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# Frankfurt U5 metro extension – the challenging high pressure inner city project

T. Schade & R. Iffländer
*PORR GmbH & Co. KGaA, Düsseldorf, Germany*

L. Langmaack & D. Uhlmann
*MC-Bauchemie GmbH & C. KG, Bottrop, Germany*

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.

## 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.

## 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.

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. The majority of the project runs

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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.

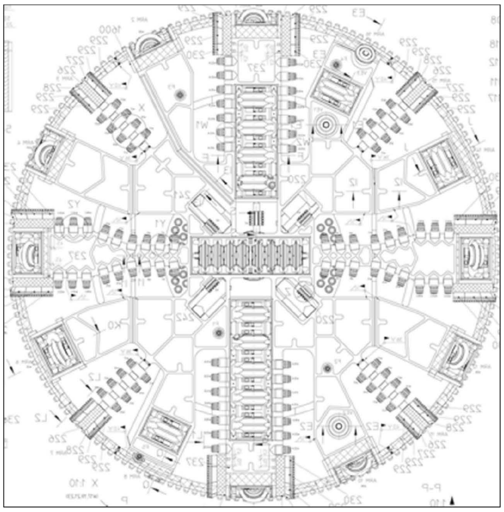
Principally, the TBM drive can be devided into 3 main areas:

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

### 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 in order 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 in order to avoid settlement and the resulting damage of existing structures.



| | |
|---|---|
| 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 |

Figure 1. TBM cutterhead schematics and details.

## 3 FLYING TBM START – EPB PRESSURE ON THE RUN

### 3.1 *Startup situation*

In order to drive the TBM into the ground, it had to drill first through a 1.20m thick trench wall as well as though a 1.10m thick sealing block. The EPB design pressure for the untreataed 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.

### 3.2 *Artificial soil: Idea & formulation*

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 handeled on EPB machines, especially under pressure.

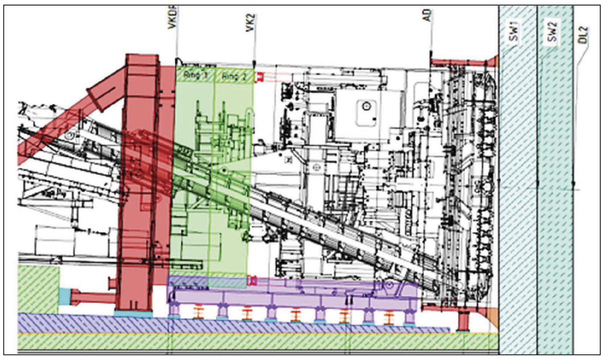


Figure 2. TBM start: cutterhead touching trench wall with blind ring No. 2.

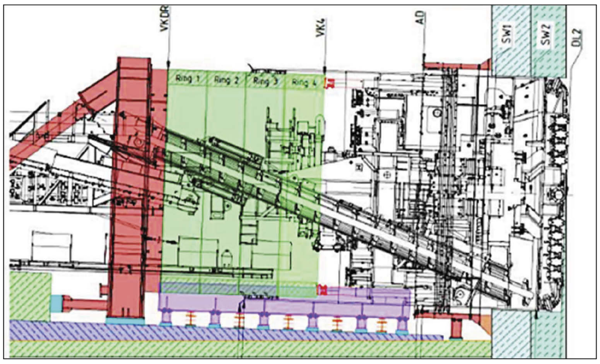


Figure 3. TBM start: cutterhead touching untreated ground with blind ring No. 4 .

Therefore, MC proposed the use of an Artificial Soil based on HDSL Slurry together with the addition of a specialized Polymer MC-Montan Drive LB02:

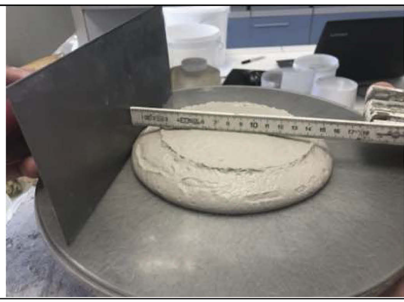
|  |  |  |
|---|---|---|
| **HDSL Slurry**<br>+ separate addition of<br>**MC-Montan Drive LB02** | **Hägermann Slump**<br>Homogeneous paste with plastic behavior | **Hägermann Spread**<br>160mm |

Figure 4. Artificial soil.

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. 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.

## 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%. The corresponding lab trials are shown in chapter 3.2.1. The lab trials for full face Frankfurt Clay are shown in chapter 3.2.2.

Aims of the laboratory trials were:

- Choice of the right foam type
- Determining the clogging risk
- Determining the amount of additional water if necessary
- Dertermining 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 characterised by full face Frankfurt Clay.

Atterberg Limits of Frankfurt Clay (according to DIN 18122; samples from d-walls Bldv. Ost 2017 & 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%

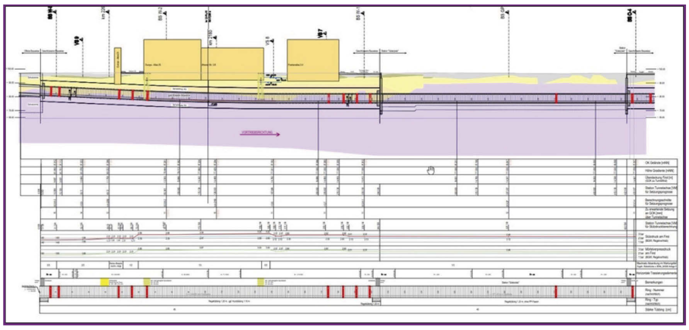


Figure 5. Geology at Güterplatz.

Figure 6. Frankfurt Clay at Güterplatz, freshly hand-excavated.

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.

In order to achieve these goals, the anti-clay 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 occurrs 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 problems.

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% by weight → 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. Due to the fact that the TBM is operating in semi-automatic mode, the laboratory soil conditioning results from chapter 3.2.2 need to be translated into flow rates for 2 different TBM target speeds.

Table 1. 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 |

Table 2. 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 |

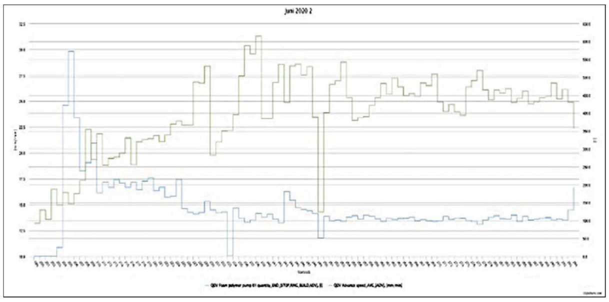


Figure 7. TBM speed (green, mm/min) vs Foam consumption (blue, l/ring) Ring No. 199-294.

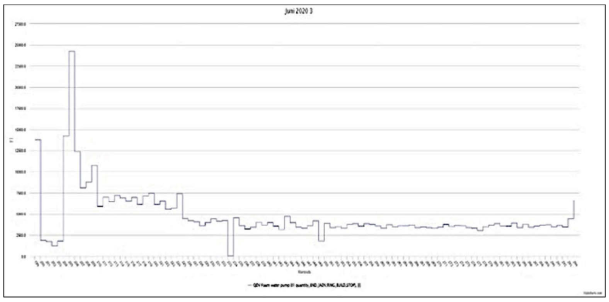


Figure 8. Water addition (litres/ring), Ring No. 199-294.

TBM screenshots from the drivers cabin were taken from Ring 207 onwards. 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 6m3 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 Figure 8).

Figure 9. 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 Figure 9).

### 4.3 *Unforeseens*

Sometimes – when everything runs according to plan and – things may change nevertheless.

Figure 10 illustrates the standard TBM power consumption driving in flull face clay conditions with a quite steady level of around 50%. As reference for the soil conditioning the Foam consumption is used at quite steady level of 3 l/min.

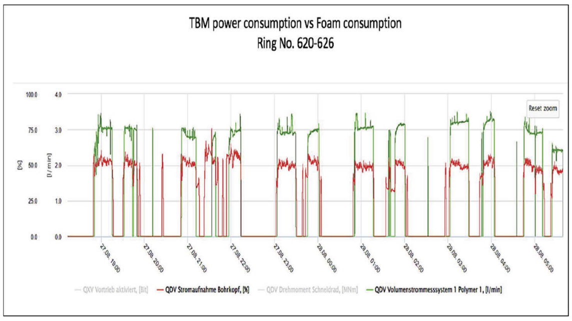



Figure 10. TBM electric power consumption vs Foam consumption, Ring No. 620-626.

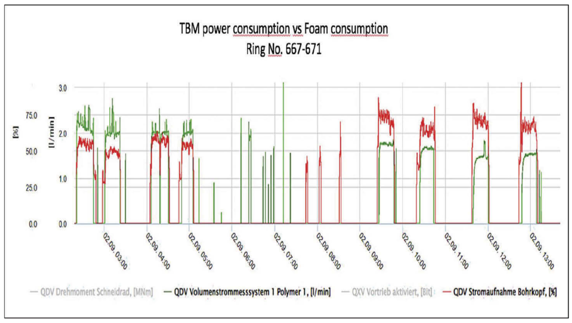



Figure 11. TBM electric power consumption vs Foam consumption, Ring No. 667-671.

What happens if all TBM driving parameters remain the same, the soil remains the same and the TBM power consumption rises from 50% to 60% and finally 75%?

Figure 11 illustrates well this increase in power consumption – and it took a while to realise that a worn out foam dosage pump was not delivering the quantity of foaming concentrate as she was supposed to deliver: The flow was reduced subsequently from the normal 3l/min target value to 2.5 l/min down to 2.0 l/min. As stated already, the TBM soil conditioning parameters at the drivers screen were kept identical and no error messages occurred – so the malfunctioning went on a while before being detected.

After replacing the posage pump and delivering the correct foam quantities, the power consumption went back to normal. This is also a quite nice example of the efficiency of the foam use.

## 4.4 *Muck analysis*

For environmental and disposal reasons, the excavated and conditioned muck underwent a environmental screening process. The test results given in figures 32 and 33 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 | | 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 | mg/kg | 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 |

Figure 12. Solid content test results (excerpt) of conditioned Frankfurt Clay.

| 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 | 7,66 | 7,55 | 7,84 |
| Leitfähigkeit | µS/cm | 443 | 592 | 510 | 583 | 942 | 755 |
| Natrium | | 36,0 | 23,0 | 83,0 | 84,0 | 117,0 | 95,0 |
| Kalium | | 20,0 | 22,0 | 19,0 | 25,0 | 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 | 18,6 | 22,2 | 18,5 |
| Sulfat [2)] | | 102 | 146,7 | 120,8 | 128 | 311 | 260 |
| Fluorid | mg/L | 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 | | < 5 | < 5 | < 5 | < 5 | < 5 | < 5 |
| Nickel | | 2 | 2 | 2 | 3 | 2 | 2 |
| Thallium | µg/L | < 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 | 60 | < 10 | < 10 | < 10 | 20 |

Figure 13. 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 soilid 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 untreaed soil, an indicator for geogenic soil contamination (see also chapter 3.3.1 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$^3$ |
| Plasticiser 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.

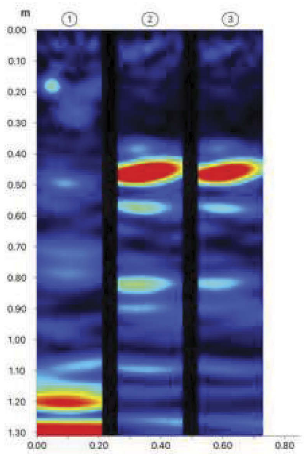



Figure 14. Ultrasonic reference measurement.

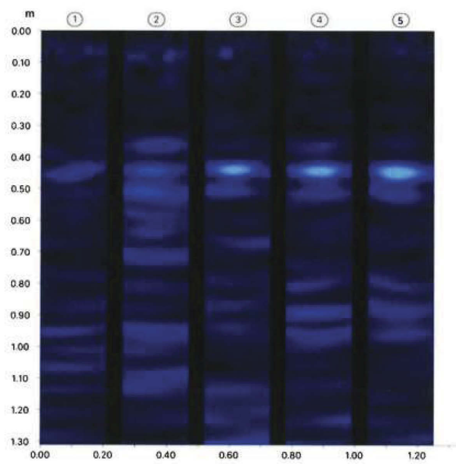



Figure 15. Ultrasonic site measurment of ring No. 80.

The reference measurement in Figure 14 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 (Figure 15) indicates well again presence of the 3 different materials (segment, annulus grout, soil) without detection of any gap area which would be coloured 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 fibres 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. For the whole project, the sealing sets had to be replaced only once for the total of the 2 drives.


Figure 16. HDT 200 T press plate pump for tail sealants.

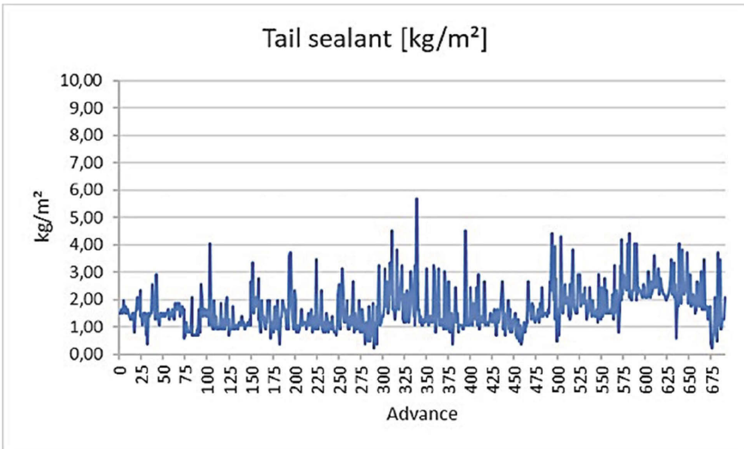



Figure 17. Tail Sealant consumption in kg/m$^2$ over the project rings.

The ST11 tail sealant worked very well with identical consumptions rates 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 COMPRESSED AIR WORKS

Towards the end of the TBM tunnels at the Platz der Republik, one of the city‘s most important traffic junctions, the new tubes are connected to the existing underground structure. As part of this connection, the shield of each EPB-TBM being used will remain in the ground. Originally, for the last stretch of tunnel between the segmental tunnel and the existing structure, the production of a DSV sealing block from the terrain surface and ground freezing bores from the existing structure were planned. Under the protection of these measures, the construction gap should be closed using conventional tunnelling.

To keep all traffic be maintained at the junction, the planning was optimized and implemented jointly by the client and contractor in such a way that the connection to the existing underground structure at Platz der Republik was fully mined without any significant above-ground activities.

However, due to unexpected obstacles, the mining connection to the existing structure had to be adjusted and partly replanned during the ongoing tunneling.

A lowering of the ground water, as realized in the past of the Frankfurt subway construction, is no longer executable today in terms of approval law. For this reason and the requirement for redundant security systems, implemented for each individual construction phase, the essential components of the final mining solution are slightly modified injection measures compared to the original planning, the adaptation of the freezing bodies that were planned anyway, and the targeted use of compressed air. Especially the compressed air works including cutterhead disassembly (hot works), the conventional tunnel driving and creating of the inner lining made high demands on the safety concepts. The works took place under a pressure of 1.5 bar.

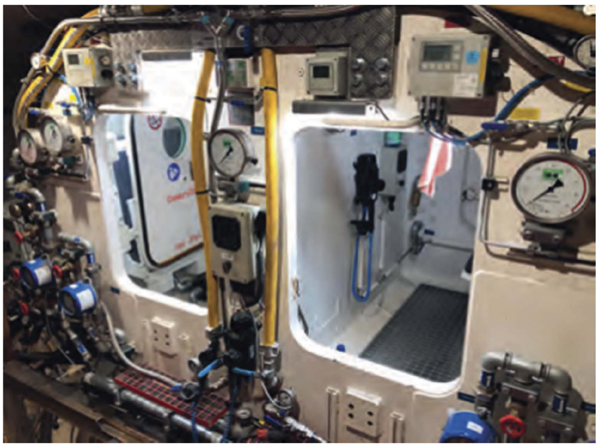


Figure 18. Air lock.

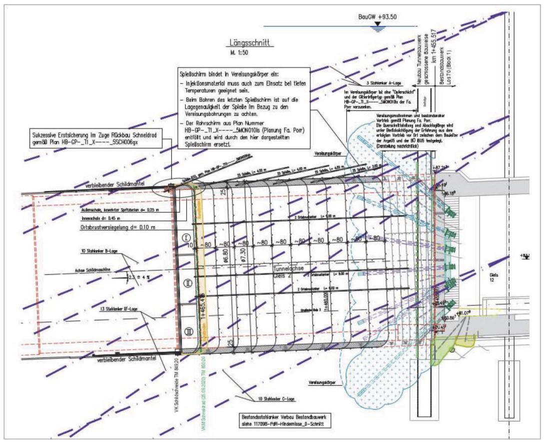


Figure 19. Design of the conventional tunnel drive to link with the existing structure.

## 8 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.

The used 2k grout worked perfectly in inner-city conditions, the use of sulfate resistant cement 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 industy standard, with bonus points for using renewable raw materials and easy acceptance from the authorities – similar than for the soil conditioning chemicals.

The compressed air works are successfully ongoing, the disassembly of the 2 TBMs worked as planned where as the original planning of the freezing bodies needed to be adapted to the actual conditions.