

Advantages of Soil Conditioning in Shield Tunneling. Experiences of LRTS Izmir

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ABSTRACT: Successful EPB tunneling strongly depends on the interaction between soil- ground-water conditions and the tunneling shield. This paper presents some results of a shield drive at Izmir Light Rail Transit System (LRTS) in Turkey. The first part focuses - besides a short project description – on the main soil characteristics and fundamental aspects of the face support. Theoretical and experimental basic-knowledge about foaming agents, polymers and their dosage will be delivered. Finally, practical tunneling experiences of the four EPB drives in Izmir will be described. An attempt will be made here to summarise the influence of the foam- and bentonite-conditioning on thrust forces, torque and costs in different kind of soils.

1 PROJECT LRTS IZMIR

1.1 General information

The Greater City Municipality of Izmir decided in 1994 on the construction of an LRTS, which is a combination of an underground and surface railway system. Izmir is the third largest city of Turkey with nearly 3,5 million inhabitants. The 11,3 km construction-length was subdivided into: 1,375 km long EPB shield tunnel, 1,7 km long NATM tunnel, 1,1 km Cut and Cover and the rest into Surface & Elevated section. Figure 1 shows a layout sketch of the whole project.

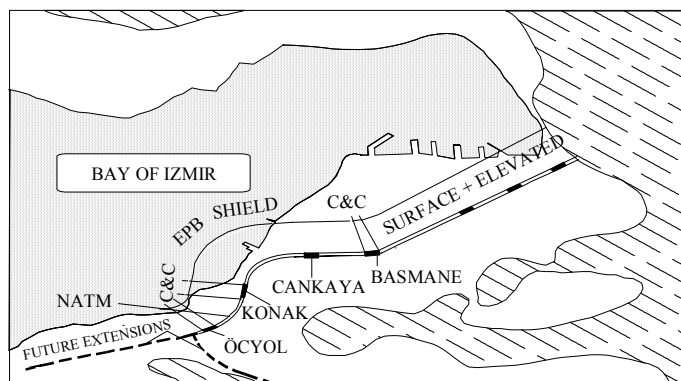


Figure 1. LRTS Izmir 1st phase, total length = 11,3 km

A Consortium, which consisted of ABB Traction and Yapi Merkezi, was responsible for the whole project. Wayss & Freytag and Yapi Merkezi formed a JV for shield tunneling and construction of the Sta-

tions. Two single track tunnel (2x1375 m) had to be bored. First shield-launching was executed at Basmane Station. First and second drive ran between the Stations Basmane and Cankaya in the same direction. After the first drive the shield was transported back to the Station Basmane. Third and fourth drive were completed between Stations Konak and Cankaya. An EPB shield - with an outer diameter of $D = 6,52$ m, delivered by Herrenknecht Ltd. – was used. Reinforced concrete segment lining (7+1 segments, $D_{out}=6,32$ m, $D_{in}=5,72$ m and $l=1,2$ m) was erected inside the shield tail. The cost of shield tunneling was estimated to approx. 23,7 millions US\$. The shield drive started in August of 1997 and was successfully finished in December of 1998 - without any collapse or large surface settlement.

1.2 Soil conditions and parameters

In the first section between Basmane and Cankaya station mainly non cohesive soils were excavated, while in the second section between Cankaya and Konak station cohesive soils with water contents near or beyond their liquid limit had to be mined. The soil investigation covered the usual scope of in situ and laboratory tests. Figure 2. gives a schematic impression of the different strata along the alignment of the tunneling drive.

Tunneling had to cope with three different groups of soil: gravelly as well as silty sands (S,SG), clayey and sandy silts (M), and clay (C).

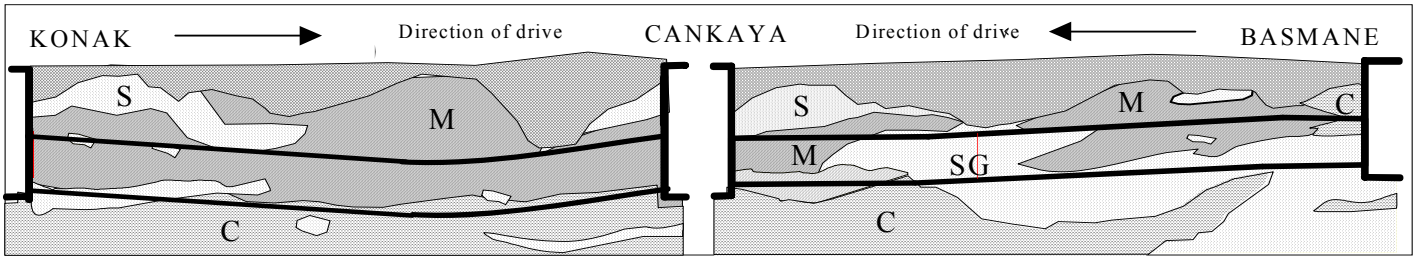


Figure 2. Geotechnical longitudinal section

The sand and gravelly sand showed a wide range of relative density from loose to very dense, but for most parts of the alignment medium dense to dense sand occurred. Figure 3. shows the lower and upper limits of the grain size distribution. The sand was classified mainly as SM but a considerable amount also as GM according to USCS.

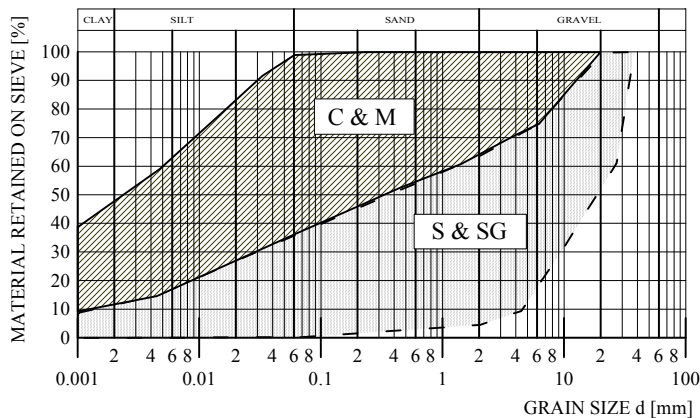


Figure 3. Grain size distribution of soils

Laboratory and in situ test results of soil type M showed, that its natural water content was equal to or beyond its liquid limit. The undrained cohesion was found at $s_u = 29$ kPa in average. The granulometric tests revealed a wide range of particle sizes (see Figure 3). The majority of soil samples were classified as ML according to USCS.

The erosive products of the underlying bedrock of Andesite mainly formed the clay along the tunnel alignment. The grain size distribution (see Figure 3) showed relatively high silt and sand content, nevertheless the mechanical behaviour of soil was dominated by the clay fraction. The average index of plasticity reached $IP = 24\%$ (see Figure 4), its undrained cohesion $s_u = 78$ kPa.

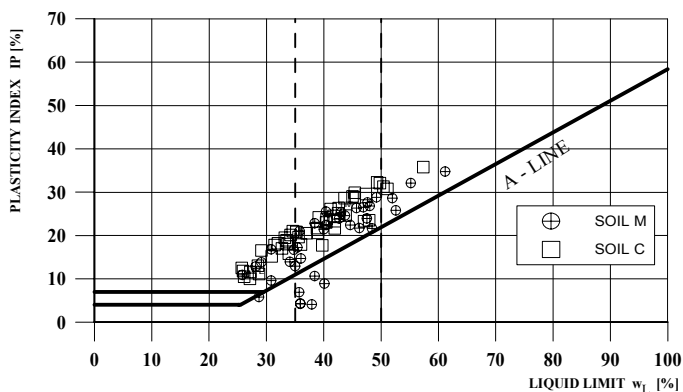


Figure 4. Plasticity chart for the soil M and C

The relative consistency index lied at $IC = 0.65$, defining the clay as stiff to very stiff. The clay was classified as CL according to USCS.

Statistical analysis of soil investigation data and safety considerations led to design-parameters of tunnel lining and tunneling face support. These parameters are summarised in Table 1.

Table 1. Soil- parameters for tunnel design

γ [kN/m ³]	Φ_u [°]	s_u [kN/m ²]	Φ' [°]	c' [kN/m ²]	E_s [MPa]	K_0 [-]	k [m/s]	Layer
21	0	60-80	22	0	9-15	0,65	1×10^{-7}	C
17	0	25-30	20	0	4,5-9	0,65	5×10^{-6}	M
21	-	-	37,5	-	40-60	0,40	3×10^{-5}	S

2 FACE SUPPORT

The control of face support is a major issue in EPB shield tunneling. Continuous support of the tunneling face must be provided by the excavated soil itself, which should completely fill the working chamber. The required support pressure at the tunneling face will be achieved through:

- shoving the shield forward - by means of hydraulic jacks - against the soil mass
- regulation of the screw conveyor-rotation.

The support pressure has to balance the earth pressure and the water pressure. Depending on soil characteristics and the cover to diameter ratio (t/D) different types of earth pressures are to be determined.

2.1 Maximum support pressure

In non cohesive as well as cohesive soils (e.g. soil layer M or C) it is necessary to balance the earth pressure according to the K_0 - State (earth pressure at rest E_0 where $K_0 = 1 - \sin \Phi$). Usually there is no need to apply a Factor of Safety because this would lead to heaves on the soil surface and/or to overloading of the concrete segments. Besides earth pressure at rest full hydrostatic water pressure has to be considered, if the soil is permeable. In fully saturated and non permeable clay, total stresses should be considered in the earth pressure calculation. Experiences in Izmir showed, that in some area a slight rising of the theoretical required support pressure was necessary. This rising can be explained by a relative uncertainty in earth pressure measuring and/or by

reduced bulk density ($\gamma_{\text{Sat}} = 13$ to 15 kN/m^3) of the soil in the working chamber. This soil is not only in loosened state, but up to 50 % of its pores are filled with air. As a rule of thumb, it seems to be reasonable to rise E_0 by approx. 10 to 15 %:

$$E_{\text{required}} = (1,1-1,15) \times E_0 \quad (1)$$

2.2 Minimum support pressure

2.2.1 Face support in granular, non or slightly cohesive soils

In non-cohesive or slightly cohesive soils the theoretically required minimal support pressure can be determined by a three-dimensional limit equilibrium model (see Figure 5).

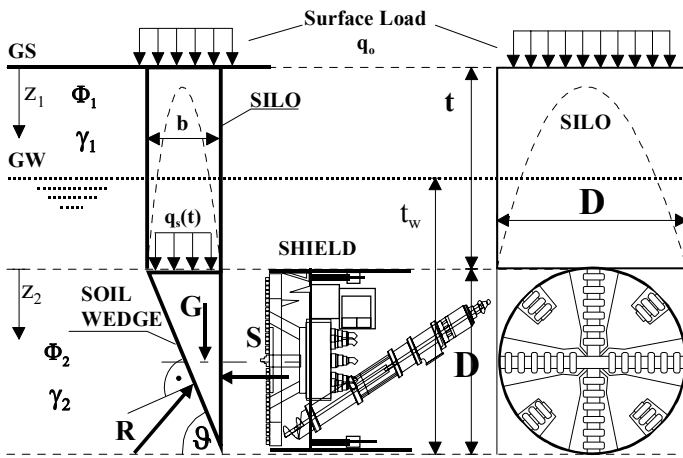


Figure 5. Three-dimensional limit equilibrium model for non cohesive soils.

The state of three-dimensional active earth pressure, $K_{A3} = f(\Phi, t/D)$ is here assumed. Details of the theoretical solutions can be found elsewhere (Jancsecz & Steiner 1994).

2.3 Face support in cohesive soils

- Limit equilibrium analysis in saturated and cohesive soil can assume following shear parameters (short-term loading): the angle of internal friction $\Phi_u = 0$ ($K_0 = 1$)
- $\tau = s_u$ kPa

Stability solution will be obtained using a simple kinematically admissible collapse mechanism. It is possible to deduct a limit function from the earth pressure equation for the so called Stability Factor (N):

$$N = \frac{4}{\pi} \times 3.4 \times \left(1 + \frac{t}{D}\right) \quad (2)$$

The Stability Factor is a critical ratio for total collapse of the face (N_{crit}) in state of limit equilibrium. It has first been defined by Broms and Bennermark (1967) as a relation between overburden pressure

reduced by face supporting pressure (if any) at the tunnel axis and the undrained shear strength of soil. It is possible to express the required support pressure p_{sreq} in a simple form of an equation:

$$p_{\text{sreq}} = p_v - \left(\frac{N_{\text{crit}}(t)}{\eta}\right) \times s_u \quad (3)$$

where p_v is the earth pressure in the shield-axis, $\eta = 1.5 - 2$ is the Factor of Safety. The calculation scheme for support pressures is based on the theory of Atkinson & Mair (1981):

$$N_{\text{AMCrit}}(t) = 5.86 \times \left(\frac{t}{D}\right)^{0.42} \quad (4)$$

The computation of Stability Factor N_{AMCrit} has been modified, so that factors greater than six were not allowed. Generally accepted limits for Stability Factors are:

$N < 2$	Small ground movements
$2 < N < 4$	Shield generally used to restrain ground movements
$4 < N < 6$	Increasing ground movements
$N > 6$	Face may be unstable. Clay may squeeze rapidly into the face

Good agreement has been found in Izmir between the theoretical support pressure - calculated on the explained semi-empirical basis - and the actually required support pressure.

3 SOIL CONDITIONING WITH FOAM AND POLYMER

The EPB tunneling often requires the use of additives which make it possible to cut, support and transport the soil with economical boring parameters. The soil conditioning can be realised by addition of foam and/or polymer. The choice of the foam type and the polymer depends mainly on the soil type in situ.

3.1 Function of conditioning additives

The original in situ soil properties can be changed by addition of foam and polymer. The range of changing comprises fluidisation and thickening possibilities as well. The development of a cake, the change of soil porosity and friction forces are strongly influenced by the use of additives, too.

Foam represents the physical state of air, dispersed in liquid. It occurs when a solution contains surfactant molecules, that form an aqueous - air interface.

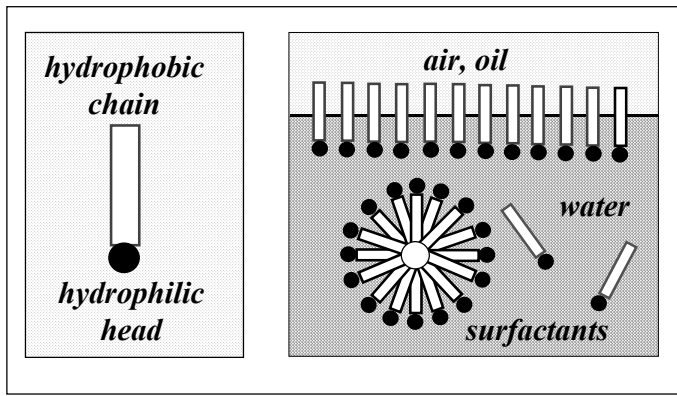


Figure 6. Surfactant molecules

Surfactants are a combination of a hydrophobic chain and a hydrophilic head (see Figure 6). Both parameters can be varied: different chain structures (length, steric structure) and different head characters (anionic, non-ionic, cationic, amphoteric) are possible.

These different chemical characters induce different properties like modification of superficial / interfacial tension, force of dispersion, solubility, emulsification, foaming capacity, etc.

The surfactants are acting as fluidizing agents, their fluidizing influence is related to the water content of the excavated soil. The intention of foam use is to reduce the torque of the shield, to avoid the heating of excavated ground and plugging of the shield. Foam decreases the necessary energy supply and increases the productivity of the tunnel boring machine. It also reduces the soil permeability and allows maintaining an “elastic” pressure.

The first polymers introduced in tunneling were polyacrylamides. New developments are based on hydrocarbon chains and are produced by fermentation. For example the MEYCO Fix SLF P polymers are water soluble, biodegradable biopolymers which are compatible to the foam surfactants. Both of them are safe for the foaming generator. The main intention of polymer usage is to manage the face support and soil transport problems in loose, coarse soils, but it can also be used to reduce stickiness on the conveyor belt, in the working chamber and screw conveyor.

It also induces a stable support pressure in the working chamber during boring and also when stopping the machine for a short time. This is possible because the polymer tends to build up a cake with the fines (silt-, clay-fraction) of the soil.

3.1.1 Generation of foam

The foam properties depend on its different compounds like air, water, surfactant and sometimes polymer. The parameters which characterise a foam are:

- Surfactant Dosage = c_F [%]
- Polymer Dosage = c_P [%]
- Air Ratio (Foam Expansion Ratio) = FER

• Foam Injection Ratio = FIR

The surfactant or polymer dosage influences the amount of molecules which are introduced to treat the soil and has also an effect on the quality of the foam. The amount of air introduced to the soil can be changed with the air ratio FER which characterizes the ratio between air and liquid volume. The amount of introduced air plays two main roles: Increase of the surfactant based fluidising effect to the excavated soil and, if desired, a migration into the ground to induce a drying effect. The foam injection ratio FIR indicates the volume of foam used per m^3 excavated soil.

Another demand is to create regularly small air bubbles to obtain a stable foam and a homogenous soil mixture. This can be influenced by the choice of the foam generator (see Figure 7).

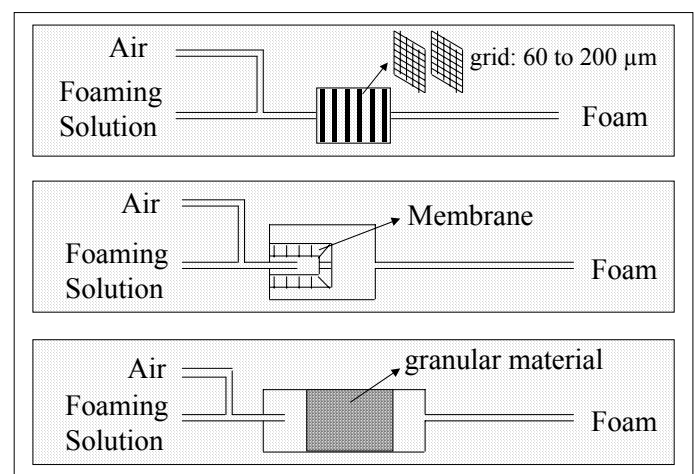


Figure 7. Different types of foam generators

Standard equipment like granular filled generators form air bubbles ranging from 0,5 mm up to 2 mm (depending on foaming agent and FER: here $c_F=2\%$ and FER = 10).

If polymers are used in combination with surfactants, the best way to create foam is to use separate dosage pumps for each additive to add to the water. This so modified foaming solution can be added without any problems to the generator.

3.1.2 Costs of Conditioning

The required amount of surfactant and polymer depends on the type and behaviour of soil which has to be cut. General consumption values are 0,5-1,0 kg surfactant and 0,01-0,5 kg polymer per $1 m^3$ excavated soil. The costs can rise from 0,30 US\$ up to 4,70 US\$, in most cases they are between 0,30 US\$ and 1,75 US\$ per $1 m^3$ excavated ground.

The advantages are increased security of conditioning and support pressure, faster boring, higher safety for the extraction screw, the cutterhead and a more easy transport of the muck.

3.2 Conditioning Tests for Izmir

For the Izmir project the following tests were carried out:

- Cone Penetrometer Tests to determine the effect of different surfactants and different dosages on specific soils.
- Slump Tests to find out the right foaming parameters (FER, FIR, ...)
- Simple Shear Tests to determine the influence of the additives on soil friction and cohesion.

The grain size distributions of the tested soils are:

- Sandy Gravel: 50 % Sand; 50 % Gravel
- Sandy Gravel + Clay: 44 % Sand; 43 % Gravel; 13 % Clay
- Clayey Sand: 75 % Sand; 15 % Clay
- Sandy Clay: 80 % Clay; 20 % Sand

3.3 Cone Penetrometer Test

For the Cone Penetrometer Test we used a apparatus where a metallic cone ($\alpha=25$, $m=235$ g) falls down into the soil sample and the penetration depth was measured. The tests were carried out by a mixture of soil and foam, created with the surfactant MEYCO Fix SLF 45. The foam variations are obtained by different surfactant concentrations in the foaming solution (surfactant concentration: c_F ; polymer concentration: c_P) and different amounts of air added to the foaming solution (varied FER).

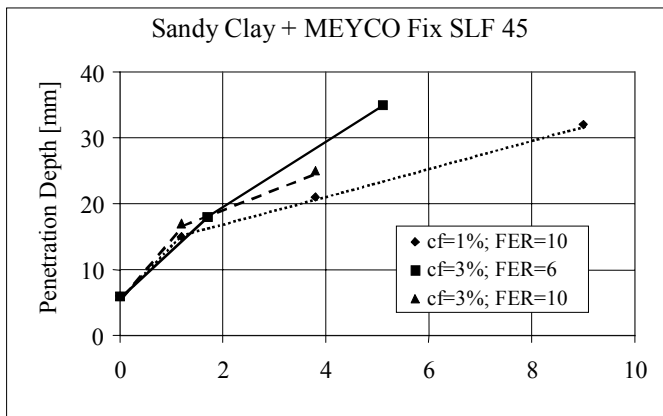


Figure 8. Cone Penetrometer Test

Three main results can be pointed out from Figure 8:

- The more foam added to the soil, the higher the penetration depth (liquifying effect).
- The higher the surfactant concentration, the higher the plastifying/liquifying effect due to a higher amount of surfactant molecules available for the foam and the soil particles.
- The surfactant MEYCO Fix SLF 45 is the suitable surfactant regarding its destructuring effects to the Izmir clay.

3.4 Slump Tests

For the slump tests we used the same test equipment as for concrete tests.

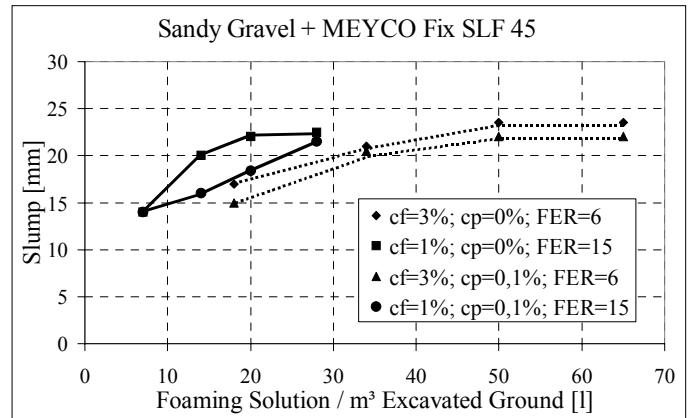


Figure 9. Results of slump tests with coarse soil

The structuring effect of the Polymer MEYCO Fix SLF P2 results in lower slump values when polymer is added ($c_P=0,1$ %). This effect occurs also in combination with foam (see Figure 9).

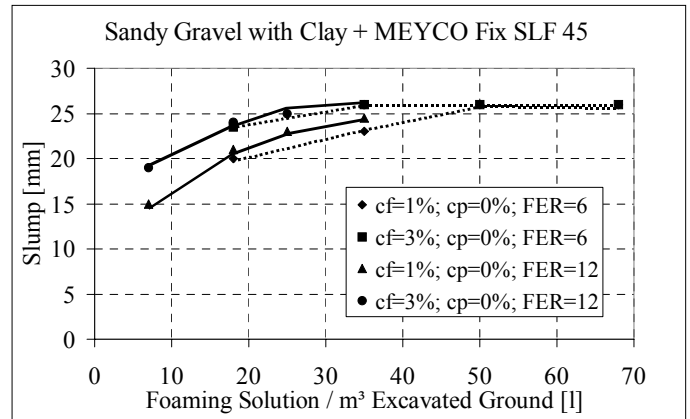


Figure 10. Results of slump tests with coarse and fine soil mixture

Plastic consistency could be obtained even with a low water content (see Figure 10). Without foam addition the soil had a too stiff character and was not suitable for the TBM.

The quality of the excavated sandy gravel with clay is quite different to the mixture without clay. The fines (silt and clay particles) change the rheological property of the soil, in this case no polymer addition was necessary.

3.5 Simple Shear Tests

The simple shear tests were carried out with undrained, unconsolidated soil which was mixed with foaming solution. Due to the apparatus dimension only the soil fraction < 5 mm is used. We measured the cohesion s_U in kPa and the internal friction angle Φ_U of the soil, which are parameters to determine the consistency and the internal friction forces of the soil.

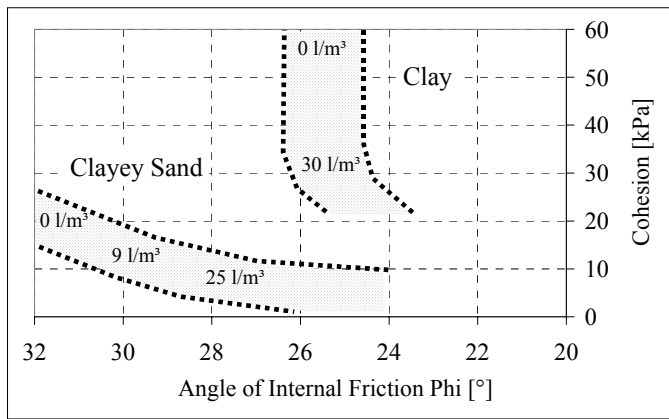


Figure 11. Simple shear test results on clayey sand and clay mixed with foaming solution (3 %)

By addition of foaming solution to sandy clay we detected a significant decrease of cohesion and friction (see Figure 11). The clay showed much higher cohesion values which could be decreased by addition of foaming solution. To decrease also the internal friction a further increase of added water is necessary.

3.6 Environmental aspects

The environmental aspects can be divided up into three main parts of interest:

- Ecotoxicity Profile
- Biodegradation Profile
- Water Pollution Class

3.6.1 Ecotoxicity Profile

This science studies the impact of chemical substances on the environment. Ecotoxicology takes into account the behavior of substances in the environment (biotic and abiotic degradation phenomena) and on the other hand toxic effects or the ecotoxicity of substances. The potential toxic effects produced by chemicals on organisms have to be detected. There are two ways to assess the ecotoxicity of chemicals:

- Field studies which are very complex (interaction between numerous parameters), long and costly
- Laboratory studies which represent a simplified approach by the choice of species to chemical laboratories and the assessment of effects.

The laboratory tests are standardized for the choice of species, the criteria studied, the exposure duration and conditions. This allows the chemicals to be compared with each other.

The aquatic ecotoxicity tests include acute or short-term tests, chronic or long-term tests and microcosm tests. For the mentioned TBM additives foam and polymer acute ecotoxicity tests were carried out: Short exposure (few days) of species to

tested substances and mortality measurement, in this case Daphnids (Acute Toxicity tests on Daphnids).

3.6.2 Biodegradation profile

Biodegradation means the partial or total metabolism of substances by microorganisms for use as source of carbon and/or energy. The mentioned tests are referring only to aerobic biodegradation:

- Ready biodegradation (Carbon dioxide evolution, OECD 301 B): biodegradation of organic substances to CO_2 and H_2O , substance as only carbon source and addition of only a low content of microbiotic organisms
- Inherent biodegradation (Zahn-Wellens Test, OECD 302 B): biodegradation of organic substances to CO_2 and H_2O , testing of the substance in favorable conditions of biodegradation (internal reserve of carbon, higher content of microbiotic organisms)

3.6.3 Water Pollution classes

The water pollution class is a German classification, also used in other countries. The existing ranking is the following:

- WGK 0: non water hazardous
- WGK 1: slightly water hazardous
- WGK 2: water hazardous
- WGK 3: strongly water hazardous

This water classification is going to be changed regarding the European harmonization according the new draft VwVwS (Verwaltungsvorschrift wassergefährdende Stoffe) dated 9th September 1998 (Verband der chemischen Industrie, 1998). The WGK 0 will not exist any more, substances are now called 'non water hazardous' (mostly for non soluble substances). In consequence all surfactants are at least ranked in WGK 1: slightly water hazardous.

Regarding their use during TBM boring, only a water based solution of surfactants (preparation) is used. Typically, the surfactant concentration during boring is 2-4 % of a 20 % water based solution. The real used surfactant concentration which is added to the soil can in consequence be calculated to 0,4-0,8 % in water. Preparations of less than 3 % of WGK 1 substances (total weight) can be classified as 'non water hazardous'.

But never forget: concentration makes things toxic.

4 ON SITE TUNNELING CONDITIONS

Soil conditioning in theory and on job site are often two sides of a coin. Rapid breakdowns in shield drive or lack of performance at different parts of the equipment are examples that can directly affect soil

conditioning. In the beginning (learning phase) the shield-crew may also not be familiar with the soil - machine interaction.

Soil conditioning as part of the TBM design should be planned as simple as possible, to allow easy handling for the shield operator. This ensures that each TBM operator knows not only how to get the best performance out of 'his' TBM after a certain time, but also facilitates maintenance work.

Shield performance data at LRTS in Izmir were won directly from the remote sensing unit of the TBM. The data could then be visualized by the manufacturer's computer program or any other spreadsheet calculation software.

5 DESCRIPTION OF TUNNELING DRIVES

5.1 First Drive

5.1.1 Silty soil and clay

At the beginning of the first drive approx. up to ring 150, the TBM had to cope with soil M with high contents of fines and occasionally soil C. It was necessary to use extensive foam-conditioning to turn this soil in suitable state for support and transport. The foam consumption started with an uneconomic high level of 1500 l/m^3 , that was 5 times higher than predicted (see Figure 12). Economical and technical reasons led to the additional use of bentonite slurry. This method of conditioning reduced foam output to 500 l/m^3 and later to 300 l/m^3 . Torque of the cutter head was also reduced by this modified foam conditioning, which saved energy, minimized tool wear, and stabilized support pressure. The benefit was very low settlements (see Figure 13 and Figure 14). It could be observed during this drive that higher contents of sand and gravel in the soil of type M led to a reduction of foam consumption.

At the end of the first drive (ring 400 – 490) the shield entered again the soil M after a passage through sand and gravelly sand. The consistency of this silty soil was far more liquid than along the total shield drive. No conditioning was necessary here to achieve high advance speed.

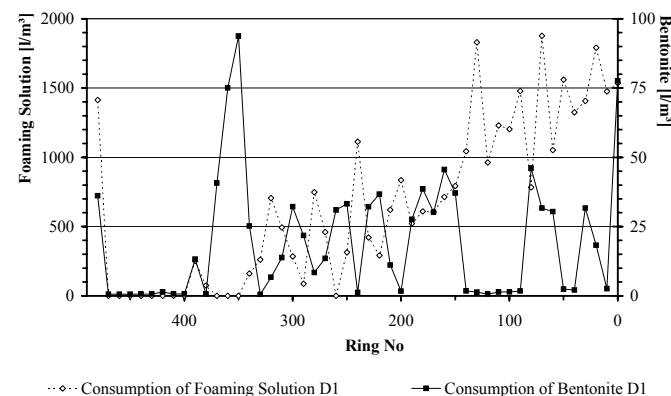


Figure 12. Conditioning of 1st drive

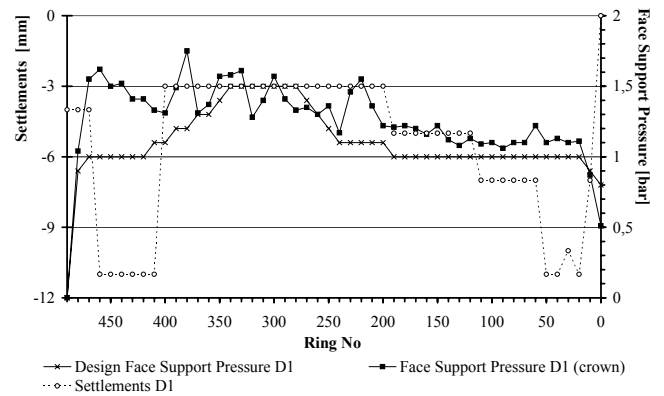


Figure 13. Face support pressure and settlements – 1st drive

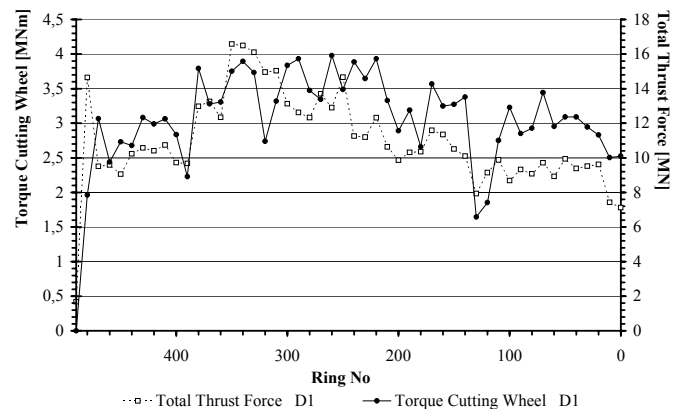


Figure 14. Thrust force and torque of cutting wheel – 1st drive

5.1.2 Sandy and gravelly soil

In Soil S or SG a remarkable increase of the water volume in relation to the volume of the solids in the excavated muck could be observed.

The conditioning parameters had to be changed thus, that the Foam Expansion Ratio (FER) was increased. This resulted in an decrease of the water content in the muck and produced a more 'pasty' consistency of excavated soil.

The support pressure had slightly to be increased for full face tunneling in sand and gravelly sand in order to produce a muck suitable for screw conveyor and conveyor belt. Tunneling especially in gravelly lenses produced water inflow through the working chamber, which made it difficult to keep the spoil pasty and caused problems with muck transport by conveyor belt. The best results were obtained then by high Foam Expansion Ratio and the use of bentonite slurry.

5.2 Second Drive

5.2.1 Silty soil and clay

The second drive was made through the same soil formation, nevertheless the conditioning parameters were totally different. Till ring 230 the consumption of foam and bentonite was constant. The FIR values

laid around 300 l/m^3 (see Figure 15). Consumption of foam was inside the scheduled economic parameters.

Due to different technical problems, such as the clogging of three of four foam injection pipes the conditioning switched totally to injection of bentonite slurry. After ring 350 the screw conveyor (auger) was affected by extraordinary wear. With 140 mm of the radius worn, the rate of advance sunk to an unacceptable value.

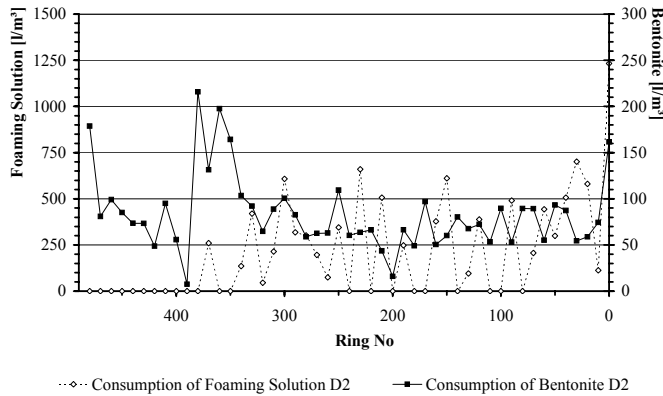


Figure 15. Conditioning of 2nd drive

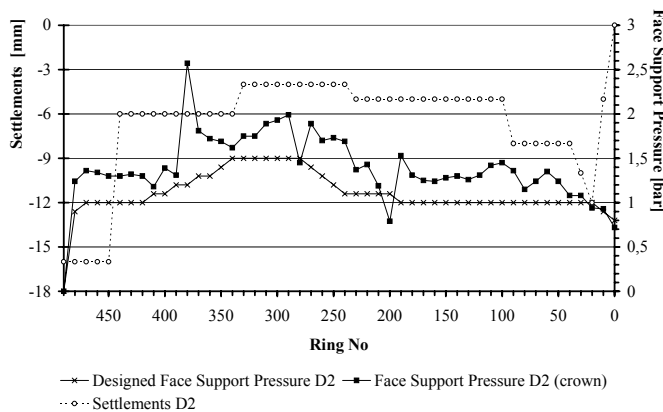


Figure 16. Face support pressure and settlements – 2nd drive

At the end of this drive the tunneling mode was changed to a kind of compressed-air face support. It was possible to maintain a small pressure-regulated air cushion in the upper quarter of the working chamber and a liquid-pasty soil mass in the lower part (see Figure 18). The support pressure was kept at the top of the tolerances with sufficient safety against blow out.

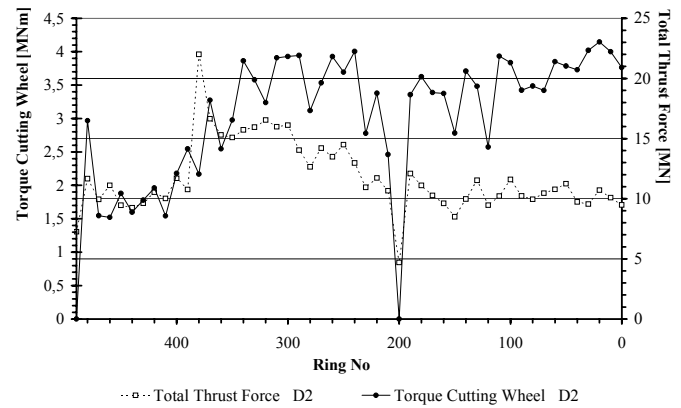


Figure 17. Thrust force and torque of cutting wheel – 2nd drive

This kind of compressed air mode was very helpful to press the muck out of the damaged screw conveyor. An acceptable rate of advance with a controlled face support could then be achieved again.

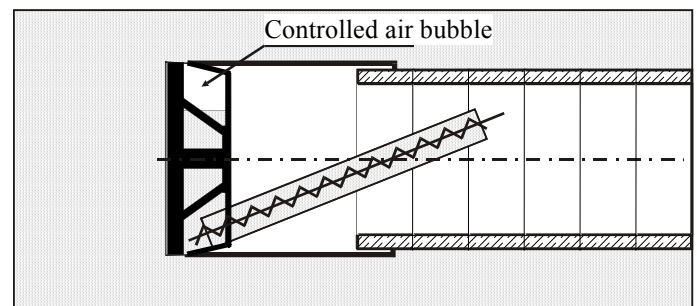


Figure 18. Compressed air mode at 2nd drive.

5.2.2 Sandy and gravelly soil

Water caused no problems and muck could be conditioned to guarantee transport on conveying equipment. No change in conditioning or support pressure was necessary.

5.3 Third Drive

5.3.1 3.3.1 Silty soil, sea-side

The third drive started in silty soil with some small sand layers. The drive at the first 250 rings was parallel to the coast line at a distance of about 150 m. The soil was loose, not very consolidated, the water content was high and the organic matter was roughly 20 %.

Driving the EPB shield in that soil caused no difficulties regarding thrust and cutter head torque (see Figure 19). Settlements were low and face support pressure laid around the design values (see Figure 20).

Soil conditioning was generally not necessary. From time to time small quantities of foam were injected to keep the water away and to make the muck less sticky on the conveyor belt. Foam consumption starts with zero. Later going up to 700 l/m^3 because of technical problems with the TBM (damaged gear

boxes). The excavation had to be made “easier” for the TBM, what meant in this case more conditioning to reduce the torque (see Figure 21) at the cutter head.

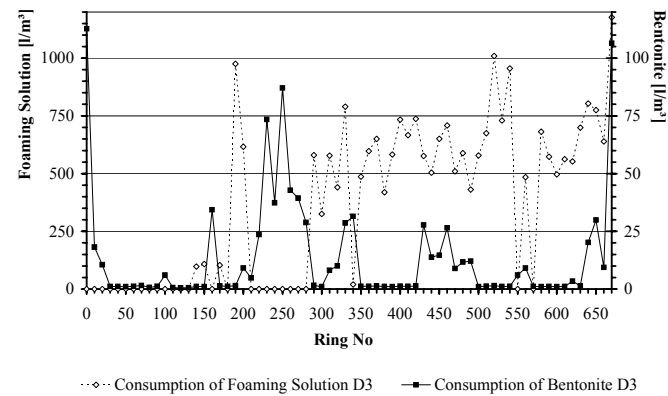


Figure 19. Conditioning of 3rd drive

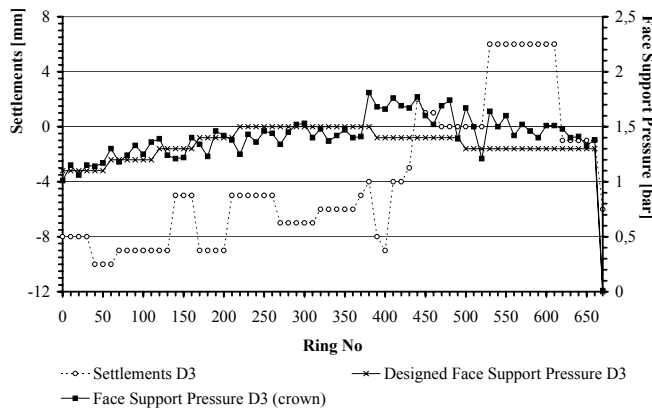


Figure 20. Face support pressure and settlements – 3rd drive

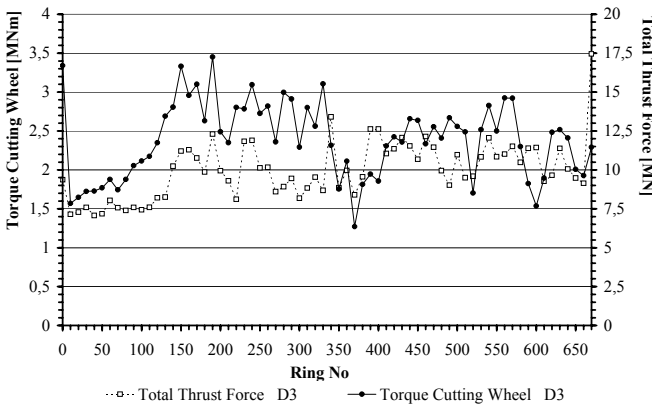


Figure 21. Thrust force and torque of cutting wheel – 3rd drive

5.3.2 Silty soil river side

After the sea-side area the third drive entered a zone of former river deltas, where the soil was silty and clayey. The muck turned out to be less pasty and required more foam conditioning with increasing distance to the coast.

At the end of the third drive the cutter head had to cope with boulders of Andesite (>300 mm) in the soil matrix. 300mm was the entrance size i.e. max. opening of the cutter head and also that of the screw

conveyor. This affected to some extent the advance rate.

5.4 Fourth Drive

Drive four ran almost parallel to drive 3 and the experiences made on drive 3 were applied. Like in drive 3 the consumption started with zero, and later went up to 300 l/m³ (see Figure 22). The soil conditioning was almost perfect which resulted in full TBM performance and best progress of all drives.

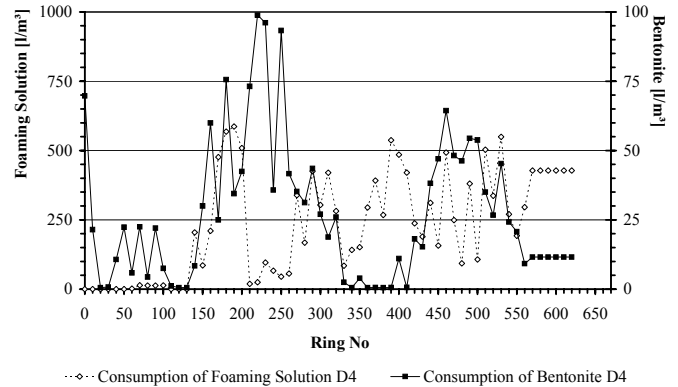


Figure 22. Conditioning of 4th drive

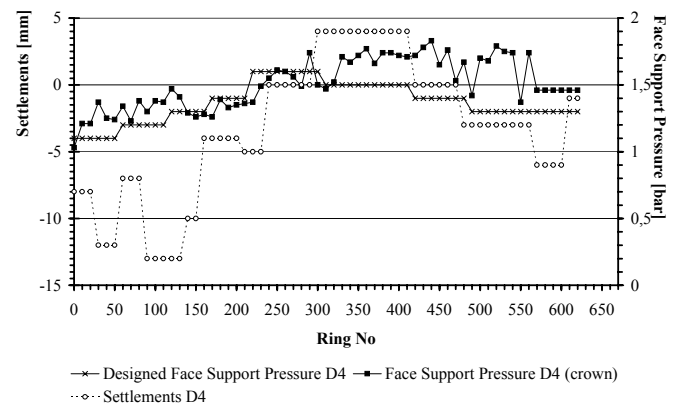


Figure 23. Face support pressure and settlements – 4th drive

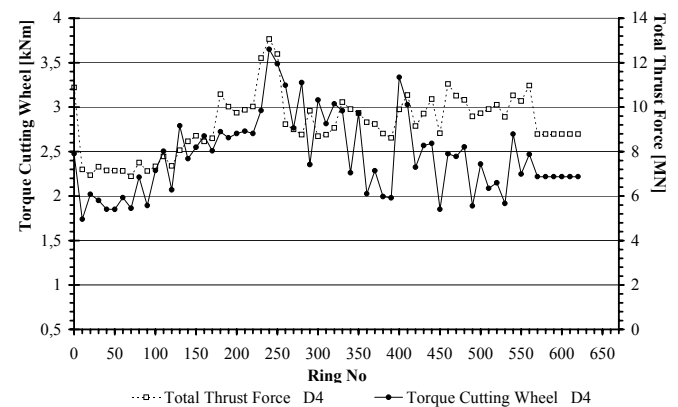


Figure 24. Thrust force and torque of cutting wheel – 4th drive

6 FOAM AND BENTONITE CONDITIONING

Effects of foam and bentonite conditioning can be interpreted best by the charts of the 1st drive (see Figure 12 to Figure 14). This drive went through all geological formations of that site. It was the 'learning' drive to check possibilities of soil conditioning. First the parameters FIR and FER given by the laboratory tests of RHODIA SA had to be transformed into input parameters for the TBM. The foam generating plant consisted of four foam generators each supplied by a liquid and an air input line. The parameters for the control units had to be adjusted to the actual speed of the TBM and the currently applied support pressure.

The original foam generation parameters ensured an acceptable advance speed right from the beginning. The soil was in a pasty conveyable condition. A moderate advance speed was reached after the first 50 rings and the temporary use of bentonite solution in addition to the foam lowered consumption of foam to an economic level.

7 THRUST FORCE AND TORQUE

7.1 Thrust forces

Thrust forces were always constant around 10000 kN (see Figure 14, Figure 17, Figure 21, Figure 24). At the first and second drive, in the area of the sandy gravel, a rise up to 17000 kN could be observed.

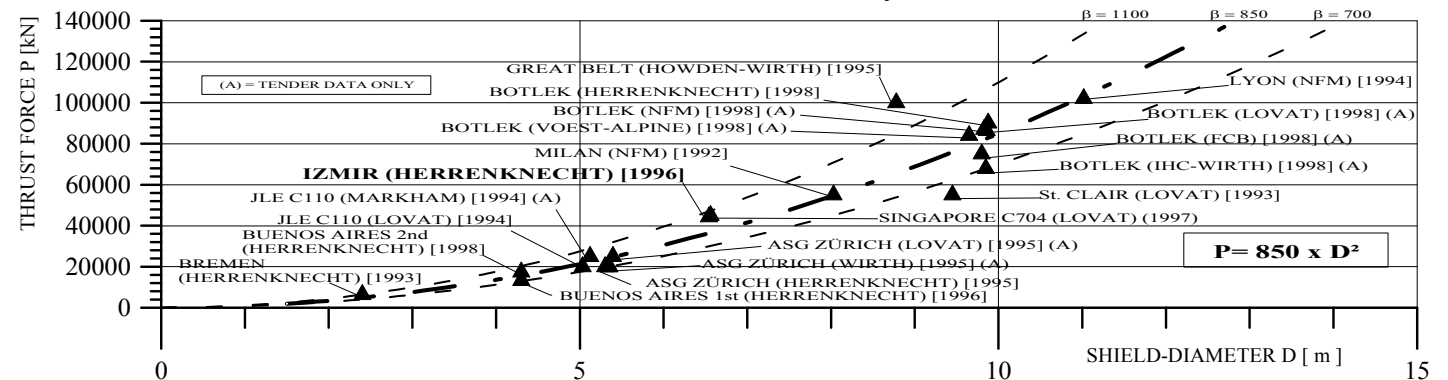


Figure 25. Installed thrust forces at different projects

Figure 26. Installed cutting head torque at different projects

At the second drive a peak value of 23000 kN was reached. This coincides with the strong abrasion on the screw conveyor, which rendered mucking extremely difficult.

The installed total thrust force has been double the needed total thrust force (see Figure 25).

7.2 Cutter head torque

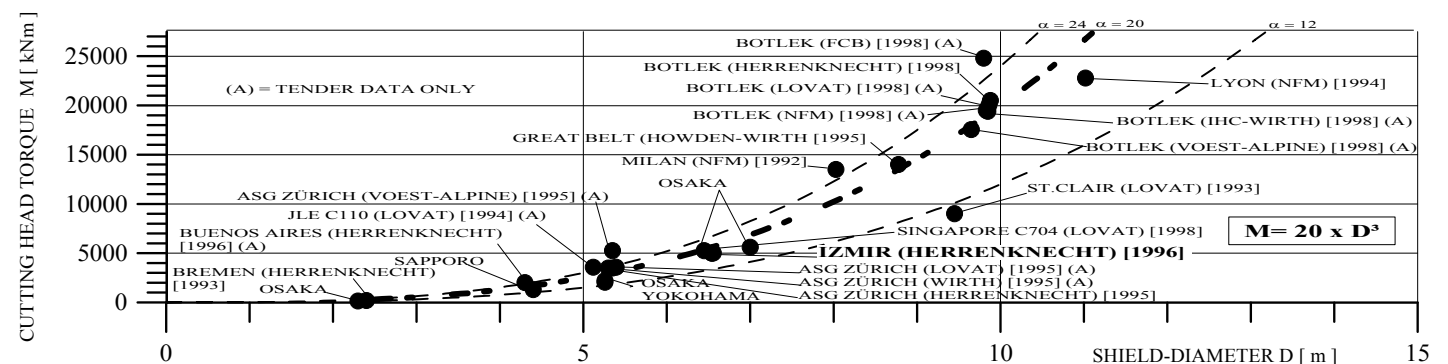
Torque of cutter head reflects best the effects of soil conditioning. The shield operators always tried to keep torque constant at an economic, material saving value. Therefore it was necessary to adjust the conditioning, when the torque rose. At first and second drive the torque was around 3500 kNm. At third and fourth drive in the silty clay of the sea-side soil the torque lied at approx. 2500 kNm. Figure 26 shows installed cutter head torque of various projects.

8 DIFFICULTIES

8.1 Usage of the polymer additives

Polymer additives are normally used to stabilize foam, to minimise wear of tool etc. The job site in Izmir had to face several problems with the application of the polymer additive. Examination of the foam generating process led to the conclusion that special care should be taken in the design of the mixing plant and the foam generation process. Bentonite slurry turned out to be an effective substitute

for polymers at this specific job site



8.2 Foam generating plant

The highly sophisticated foam generating plant was build in at the backup trailer behind the TBM. The parameters FER, FIR could be adjusted at any rate. Operating and maintenance of this complex 'machinery' was difficult. The highly erratic foam consumption curve in Figure 15 is a result of the complex technology used. It is obvious that severe difficulties had to be overcome.

8.3 Gravelly soil

As already mentioned, drive 1 and 2 had some short areas of gravel soil with very low quantities of fines. In these parts of the alignment it was difficult to keep the ground water out of the excavated soil. Regardless of foam and even bentonite conditioning problems arose due to the high water content in the muck. Fortunately these soil areas, which do not fit in the definition for an EPBM drive, were very short.

8.4 Standstill periods

Standstill periods are most critical in tunneling. They can either be due to technical reasons (e.g. maintenance works, breakdown etc.) or to organizational reasons (weekend, holiday etc.). A standstill has to be dealt with in terms of soil conditioning. After mining the excavated soil is mixed with a lot of air bubbles, in average 300 l/m^3 . Therefore foam conditioned soil is not stable for longer periods of time.

On the Izmir site this problems was overcome by changing the conditioning mode from foam to pure bentonite conditioning before any standstill. This ensured that air content in the muck decreased to an acceptable limit.

9 CONCLUSIONS

9.1 Laboratory Tests of Soil Conditioning With Foam and Foam/Polymer Additives

Without additives the Izmir type of soil was relative dense and could not be measured in any test due to its granular or sticky behavior. After addition of additives the soil became more fluid and plastic as shown by increasing slump values. The soil treated under these conditions could then be successfully managed by EPB tunnel boring machines.

The cone penetrometer tests showed that one surfactant type reacted well with the ground particles. It fulfilled the requirement of clay destructuring in order to avoid clogging problems.

Simple shear tests pointed out that the addition of foaming solution decreases in a significant way the

cohesion and internal friction of the soil - the effect is even stronger when foam (foaming solution + air) is added. The results are a significant lower power consumption (torque) and easier muck transport.

Concerning the environmental aspects we stated that modern additives for TBM use do not represent environmental dangers. They are not dangerous to aquatic organisms, are well biodegradable and in the used concentration not water hazardous.

9.2 Consequences for Application of EPB Tunnelling

The four drives at Izmir showed that classical measures of judging a soil to be suitable for EPB - tunneling have somewhat to be revised due to new methods of soil conditioning. Figure 27 is a reflection of current experiences. The shaded area represents the grain size distribution of the encountered soil C&M.

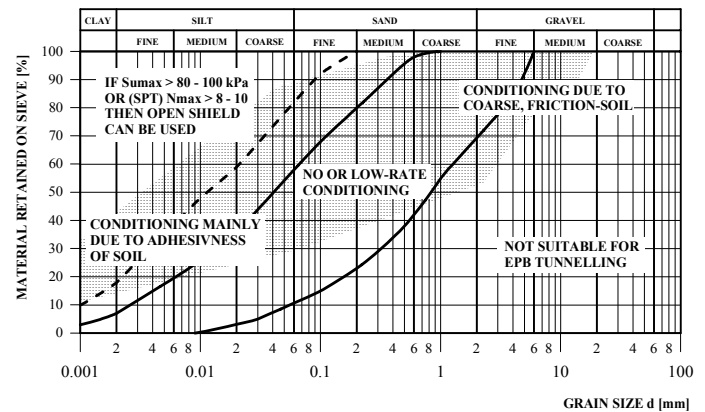


Figure 27. Limits for EPB - tunneling

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- NN Verband der chemischen Industrie. Allgemeine Verwaltungsvorschrift zum Wasserhaushaltsgesetz über die Einstufung wassergefährdender Stoffe in Wassergefährdungsklassen. Bundesrat, Bonn, Drucksache 782/98
- NN Zahn Wellens Test. Directive 87/302/EEC; OECD 302B