Tunnel as described in the literature (Fernandez et al 2002) and in chapter 6.1

2.3 *Clogging and adhesion*

EPB drives in clay formations – either full face or mixed face – often run into clogging and adhesion problems.



Figure 2: clay clogging on the TBM cutterhead

Figure 2 shows how easily the cutterhead 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 only few things can be done like the design of an open cutterhead – especially in the center – 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 Foams or / and special anti-clay Polymers (details in chapter 3.3). Site examples are Madrid MetroSur (MBT Online) and Roma 4 Venti (MBT Online) as described in chapter 6.2 or Toulouse Metro in chapter 6.3

3 NECESSITY OF SOIL CONDITIONING

Only the use of soil conditioning additives enable to fill the TBM working chamber, to reduce the TBM torque and to reduce the abrasion. No other modes of advance are suitable for instable ground and sensitive surface areas (Babendererde 2003) as shown in figure 3.

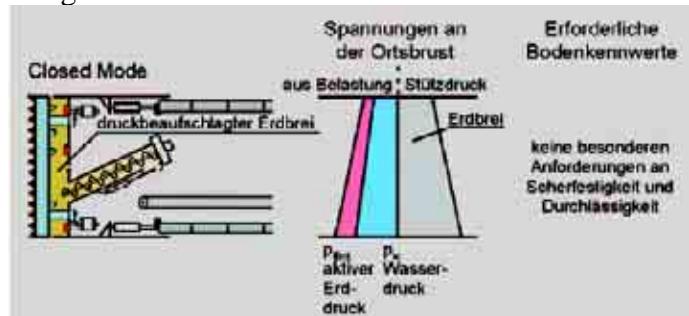


Figure 3: EPB mode (Babendererde 2003)

The earth pressure equilibrium can only be achieved if the TBM working chamber is filled completely with soil (Herrenknecht et al 2003, Steiner et al 1994). Therefore the soil must be treated during excavation with soil conditioning agents:

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

either separately or in combination.

3.1 *Foam*

The main demand of foam as 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. Figure 4 demonstrates the effects of a foaming solution on clay and clayey sand. Due to test limitations, it was impossible to use foam. The tests are used to distinguish effective from ineffective agents; the quantity indications as given in figure 4 must not be transformed to site use and will be drastically reduced when using the same surfactant as foam due to the additional effect of air bubbles.

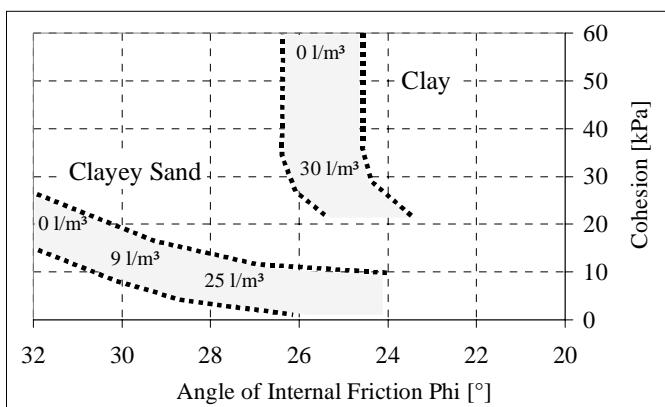


Figure 4: surfactant solution effects on soil (Jancsecz et al 1999)

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 which shall be used for a specific site has to be determined by preliminary laboratory tests with the original in situ type of soil.

3.2 Polymer for clay soils

As indicated already in the foam chapter 3.1, 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.

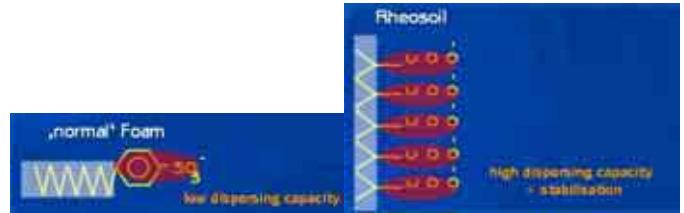


Figure 5: difference between Foam and Polymer

Anti-clay agents are mainly used to support the de-structuring properties of the foam, but they might be introduced without foam, too. Figure 6 illustrates the effect of those polymers in clay soil.



Figure 6: clay behavior without and with anti-clay polymer

Using only foam and water, the clay particles agglomerate immediately and show extensive adhesion to metal surfaces (figure 6 left part). 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 6 right part). A proper EPB mode with a reasonable TBM speed and reasonable maintenance work is only possible under this conditions.

3.3 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.



Figure 7: 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. Both of them are safe for the foaming generator, in consequence they can be mixed with the foaming solution and passing 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 be preferably in liquid form to avoid dosing problems and additional installation to get a solution or suspension out of the powder.

4 ECOLOGICAL AND TOXICOLOGICAL PROPERTIES OF SOIL CONDITIONING AGENTS

As substantiated in chapter 2 and 3, the use of soil conditioning products is unavoidable when using a EPB machine. They have not only to fulfill performance criteria but also toxicological and ecotoxicological criteria. In consequence the possible impact on the surrounding environment plays an important role for the choice of soil conditioning additives and is one of the exclusion criteria.

In order to determine the possible risk of a product, a risk assessment study should be carried out. The most important factor in this study is the risk evaluation to human beings and the environment. It is mainly determined by the following four points:

- The amount of substance entering the environment
- The chemical and physical properties of a substance which determine the distribution in the environment. In most cases this is the leachability into ground water. In addition, bioaccumulation has also to be taken into consideration.
- The toxicity of a substance for the environment, respectively the toxicity towards aquatic organisms and for humans
- The elimination process (degradation and / or immobilization) also determines the distribution in the environment. Organic substances can be degraded in three separate ways:

→ Biodegradation:

by organisms which already exist in the soil or added separately

→ Hydrolysis:

degradation in presence of water;

→ Photolysis:

degradation under influence of light

For a complete risk assessment, the emission into ground water during application, the working place

concentrations and emissions from the land filling of the treated soil have to be taken into consideration.

4.1 *Definition of Toxicity*

Toxicity is the intrinsic capacity of substances to cause negative effects to organisms. Toxic effects depend on the amount of a substance which is available to the organism. Toxicity tests carried out in the laboratory are used to predict the so called 'safe concentrations' at which no negative impact on the organisms is expected. The acute toxicity differentiates toxicity to mammal organisms and toxicity to aquatic organisms. For mammals the lethal oral dose for 50% of the population (LD_{50}) is listed in mg substance per kg of organism weight, for aquatic organisms the lethal concentration for 50% of the population (LC_{50} or EC_{50}) is listed in mg per liter of water.

4.2 *Definition of Bioaccumulation*

Bioaccumulation is a process by which organisms concentrate chemicals within themselves. This can result either from their food or directly from the surrounding environment.

4.3 *Definition of Biodegradation*

Biodegradation is the breakdown of an organic substance by the action of micro-organisms. Before degrading completely to water and CO_2 , substances may degrade to smaller intermediates.

Persistence is the ability of substances to resist degradation.

5 SUITABLE SOIL CONDITIONING PRODUCTS

Suitable soil conditioning products should only be those, which show the desired functional properties and in the same time are as safe as possible for the workers and the environment. This implicates a judgment of the acute aquatic toxicity, potential for bioaccumulation, biodegradation and chronic aquatic toxicity by risk assessments.

5.1 *Toxicological recommendations*

The most sensitive area is the acute aquatic toxicity. Tests should be done according OECD Guidelines 201 to 203.

Generally, the LD_{50} and $L(E)C_{50}$ product data shall be as high as possible. For all types of Polymers the $L(E)C_{50}$ data for Daphnids and Algues shall be preferably $> 100\text{mg/l}$ water in order to be not classified for acute toxicity. Foams, due to their reduction of surface tension, should reach LC_{50} data of $>10\text{mg/l}$ concerning fish (class acute III).

5.2 Ecological recommendations

The ecological properties of a product are judged by biodegradation data, using OECD Guidelines with a defined amount of starting bacteria.

Generally, soil conditioning products shall be either

- readily biodegradable
- or
- not biodegradable (inert material) and non-toxic

Both possibilities guarantee the lowest possible impact to the surrounding ecology.

5.3 Preferable risk assessment results

5.3.1 Risk for workers

The expected impact on the environment should generally be low if the substances are adequately handled and the recommendations of the Material Safety Data Sheets are implemented.

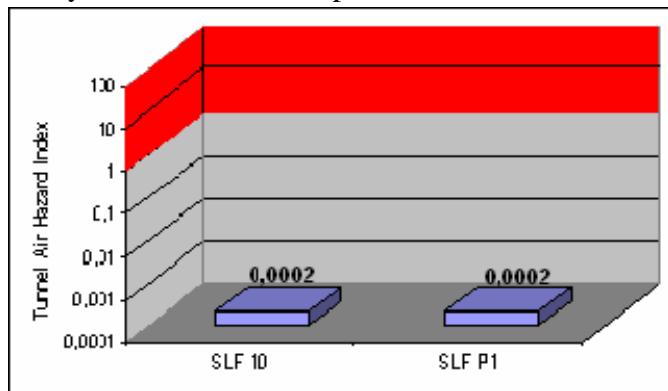


Figure 8: Example of Human Risk Assessment, air hazard index

Ideally the concentrations in the tunnel air are even under worst case assumptions more than 1'000 times below the respective occupational exposure limits (air hazard index = 1) as shown in figure 1.

5.3.2 Risk for the environment

No risks to surface water from emission due to pumped tunnel water or run-off water should be expected, providing that the water is drained into the municipal sewage system for treatment.

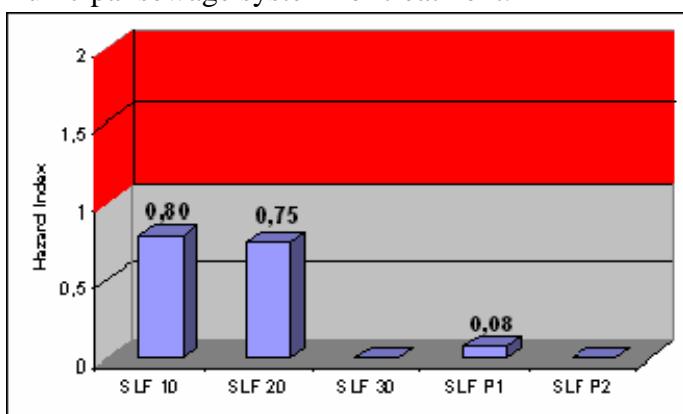


Figure 9: Example of worst case environmental assumptions for various soil conditioning polymers and foams, hazard index

The potential infiltration of ingredients into the ground water during the product application should not cause any relevant risk for the environment. Based on the available information of the ingredient concentration in the treated soil, it should be able to be disposed on an appropriate landfill site without any special pre-treatment.

6 SITE EXAMPLES

The following chapters introduce 3 TBM sites with difficult geologies, where the soil conditioning performance and Ecotoxicological properties lead to success.

6.1 Aviles Sewer (Spain)

The Aviles Site works with a Lovat EBP machine, diameter 3,40 m. After facing stiff clayey silt, the soil changed over a length of approximately 1.000m to pure gravelly beach sand with a seawater pressure of up to 3,0 bar. The grain size distribution is shown in figure 10:

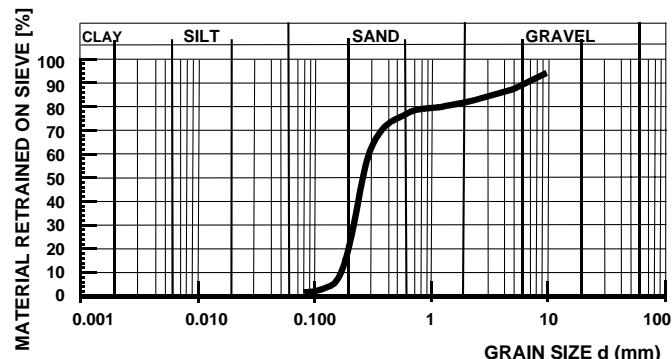


Figure 10: Grain size distribution curve of Aviles Sand

Only the use of foam in this type of geology resulted in incorrect pressure in the working chamber, uncontrolled water inflow and very slow TBM advance rates.



Figure 11: sand excavation only with foam

There was no possibility on the machine to introduce additional filler suspension into the working chamber.

ber. An extra installation had been too costly and too time intensive. The alternative solution was to use additional Polymers – in order to make the soil as plastic as possible to be able to install a counter pressure against the seawater and to reduce the water content of the outcoming soil. The result is shown in figure 12 and visualises the tremendous change.



Figure 12: sand excavation with Foam & Polymer

With the above mentioned soil conditioning by using a combination of foam and structurising polymer, the average daily progress achieved 27 meters with a maximum daily performance of 50,50 meters with fully filled and pressurized working chamber up to 3 bars and without any trouble with water income. Details concerning this jobsite are given by Fernandez 2002 and Langmaack 2001.

6.2 Roma 4 Venti (Italy)

The Herrenknecht 7,90 m diameter EPB TBM S-184 operated by Astaldi / Impregilo JV was working on the Rail Link Tunnel project in Rome, Italy. After heading first through silty sand (tuff) formation, the ground later changed into very sticky and adhesive Vatican Clay. In order to overcome clay clogging at the cutterhead and stirring problems as well as very low advance rates, it was necessary to use Foam in combination with anti-clay additives.



Figure 13: clean cutterhead after breakthrough

Figure 13 shows the TBM breakthrough in the receipt shaft with a clean cutterhead, using foam and anti-clay additives. The clogging problems could be drastically reduced and the TBM speed increased. Further project details are given by Marchionni et al 2002 and MBT Online Roma 4 Venti.

6.3 Toulouse Metro (France)

The Herrenknecht 7,72 m diameter EPB TBM S-208 operated by Vinci / Eiffage JV was working on the Toulouse metro extension project Lot 2 in France. The geologic formation is dry clayey silt with incorporated sand lenses under water pressure. In homogenous clay formation it was possible to excavate in dry mode under air pressure, but as soon as the sand lenses were hidden, the face support collapsed and water ingress was observed. This resulted in overall slow advance rates, extensive TBM cleaning, conveyor belt difficulties and last but not least in doubts on face stability and surface settlements.

Only by using foam and anti-clay polymer together with water it was possible to create a non adhesive, non-clogging soil paste to fill the working chamber completely and work in EPB mode. Figure 14 illustrates the quality of the excavated soil.



Figure 14: soft but not adhesive soil after excavation

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 15 shows the clean cutterhead after the TBM breakthrough.



Figure 15: clean cutterhead after breakthrough

7 CONCLUSION

As demonstrated by the site examples, it is possible to drive a TBM successful and quick also through difficult geologies. In addition to the choice of a well adopted 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 soil with high clogging and adhesion potential.

All additives used in the site examples passed in addition 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.

8 REFERENCES

Babendererde 2003
TBM mit Slurry- oder Erddruckstützung – Einsatzbereiche und Zuverlässigkeitssanalyse
 Felsbau 21 (2003), No.5, p. 155 ff

Bentz et al 1997
Optimierung des schaumgestützten EPB-Vortriebs, Boulevard Périphérique Nord de Lyon
 STUVA Tagung Berlin 1997, Alba Verlag Berlin, 1998, Volume 37, p. 88, ISBN 3 87094 636 9

Fernandez 2002
Aviles Sewage Tunnel, a tunnel below sea water level
 AFTES 2002 Toulouse, p. 131 ff, Specificue ISBN 951 04 16 2 4

Gabarró et al 2003
Metro Barcelona Linea 9 – Europe's greatest metro project with tunnel boring machines of large diameter
 ITA 2003 Amsterdam, p 637 ff, Balkema ISBN2: 90 5809 542 8

Grandori et al 2003
Turin Metro Systems – Design and operation of EPB TBMs beyond the limits of this technology
 Felsbau 21 (2003), No.6, p. 34 ff

Herrenknecht et al 2003
Geotechnische und mechanische Interaktion beim Einsatz von Erddruckschilden im Fels

STUVA Tagung 2003, Dortmund, p. 175 ff, Bauverlag ISBN 3 7625 3602 3

Jancsecz et al 1999
Advantages of soil Conditioning in shield tunneling: Experiences of LRTS Izmir
 ITA 1999 Oslo, p. 865 ff., Balkema ISBN 90 5809 063 9

Langmaack 2000
Advanced Technology of Soil Conditioning
 North American Tunnelling Congress, Boston 2000, A.A. Balkema, Rotterdam, Brookfield, 2000, p. 525
 ISBN 90 5809 162 7

Langmaack 2001
Application of new TBM Additives
 BAUMA 2001, 6th int. symposium for tunnel construction Verlag Glückauf GmbH, Essen, 2001, p. 27, ISBN 3 7739 5964 8

Langmaack 2004
EPB-Vortrieb in inhomogenen Böden: Möglichkeiten neuer Konditionierungsmittel
 Tunnel- und Tiefbautagung 2004, Györ, p. 121 ff

Marchionni et al 2002
Galleria Quattro Venti in Rom
 Tunnel No.8, 2002, p. 8 ff

MBT Online Madrid MetroSur
www.degussa-ugc.com

MBT Online Roma 4 Venti
www.degussa-ugc.com

Rehm 2004
maschineller Tunnelvortrieb unter sehr schwierigen geologischen Verhältnissen
 Tunnel- und Tiefbautagung 2004, Györ, p. 99 ff

Steiner et al 1994.
Face support for a large Mix - Shield in heterogeneous ground condition
 Proc. of Tunnelling '94. London : Chapman & Hall