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TBM Tunneling in geotechnically and structurally sensitive Metropolitan Areas

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Abstract: Frankfurt, one of the most densely populated capitals in Germany, needed an extension of its Metro Line U5 from the main railway station towards the newly created district 'Europaviertel' which is part of an urban rehabilitation plan affecting over 30.000 people.

For the first time in Frankfurt, TBMs were used for metro construction. Driving in full EPB mode at up to 3,2 bar in clay and sand/clay mixed face geology with sensitive surface construction as well as the connection to the existing tunnel system from the 1970s makes this project unique.

Apart from the 2k annulus grout – first time implemented in Germany for a city tunnel project, EPB startup with a prefilled working chamber has been used very successfully together with highly ecologic tail sealants and soil conditioning system with minimum impact on the excavated soil.

Keywords: TBM; Soil Conditioning; Foam; Polymer; Tail Sealant

1. Introduction

In the city center of Frankfurt, the Joint Venture U5 Europaviertel consisting of the companies Porr and Stump, builds a dual tube tunnel on behalf of Stadtbahn Europaviertel Projektbaugesellschaft (SBEV GmbH). The extension the of the existing metro line U5 will connect the new 'Europaviertel' district with the central railway station. The Europaviertel is an urban rehabilitation project for the area of the old railway freight terminal.

Fig. 1 illustrates well the inner-city center situation of the jobsite as well as the fact that the TBM is underpassing numerous buildings and other critical infrastructure. In addition, the project is in very close distance to the river Main.

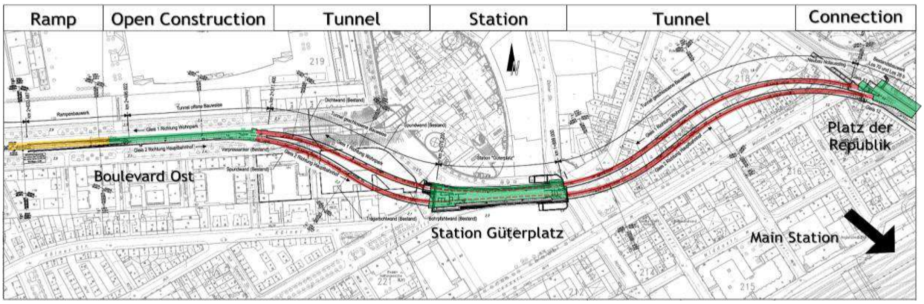

Fig. 1. Project overview, situation 2018.

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The paper focuses on the identification of sensitive environments like inner city launching shafts and spans the spectrum from examination of soil samples in the laboratory, proposing suitable solutions for the jobsite, implementing these solutions at site and optimizing them – all for one goal: safe and secure tunneling through highly populated urban areas without disturbance and technical difficulties.

2. Project Description

2.1. Project location

The project includes the construction of the inner-city metro extension of the metro line U5 and the underground connection to the existing metro network at Platz der Republik. Fig. 2 shows the Platz der Republik close to the Center Railway Station from 1888 (mid right), the worldwide known Frankfurt Fair buildings (center) and the new Europaviertel on the left side.

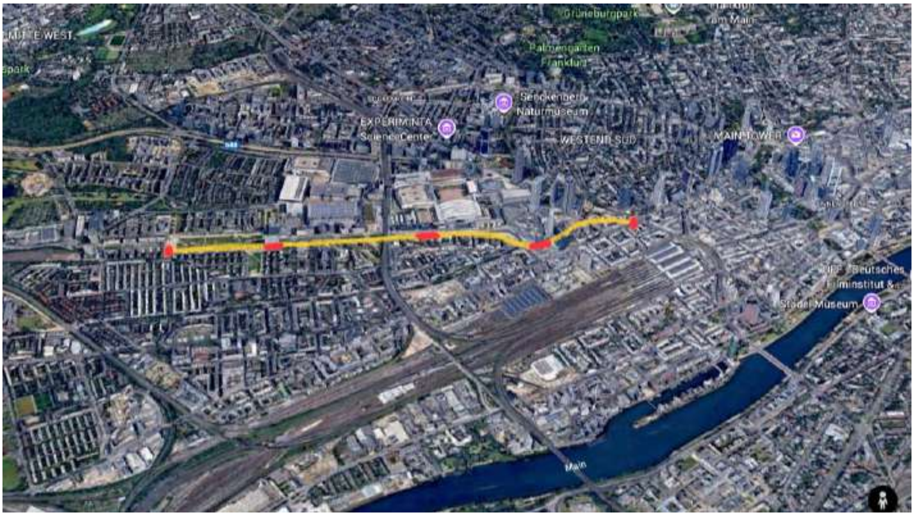


Fig. 2. Frankfurt City Center with river Main, the new Europaviertel district and the U5 extension line.

The metro extension will be build as a 186 m open construction section followed by a 2x830 m TBM section with two 7.10m outer diameter tunnels. For the connection to the existing metro tunnel, the TBMs will drive into a ground freezing area at Platz der Republik where they will be underground dismantled. The connection itself will be carried out conventionally by excavator under compressed air conditions supported by injections.

2.2. Geology

The geology in the metropolitan area of Frankfurt is generally characterized by cohesive soils with a high proportion of clay or silt and low permeability. Most of the project runs through “Frankfurter Clay” which is overlaid by 2 - 10m thick quaternary top layers of limestone and gravel, which is in the area of the excavation pit. Occasionally, sandstone formations up to 240 MPa can penetrate into the clay layer and also appear further along the planned TBM route, details are shown in Fig. 3.

Principally, the TBM drive can be divided into 3 main areas:

1. Start shaft to Station Güterplatz: mixed face conditions clay, sand, limestone
2. Station Güterplatz: 180m full face Frankfurt Clay, protected by sealing wall
3. Station Güterplatz to Frankfurt Main Station: full face Frankfurt Clay with Limestone layers

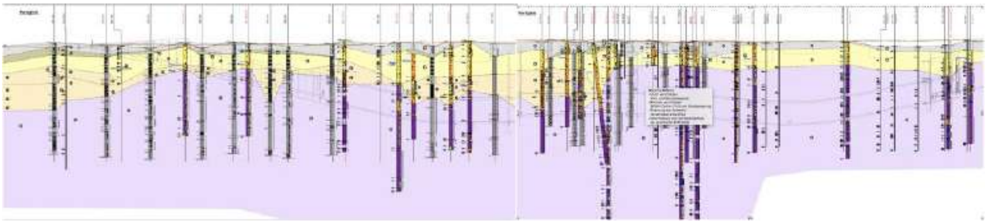
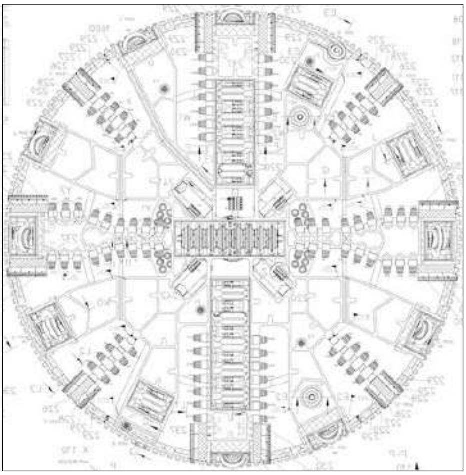


Fig. 3. U5 Extension geology: Frankfurt clay (purple) being dominant; sandstone, sand and gravel (yellow and grey).

2.3. TBM details

The U5 Extension project used a tunnel boring machine with earth pressure support (EPB TBM) which has been selected as ideal tunneling method for Frankfurt's Europaviertel. The TBM was baptized 'EVA' standing for "Europa-Viertel-Anbindung". The TBM has been already used in Doha (Qatar) for the Green Line Metro project and was refurbished and adjusted specifically for the U5 project in Frankfurt.

Due to the inner-city tunneling, very high demands were put into practice to minimize settlements. The support pressure of the shield machine had to be secured at any time according to the existing subsoil pressure as well as according to the existing loads to avoid settlement and the resulting damage of existing structures. Fig. 4 illustrates the used TBM cutterhead design and mentions further detailed TBM parameters.



Manufacturer	Herrenknecht (S-1127)
TBM type	EPB
Nominal diameter	7.1 m
Installed power	960 kW
Cutterhead torque	4133 kNm
Max. push force	36'500 kN
TBM length total	84.0 m
Weight	580 tons

Fig. 4. TBM cutterhead schematics and TBM details.

3. Flying TBM start – EPB pressure on the run

3.1. Startup situation

To drive the TBM into the ground, it had to drill first through a 1.20m thick trench wall as well as tough a 1.10m thick sealing block. The EPB design pressure for the untreated ground was 1.4-1,6 bar at the crown – mandatory to be reached already during blind ring No. 4 drilling through the sealing lamella. Fig. 5 describes the technical startup situation in the TBM launching shaft.

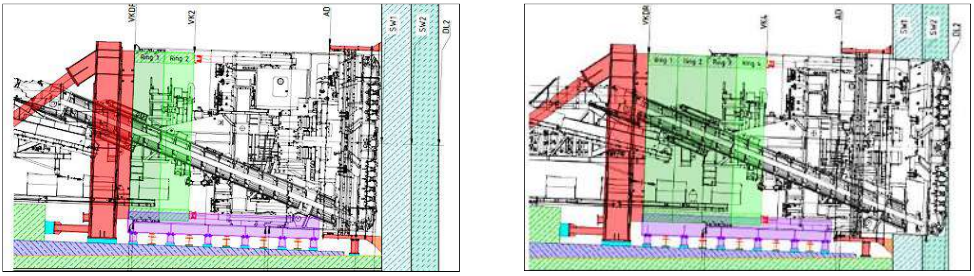


Fig. 5. (left) TBM start: cutterhead touching trench wall with blind ring No. 2; (right) TBM start: cutterhead touching untreated ground with blind ring No. 4.

3.2. Flying EPB start with ArtSoil™ technology

The aim of the Artificial Soil is to drive in a pressurized EPB mode through the remaining trench wall and sealing block into the ground. Just adding water and foam will not work and the addition of only Bentonite Slurry is not productive: The obtained rheology will be far to liquid to be handled on EPB machines, especially under pressure.

Therefore, MC proposed the use of an Artificial Soil based on HDSL Slurry together with the addition of a specialized MC Polymer (see Fig. 6):

HDSL Slurry + separate addition of **MC-Polymer**	**Hägermann Slump** Homogeneous paste with plastic behavior	**Hägermann Spread** 160mm

Fig. 6. Artificial Soil in different stages.

The HDSL was produced above ground with the existing grout plant and then pumped down to the TBM. Ideally, the Polymer will be mixed into the HDSL via Y-connector directly before running into the TBM working chamber.

3.3. Site use

The filling of the working chamber with artificial soil started with blind ring No. 3, reaching the top level and got pressurized on 2nd September 2019 early morning as shown in Fig. 7. During excavation of blind ring No. 4, the EPB pressure was rising to 1,5 bar crown pressure until end of the day. Pressure drops are a result of releasing the air with was remaining in the working chamber as well as releasing water – until no air bubble was left and the muck showed a homogeneous consistency.

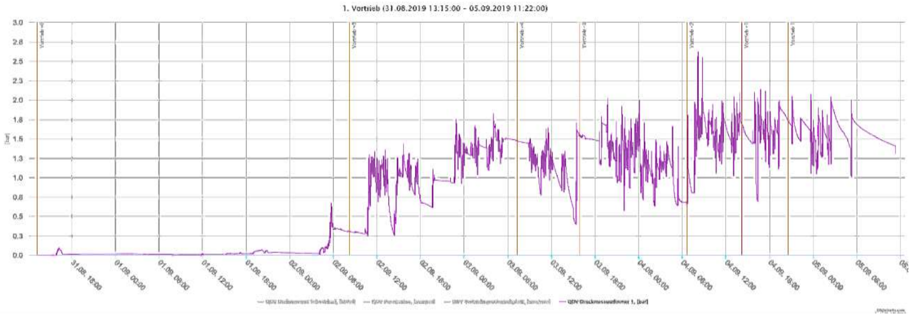


Fig. 7. Filling the TBM chamber and start of the 1st drive (pressure in bar over time / rings).

This procedure worked out very well and could guarantee a safe and secure full EPB start of the TBM out of the station into the challenging heterogeneous ground. This technology was used subsequently for all startup situations in Frankfurt as well as London City for example.

4. Soil conditioning – from laboratory to reality

As indicated already, the Frankfurt Clay is the predominant geology for the project. Especially the startup phase shows mixed face conditions of Frankfurt Clay, sand and gravel up to 25%.

Aims of the laboratory trials were

- Choice of the right foam type
- Determining the clogging risk
- Determining the amount of additional water if necessary
- Determining the best starting parameters concerning FER and FIR

4.1. Laboratory trials for full face Frankfurt Clay at Güterplatz

The Güterplatz area and the final drive towards the existing tunnel is characterized by full face Frankfurt Clay as shown in Fig. 8.

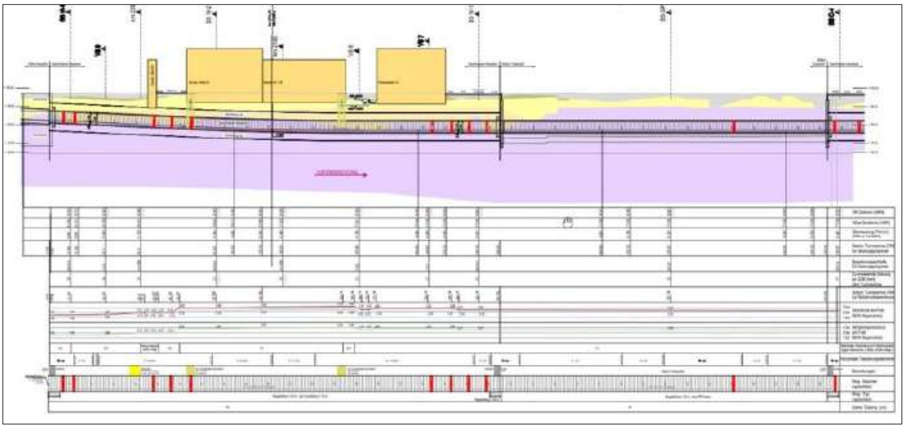


Fig. 8. Frankfurt Clay at Güterplatz, freshly hand-excavated.

Fig. 9. Frankfurt Clay at Güterplatz, freshly hand-excavated

Atterberg Limits of Frankfurt Clay (according to DIN 18122; samples taken from d-walls Bldv. Ost 2017 and Güterplatz 2020):

- Natural humidity Güterplatz : 34-45%, approx. weighted average 35-39%
- Plastic Limit (wP) : 25-56%, approx. weighted average 27-39%
- Liquid Limit (wL) : 74-108%, approx. weighted average 74-91%

The Atterberg Limits indicate a quite high clogging risk for this type of geology. In consequence, the aim of the soil conditioning is to reduce the clogging risk in general, particularly keeping the cutterhead openings free, allow the muck flow through the cutterhead into the working chamber and allow a consistent TBM advance speed.

To achieve these goals, the anti-clay soil conditioning foam MC-Montan Drive FL04 was used in a higher concentration and higher FIR than necessary for soil 4b, also the addition of water was found to be beneficial.

Again, the tasks of the laboratory tests are to find the correct starting parameters for the TBM. Once the clay clogging occurs on the cutterhead and in the working chamber, it can in most cases only be cleaned by intervention. Therefore, the TBM startup should be realized with an exceeding soil conditioning avoiding any kind of problem.

Proposal for TBM parameters after laboratory test results with MC-Montan Drive FL04:

- cF 2-4%
- FER 10
- FIR 80-120 → approx 150l/ring of foam concentration
- WIR 5-7% → approx 4.8-6.5m^3/ring additional water

4.2. Jobsite soil conditioning results

Since the Frankfurt Clay is the predominant geology, the following site examples are taken from the Güterbahnhof section, the TBM advancing full face in Frankfurt Clay.

Because the TBM is operating in semi-automatic mode, the laboratory soil conditioning results from chapter 4.1 need to be translated into flow rates for 2 different TBM target speeds.

Quantity range in l/min at 20 mm/min TBM speed

Foam	Water from the foam	Additional water	Foam FL 04
800-964	76-92	68	3,2-4,3

Quantity range in l/min at 25 mm/min TBM speed

Foam	Water from the foam	Additional water	Foam FL 04
1.005-1.205	96-115	85	4,0-5,4

The following Figures 10 and 11 illustrate the Foam and Water consumption of the TBM starting out of the Güterplatz Station over 100 rings and puts them in relation to the TBM speed.

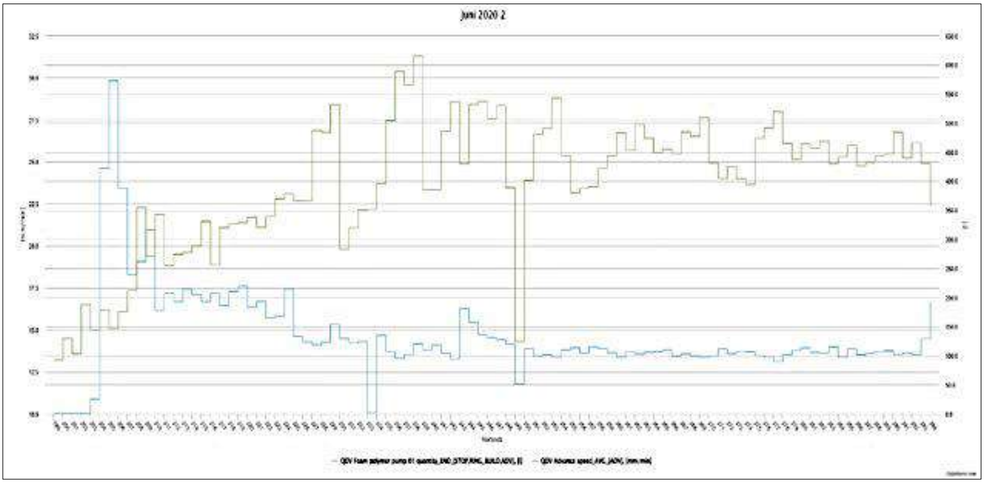


Fig. 10. TBM speed (green, mm/min) vs Foam consumption (blue, l/ring) Ring No. 199-294.

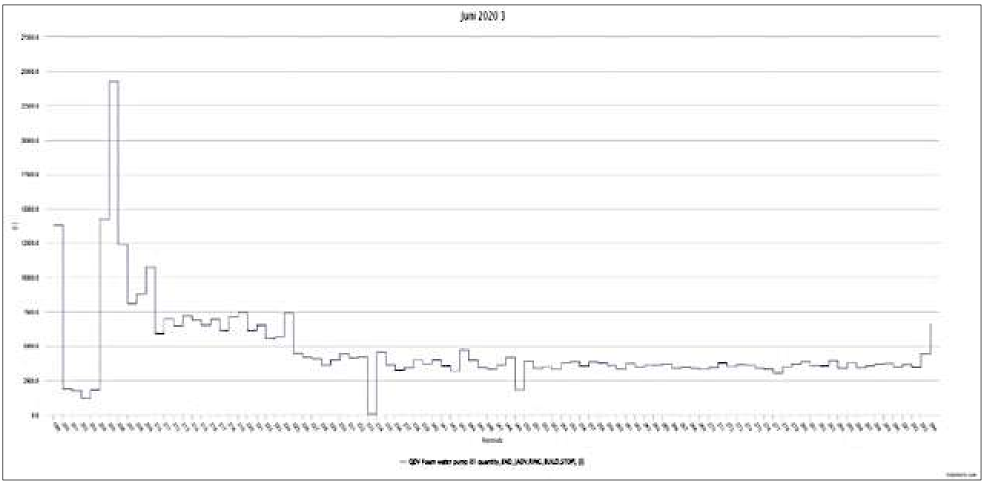


Fig. 11. Water addition (liters / ring), Ring No. 199-294.

On site optimization of the soil conditioning parameters result in speeding up the TBM to 20-22,5 mm/min and reducing the soil conditioner quantity by optimizing its efficiency. After some 20 rings, the TBM speed was subsequently increased to 25-30mm/min since the machine was running fine, reducing simultaneously the soil conditioner use from 200 l/Ring to 100-150 l/Ring.

The findings from the laboratory testing were confirmed and the TBM was driving steadily with excellent advance rates without any problem.

The TBM steady speed of 25-30 mm/min in Frankfurt Clay could be easily maintained even with TBM crown pressures of around 2 bar. Also the pressure level itself could be easily maintained, no air bubble in the crown level could be detected. The water injection was initially set to 6m^3 per Ring to start on the safe side. It could be further reduced due to the smooth TBM operation to around 4m^3 per Ring, the lower end of the laboratory findings (see Fig. 11).

Fig. 12. Conditioned Frankfurt Clay at station surface, June 2020.

The soil could be easily excavated and transported by muck cars, the muck car emptying process was without any difficulties. The further manipulation with excavators and truck loading, truck transport and transfer to barge carriers was smooth and without any problems (see Fig. 12).

4.3. Muck analysis

For environmental and disposal reasons, the excavated and conditioned muck underwent a environmental screening process. The test results given in Fig. 13 describe the effects of the soil conditioning, comparing values for the unconditioned soil with conditioned soil after 1 day as well as 4 days.

Soil conditioning parameters used for the following muck analysis:

MC-Montan Drive FL 04, cF=2.5%, FER=10, FIR=80, WIR=6.5%

Parameter	Einheit	Gehalt (bezogen auf die Trockensubstanz)					
		Null-1	Null-2	1d-1	1d-2	4d-1	4d-2
Arsen	mg/kg	33	31,2	23,7	21	29,7	26,3
Blei		20	21	18	17	21,0	21,0
Cadmium		< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
Chrom (gesamt)		53	56	47	52	50	51
Kupfer		24	25	22	22	24	24
Nickel		49	50	45	43	46	47
Thallium		0,4	0,4	0,3	0,4	0,4	0,4
Quecksilber		< 0,07	0,08	0,07	< 0,07	< 0,07	0,07
Zink		77	76	68	67	73	75
TOC	M.-%	8,9	5,57	8,29	8,6	8,09	8,75
EOX		< 1	< 1	< 1	< 1	-	-
Kohlenwasserstoffe C_{10} - C_{22}		< 40	< 40	< 40	< 40	< 40	< 40
Kohlenwasserstoffe C_{10} - C_{40}		< 40	< 40	< 40	< 40	< 40	< 40

Parameter	Einheit	Gehalt (bezogen auf die Trockensubstanz)					
		Null-1	Null-2	1d-1	1d-2	4d-1	4d-2
pH-Wert [1]	-	7,99	7,29	8,2	7,86	7,55	7,84
Leitfähigkeit	µS/cm	443	592	510	583	942	755
Natrium	mg/L	36,0	23,0	83,0	84,0	117,0	95,0
Kalium		20,0	22,0	19,0	26,0	26,0	22,0
Calcium		15,4	21,4	19,4	20,4	43,0	25,9
Chlorid [2]		19,3	17,8	17,9	18,8	22,2	18,5
Sulfat [2]		102	146,7	120,8	128	311	260
Fluorid		0,4	0,3	0,5	0,4	0,4	< 0,1
Cyanide [3]		5	3	2	5	5	5
Arsen		2	3	3	2	2	2
Blei		< 1	< 1	< 1	< 1	< 1	< 1
Cadmium		< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3
Chrom (gesamt)		< 1	< 1	< 1	< 1	< 1	< 1
Kupfer	µg/L	< 5	< 5	< 5	< 5	< 5	< 5
Nickel		2	2	2	3	2	2
Thallium		< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
Quecksilber		< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
Zink		30	80	< 10	< 10	< 10	20

Fig. 13. (left) Solid content test results (excerpt) of conditioned Frankfurt Clay; (right) Eluate test results (excerpt).

None of the results show a significant change due to the soil conditioning, no metals were mobilized and even the TOC in the solid content test did not change really.

The Eluate results show only an increased Na content due to the soil conditioner used. The Sulfate values vary a lot even in the untreated soil, an indicator for geogenic soil contamination (see also chapter 5. annulus grout). The conductivity results are influenced accordingly.

5. 2-k Annulus Grout

For the first time in in a German inner city project, 2k annulus grout has been used.

5.1. Requirements & Formulation

The concerns on durability, lifetime and on ecologic aspects were high. Therefore, a sulfate resistant CEM III has been used for the annulus grout.

Formulation

Cement (CEM III/A 52,5N-HS/NA)	200 kg/m^3
Bentonite	40 kg/m^3
Water	883 kg/m^3
Plasticizer Grout 02	10 kg/m^3
Accelerator	103 kg/m^3

Gel time:	10-15 sec
Bleeding:	< 3% after 24h
Shear strength:	2h:98 kPa*s; 4h: 120 kPa*s; 6h: 185 kPa*s
Compr. strength:	24h: 1.5 N/mm^2; 7d: 1.8 N/mm^2; 28d: 3.1 N/mm^2

5.2. Ultrasonic fault detection

Various tests were carried out to check if the annular gap was completely filled with 2-component grout. Because of the high groundwater pressure and in order not to damage the segments, the use of control drillings was minimized.

An ultrasonic measuring device was used as an equivalent measuring method. This device was calibrated before each measurement on a sample segment (width 1.2m, thickness 0.45m). It was taken 3 measurements per ring and on over 150 rings per tube.

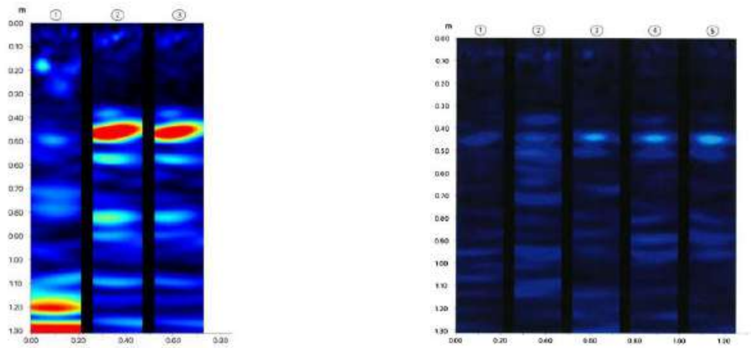


Fig. 14. (left) Ultrasonic reference measurement; (right) Ultrasonic site measurement of ring No. 80.

The reference measurement in Fig. 14 left shows well the segment concrete material (dark area from 0-0.45m), the gap (red area at around 0.45m) as well as the different material from 0.50m onwards. The site measurement of ring No. 80 (Fig. 14 right) indicates well again presence of the 3 different materials (segment, annulus grout, soil) without detection of any gap area which would be colored in red.

6. Tail Sealants

The U5 extension project used the highly ecologic MC-Montan Seal ST11 tail sealant, based on renewable oils and exempt of plastic fibers to protect the environment as best as possible.

Furthermore, HDT 200 T press plate pumps were plug and play installed on the gantry to ensure an almost revision free pumping (see Fig. 15). For the whole project, the sealing sets had to be replaced only once for the total of the 2 drives.

Fig. 15. HDT 200 T press plate pump installed on Herrenknecht gantry.

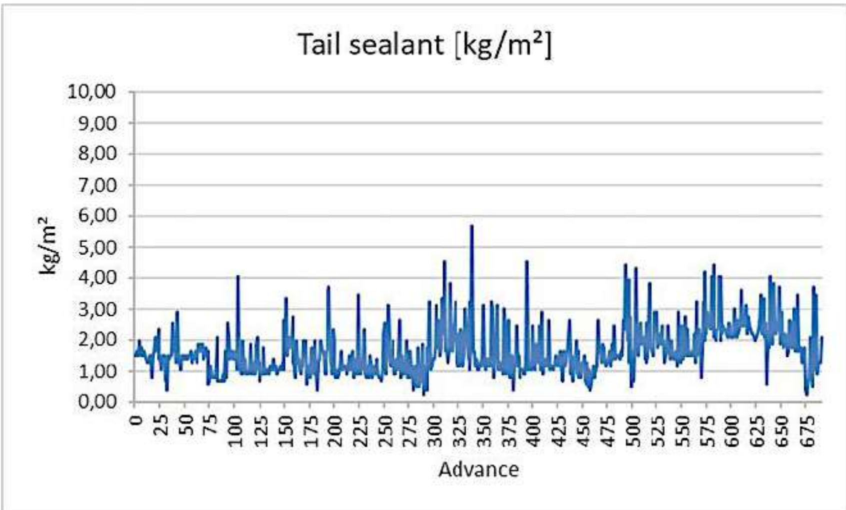


Fig. 16. Tail Sealant consumption in kg/m2 over the project rings.

The ST11 tail sealant worked very well with prefect consumptions rates (see Fig. 16) compared to the industry benchmark – despite relatively high EPB pressures and relatively liquid 2k annulus grout used. Over the whole project, the medium consumption reached 1.6 kg/m^2 segment surface.

7. Conclusion

The flying EPB start with artificial soil was as easy as efficient. It has been successfully repeated already at other jobsites.

The laboratory soil conditioning proposal with respect to the TBM parameters gave perfect and safe starting conditions for each main geology, avoiding clogging from the beginning. Only small scale-up adaption was realized on site – reducing the proposed foam and water consumption. The decision to drive the TBM with a steady speed especially within the clay section was definitely the right one, cutterhead and working chamber blockage was very successfully avoided even under high EPB pressures throughout the whole project by using adapted anti-clay foam. That illustrates quite well that detailed laboratory testing prior to the project execution saves time and money and also increases significantly the safety of tunneling.

The used 2k grout worked perfectly in inner-city conditions, the use of sulfate resistant cement – which has never been used before for such a project - did not lead to any difficulties.

The tail sealant pumps worked well under all conditions with just 1 service; and the highly ecologic tail sealant was as efficient as the industry standard, with bonus points for using renewable raw materials and easy acceptance from the authorities – similar than for the soil conditioning chemicals.

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