

THE TRUTH ABOUT SOIL CONDITIONING: DOS AND DON'TS

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KEYWORDS

TBM, EPB, soil conditioning, foam, polymer, anti-clay-agents.

INTRODUCTION

Analyzing the operation mode of tunnel boring machines worldwide, the sometimes non-proper use of earth pressure balance (EPB) tunnelling technology and contradictory statements from the industry, may cause a general negative impression when compared to Slurry (or Mixshield) technology & safety. In reality, both technologies allow very safe advances in urban areas if driven correctly. It is however also true that both can be very unsafe if used in incorrectly.

In EPB technology particularly, the knowledge about the correct use of soil conditioning Foams & Polymers is essential for a successful and efficient TBM drive. Soil conditioning must not be regarded as a black art: contractors and owners shall have a basic knowledge about soil conditioning. Furthermore, the suppliers shall assist in judging and optimizing soil conditioning parameters on site in order to reduce the variety of parameters that need to be adapted whilst on site.

DRIVING MODE OF EPB-TBM'S

The most decisive factor for successful EPB tunnelling is the method of correctly applying pressure inside the working chamber:

- open mode: working chamber only partly filled with excavated soil, non pressurised;
- air pressure mode: working chamber only partly filled, use of compressed air; and
- earth pressure mode: working chamber completely filled with soil, pressurised;

The TBM driving mode shall be defined by the project owner as early as possible according to the geological conditions along the tunnel alignment – preferably at the tender stage.

Open mode

This driving mode can only be used in stable geology with no or low water ingress. The risk of settlements is fairly high – consequently this driving mode shall not be used under sensitive construction areas.

The advantage of this mode is the relatively low torque requirement and the possibility of excavating more or less dry material.

Driving a TBM in open mode can be risky, since the change from open mode to EPB mode (closed mode) is not simple and, depending on the geological conditions, requires at least 2 rings with an experienced tunnel team. Inexperienced teams will need far longer. Even at the first signs of changing geology and the achievement of an EPB mode, severe settlements on the surface or soil / water inrush may take place.

Consequently, the open mode shall only be used where no geological surprises may be expected following an extensive geological survey.

Air pressure mode

In contrast to the open mode, a certain pressure is applied to the excavation face. The main difficulties with this driving mode are:

- a. Possible loss of compressed air into the surrounding soil - This implicates the danger of soil loosening-up at the face and creation of pathways, both increasing the risks of surface settlements or surface collapse. Consequently compressed air shall only be applied in case of a homogeneous and impermeable geological situation at the cutterhead.
- b. Air pressure never counterbalances correctly the soil pressure - The air pressure inside the working chamber always has the same rectangular profile, independent of height of the working chamber. The soil pressure in front of the TBM has a trapezoidal profile: increasing pressure with increasing depth. This implicates that the air pressure can never match the actual soil pressure – either being too high with blow-out risks – or being too low with uncontrolled water /soil inflow. Consequently compressed air shall not be applied where mixed face soil conditions and water bearing zones are expected.

The switch from compressed air to EPB closed mode can take place slightly more easily than the switch from open to compressed air mode. The transition time of 1-2 rings also has to be taken into account – in addition to the risks of surface settlements or soil / water inrush into the TBM.

Earth pressure mode (EPB mode or closed mode)

The earth pressure mode is the only mode that can exactly reproduce the trapezoidal pressure profile of the soil and water in front of the TBM. Uncontrolled water or soil inflow into the working chamber becomes impossible through the adjustment of the necessary counterpressure inside the working chamber. The correct earth pressure mode enables the TBM to excavate tunnels with minimum surface settlement.

In order to be able to fill the working chamber completely, a certain pasty rheology and impermeability of the excavated soil is necessary. This transformation can only take place through the addition of soil conditioning agents – chosen and adopted according to the actual geology.

Which soil rheology is suitable?

A suitable rheology depends on various circumstances and is never universal. It should always be related to:

- the way of mucking out the excavated soil (conveyor belt, train, muck pumps, ...)
- the type of disposal area and machines used
- the experience & preferences of the contractor
- the design of the TBM (installed torque, length of the screw conveyor, ...)
- the type of soil (sand, gravel, clay, ...)

Generally, the soil consistency shall be solid/plastic-like in order to ease the mucking out and allow cost efficient soil disposal or landfill. The limiting factors for the semi-solid consistency are the cutterhead torque and wear together with the efficiency of the soil conditioners.

HOW TO BUILD CONFIDENCE TO THE SOILCONDITIONING

Knowledge of correct use of soil conditioning Foams & Polymers is an essential element for a successful and efficient TBM drive using the EPB technology.

Soil conditioning must not be regarded as a black art: Contractors and owners shall have a basic knowledge about soil conditioning. Suppliers shall execute laboratory pre-trials with the original soil in order to pre-select the best soil conditioning additives and the injection parameters. They shall in addition assist in judging and optimizing parameters on site in order to reduce the complexity of the soil conditioning system and train the TBM drivers which parameters to change during a normal TBM advance.

The following are contradictory industry statements made quite recently:

- *'playing around with all parameters is necessary'*
No. This is absolutely not necessary and not useful for successful tunnelling. Preliminary laboratory tests and a soil conditioning concept based on the geological conditions require only a couple of parameters to be optimised during the TBM advance.
- *'everything will change in a second'*
No. The soil in front of the TBM may change quickly, but the soil conditioning concept shall not be so specific as to result in a "tightrope walk". The soil conditioners used shall be able to cope with a certain variety of geological conditions.
- *'suppliers will test, but you have to be sceptical about the results given (only university testing is good)'*
No, definitively not. If the results of a soil conditioning supplier are not useful or incorrect, then this will rapidly spread throughout the industry. Suppliers therefore have no interest in issuing incorrect results. University testing is excellent for basic research and scientific background, but the latest practical know-how about soil conditioning products and their possibilities, the knowledge-return from (difficult) jobsites and from technical on-site assistance can only be given by the suppliers.

LABORATORY TESTING

Laboratory testing is very important. As already indicated in the previous chapters, laboratory testing can define the effectiveness of soil conditioners and indicate the most suitable chemicals. They do not only indicate the type of chemicals but can also determine the effect of water addition as well as the effect of different concentrations.

Laboratory tests in general and particularly with mortar or concrete cones (slump tests) cannot be translated 1:1 into the site operation: pressure, cutterhead design and the way of driving a TBM are most influential factors. The correct interpretation of laboratory test results regarding the creation of the soil paste and the effects of changing FER & FIR parameters is not easy and requires site knowledge.

Creation of soil paste

Generally, the creation of an EPB-suitable soil paste is possible with every type of soil. The successful transformation depends on the following parameters:

- Use of foam (the use of correct foams is one of the basics)
- Use of polymers (in porous soils)
- Use of anti-clay-agents (in clayey soils)
- Use of water

Everything depends on the choice of soil conditioning foams & polymers, anti clay agents, water and filler addition. Any soil plasticity can be achieved according to the needs on site:

- Transformation of dry stiff clay into a pumpable and homogeneous slurry
- Transformation of clayey soil into semi-solid consistency
- Transformation of running sand under groundwater into dry sand

Foam stability

The discussion about the foam stability is one of the trickiest issues and is nearly always misleading with regard to the final use on site. The four most important topics are:

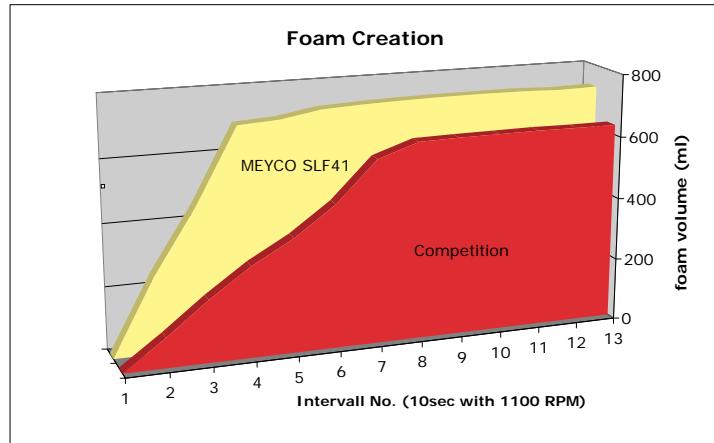
- a. How should the foam creation be taken into account?
- b. How should the foam stability (or the half life time) be measured?
- c. Are pure foam parameters representative of the foam/soil mix?
- d. Is high or medium foam stability better?

Ad a. Measurement of foam creation

The foam needs to be created first – discussions on foam stability shall follow later. Foam creation is important since it defines how efficiently the foam can be used at the cutterhead and in the working chamber. Generally, two main parameters have to be taken into account:

- How easily can a foaming solution be transferred into foam?
- What foam volume can be created (how much air can be incorporated)?

The easier it is to create the foam, the lower are the requirements for a foam generator (especially valid over the lifetime of the generator). The higher the foaming capacity is, the better the incorporation of air inside the foaming solution. The foams actually used on site differ considerably in their foam creation behaviour.



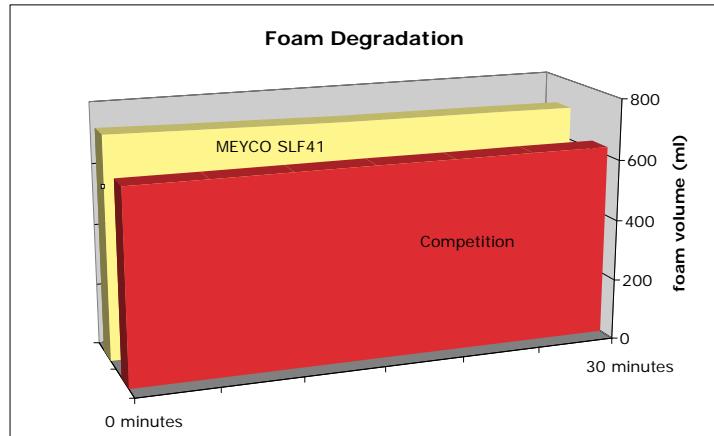
Ad b. Measurement of foam stability

Generally, two different test methods can be used:

- Draining and measuring the quantity of the liquid fraction
- Measuring the remaining foam volume

EFNARC recommendation refers to the draining method. For site evaluation the remaining foam volume must be of much higher relevance, since the remaining foam volume is the valid parameter to judge the stability of the foam / soil mixture.

Generally, foam shall be active and stable whilst located inside the working chamber, but shall decompose as rapidly as possible once excavated. Leading tunnel foams currently available on the market, already show quite a good stability over time – indicating safe behaviour of the soil / foam mix during ringbuilding.



Ad c. How to judge / appraise the foam stability results?

Generally, the correct question should be: How stable is the mixture of soil and foam?

Since this is not so easy to measure and also depends on the type of soil, quite often pure foam characteristics are judged, however this is often misleading. The stability of pure foam might in some cases be relatively high but degrading very quickly if mixed with soil.

In general, the stability of tunnel foams increase if mixed with soil, especially with fine graded soil like clay.

Ad d. Better high or medium foam stability?

This question cannot be answered generally but is dependent upon many factors, such as the surfactant (and polymer) concentration, the type of excavated soil itself and the way of mucking-out the excavated soil. Where muck trains are used, foam stability should be lower in order to reduce the volume of excavated soil. Example: FIR=70 implicates that 1m³ of soil will be mixed with 700

Litres of Foam, which means that theoretically 1,7m³ of soil has to be transported out of the tunnel instead of 1m³ (even without taking into account the loosening factor of the soil).

USE OF POLYMERS AND ANTI-CLAY-AGENTS

Every now and then the same question arises from contractors and project owners: Do polymers and anti-clay agents really help or is it just a good marketing ploy?

Comparisons between a number of EPB drives between 1999 and 2009 as well as different geologies mastered successfully by using EPB mode show not only the substantial progress made by the machine construction but also the quantum leap made possible thanks to the development of new soil conditioning agents: Madrid MetroSur project during the years 2000 would not have been that quickly finished; Madrid M30 project with 15m diameter machines would have never been that successful; Toulouse Metro, North Dorchester Bay or Esfahan Metro projects would look different without having been able to benefit from the product development.

Use of polymers in porous soils

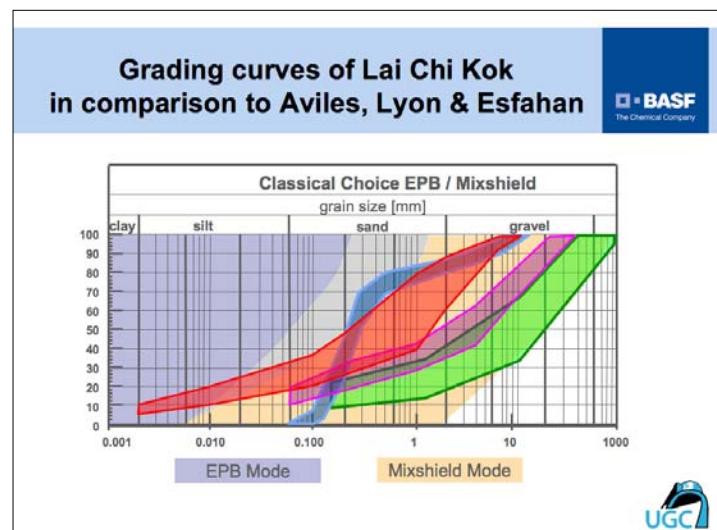
Generally, the creation of an EPB-suitable soil paste is possible with any type of soil; it all depends on the sieve curve of the soil at the face and the correct use of soil conditioning foam and polymers. The denomination 'polymers' shall only be used for agents used in porous soils like sands & gravel. This is necessary in order to differ from anti-clay-agents used in clay soil – having quite the opposite effect of polymers in porous soils.

There are a couple of different polymers typically available on the market, having totally different properties. Some are still based on powder requiring colloidal mixers in order to be transformed into a usable liquid. This method of preparation is potentially erratic (dosing error), time consuming, has to be realized at the surface and then shipped down to the TBM and implicates a possible degradation in the storage tank. In other words: it's no longer state-of-the-art and cannot react as quickly as necessary on the soil changes.

Contemporary polymers are already present in liquid form and can be easily and rapidly dosed by dosing pumps. They shall also be safe for the foaming generator in order to avoid its paste up.

State-of-the-art polymers like MEYCO SLF P1 and P2 can easily be dosed on the TBM, are immediately efficient for soil conditioning and enable tunnel boring machines to excavate in cohesionless soils like present in Lai Chi Kok (red curve), Aviles (blue curve) or Esfahan (purple curve) even under water pressure. In these cases, soil conditioning only using foams would never be possible – the use of polymers makes the difference. Soils like Lyon (green) still need the addition of fine filler suspension.

The pictures from Aviles excavation illustrate quite nicely the effect of those



polymers: left side only foam used, right side dry sand excavation by using foams in combination with polymers.

Use of anti-clay-agents in clayey soils

Generally, the creation of an EPB-suitable soil paste is also possible in clay soil. Like in porous soils, the use of foam only will, in the majority of cases, not be successful. In order to create the soil paste properly, the use of anti-clay-additives like Rheosoil is necessary.

Pictures from recent construction sites like the Moscow Escalator TBM illustrate the dramatic effect of the anti-clay-agents: The left side shows the use of water – resulting in a sticky agglomeration of clay lumps. The use of foaming agents did not ameliorate the situation. Only the correct use of Rheosoil transformed the clay soil into a pumpable and homogeneous earth



pulp. If desired, a plastic (semisolid) soil rheology can also be created with the use of Rheosoil, depending on the amount and way of introducing the anti-clay-agent.

CONCLUSIONS

Laboratory testing prior to site use is essential for successful soil conditioning and for an overall cost-effective solution. The suppliers shall undertake this testing – same as the optimisation of the starting parameters on site.

Essential for the successful EPB tunnelling is the completely filled working chamber in order to apply the correct counterpressure. The working chamber can only be completely filled with the correct use of soil conditioning agents – enabling furthermore the TBM to maintain a significant excavation speed and reducing the wear of excavation tools, the cutterhead itself and the screw conveyor.

In case of porous soils, polymers or polymer/foam premixes have to be used; in clayey soils the use of anti-clay polymers makes the difference.

ACKNOWLEDGEMENTS

The author would like to thank Claire Verani, Herbert Egli, Daniel Montalban and Jamie Ibarra for their valuable co-operation and continuous support.

The paper is dedicated to Rafael Valenzuela who passed away suddenly in December 2008. He was unquestionably one of the fathers of the modern soil conditioning systems and has left his mark on all of us.

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