EPB tunnelling in hard rock conditions and transition zones.

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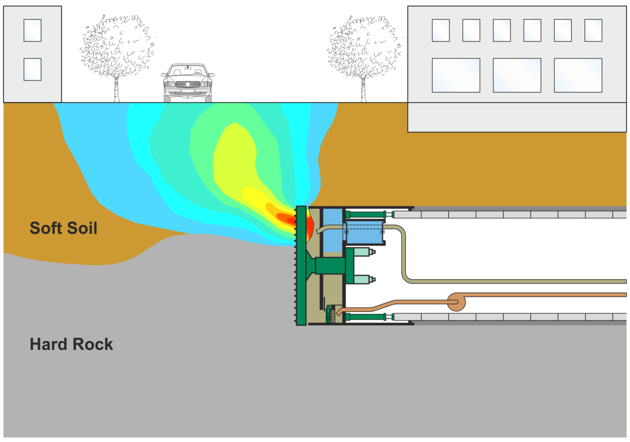
ABSTRACT: Various TBM projects around the world are digging in predominantly hard rock conditions – facing difficulties when weathered rock or even soft ground zones penetrate the tunnel profile. To tunnel through these „weak zones", like in Oslo centre, is a risk to the environment and causes high costs for treating the soil or additional measures if not handled properly.
So far, only one TBM project has used an Earth Pressure Balance (EPB) TBM to ensure a safe face pressure in the transition zones from hard rock to soft ground and vice versa. The use of special admixtures and other additional measures enabled safe and controlled tunnelling through these difficult zones, maintaining perpetual earth pressure and thus avoiding settlements.

1 INTRODUCTION

Tunnelling with tunnel boring machines (TBM) has become the preferred excavation method for infrastructure and utility projects worldwide. While tunnelling through homogenous ground (hard rock or soft soil) is more and more standard and less incidents occur, mixed face conditions are still challenging. Especially mixed face situation where hard rock in the lower part and soft ground at the top of the excavation face is present, a lot of precaution has to be taken. The hard rock is slowing down the excavation and the soft ground needs to be supported in order to avoid over excavation, settlements or sinkholes. Generally transition zones are easier to handle with a Slurry-TBM. But if a long hard rock stretch has to be tunneled as well, the advantage of the easy support is eaten by the high wear which will occur, while the EPB TBM could drive in open mode. Thus, the EPB-TBMs have to plastify the hard rock into earthpaste, which is necessary to work as a support media.



Picture 1: Settlements in mixed face conditions

Nevertheless, there might be reasons to choose a EPB TBM even though transition zones or mixed face conditions are present. EPB TBM encounter the lack of fines in hard rock stretches as difficulty to create a proper earth paste. The EPB tunnelling method needs a proper earth paste to ensure the required face pressure and stability of the face. The earth paste has to be plastic in order to transfer the pressure onto the face, to flow through the cutterhead, to be extracted by the screw conveyor but to have enough internal friction in the screw to reduce the pressure from face pressure at the entrance of the screw to atmospheric pressure leaving the screw. The preferred type of ground for EPB tunnelling is cohesive clayey soft ground. It bears a large surface for water and tensides to connect and reduce the cohesion, making the soil plastic.

Picture 2: Well-conditioned soil

With the shown earth paste the requirements for safe tunnelling with no settlements and efficient tunnel drive are easy achievable. By adapting the air content, water content and additive type and content, the behavior of the earth paste is controllable and adaptable to the optimum for efficiency.

Picture 3: Cutterhead in hard rock conditions

When it comes to hard rock tunnelling the conditions for EPB tunneling change dramatically. Some authors even describe hard rock as not to plastify and therefore not possible for EPB tunnelling. In the following the first and only project worldwide which successfully has proven that hard rock can be excavated with real EPB mode (face pressurized) will be described. The project, the preparations and lessons learnt will be demonstrated in the following.

This project demonstrates that with a proper system the borders of EPB tunnelling can be pushed further.

2 EXAMPLE PROJECT KAISER WILHELM TUNNEL, GERMANY

2.1 *Description of the Project*

The 2-track Kaiser Wilhelm Tunnel, which opened in 1879, is located on the Coblenz-Perl Moselle rail route between Ediger-Eller and Cochem, and is an important part of the Trans-European Network (TEN for conventional traffic). To renew the old tube a new tube was built and used in 2 direction. After renewing the old tube both tubes will be used each for one direction. Due to the very narrow valleys the new tube was located very tight to the existing tunnel and the station in Cochem.

Picture 4: Both tunnels at Cochem station, source Deutsche Bahn

The mechanised drive for producing the 4,242 m long New Kaiser Wilhelm Tunnel was successfully completed with the breakthrough on November 7, 2011.

2.1 *Description of the geology*

The geology in the project started at the launch area with a hard rock stretch consisting out of clay shale and claystone from the Rheinischen Schiefergebirge.

Picture 5: Cutterhead in hard rock section

This sedimentary hard rock has layers and fissures, is quarzit bonded with blocks.

The soft ground area was supposed to be in the last 250 m of the drive underneath the Uptown of Cochem. It consists of weathered rock, to gravel silt and silt.

2.2 *Description of the TBM*

Due to above mentioned geology and the necessity to support the face in case of instabilities, an EPB TBM was chosen, knowing that it will drive long stretches in open mode. As short overview the technical data of the TBM in a chart:

Excavation Diameter	10.15	m
Shield Diameter	10.10	m
Length incl. Backup	99	m
Gross weight	1710	t
Max. Thrust	67.557	kN
Cutterhead tools		
Disccutters 17”	60	pcs
Scrapers	184	pcs
Foam ports	8	pcs

The concept for this drive required a TBM which could switch between Open Mode with no face pressure and Closed Mode (EPB-mode with face pressure) in less than 30 minutes.

To be able to drive long sections in hard rock with this more EPB type TBM it was necessary to adapt the cutterhead for both geologies. Beside the above mentioned cutting tools the cutterhead was protected by huge passive wear protection, especially close to the openings a lot of additional wear plates have been installed. Additionally, a hydraulic wear detection system with 5 single point sensors was installed.

For the conditioning of the soil or rock 8 foam nozzles have been installed, which as well could redirect the foam into the screw for lubricating and building up a plug.

Picture 5: Cutterhead

The cutterhead had a closed rim, was retractable and tiltable for overcut. The muck was extracted by a screw conveyor with a gate valve at the end. The screw itself was retractable to isolate the excavation chamber totally.

3 HARD ROCK SECTION / TBM DRIVE EXPERIENCE

3.1 *Advance in Hard Rock conditions*

The main portion of the New Kaiser Wilhelm Tunnel had to be driven in hard rock conditions. The contract had foreseen to drive this stretch in open mode, only short fault zones were to be tunneled in closed mode.

The hard rock stretch was mainly excavated by the disc cutters. The breaking of the rock by the disc cutters produced a lot of fines. To avoid clogging of fines and rock chips the muck was excavated dry. Even during maintenance, no water was used to clean the disc cutters. Only for creating an additional wear protection some water was injected for clogging in front of the cutterhead structure. These measures prevented clogging of the soil in the excavation chamber. For dust reduction, a small amount of water was injected in the middle of the screw conveyor to fulfill the hygienic regulations underground.

3.2 *Unpredicted geology*

There were many more fault zones in the hard rock stretch of the project. Some were merely approx. a meter long, but they led to disturbances during excavation and created over-excavation.

3.3 *Fault zones*

Several fault zones had been predicted and known by pre-investigation. The TBM started in hard rock conditions in open mode and was supposed to continue in open mode as the overburden reached quickly more than one hundred meters. But after roughly 50 m the TBM reached the first fault zone, which had not been predicted; the first change of tunneling mode became necessary. After some over-excavation, the TBM was switched to closed mode. Nevertheless, settlements occurred and had to be stabilized by injection. Finally, the TBM could stabilize the face and continued in closed mode.

3.4 *Lessons learnt*

Key factor to reduce risk and ensure safe tunneling was the development of criteria to change from open mode to closed mode. After some optimizations, this worked very well and the duration to fill the excavation chamber and pressurize it was within the limit of 30 minutes. Main criteria for changing from open to closed mode was the power consumption of the main drive and the balance of mass. While the power consumption is directly retrieved from the data acquisition system of the TBM, the mass balance had to be measured by two conveyor scales and compared to the theoretical mass. As soon as one of the alarm values was reached closed mode was selected.

4 TRANSITION ZONE TO SOFT GROUND / TBM DRIVE EXPERIENCE

The technically most difficult area of the mechanised drive in tunnelling terms, was the EPB mode section located uptown Cochem (Figure 1). Switching from open hard rock mode to full EPB mode (below house No. 28) was a challenge – especially at this location.

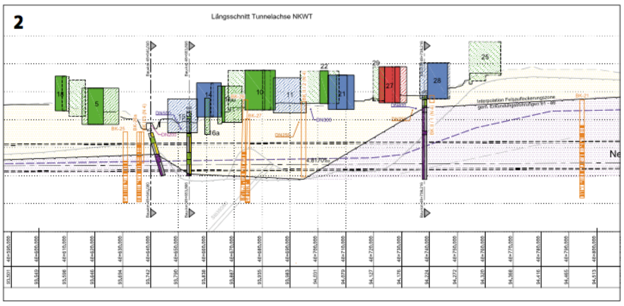


Figure 1: Longitudinal section uptown Cochem, driving direction right to left

Buildings with a minimum distance of 3.2 m from the tunnel roof had to be undercut with minimal settlements allowance. This was the first time this driving method was applied anywhere in the world, for under-tunnelling a built-up area with such slight overburden. What made circumstances even more difficult was that mixed face conditions appeared in this area: On the one hand rock face, on the other soft ground. The damages recordings taken during the preservation of evidence, proved that the structural state of the affected houses was critical for tunnelling.

Related to the events discussed in chapter 3.3, it was decided to switch into full EPB mode already within the hard rock section: Advance the TBM with completely filled and pressurized working chamber into the fault zone. Laboratory tests had to be carried out to cross-check the technical possibilities and determine the necessary soil / rock conditioning process.

4.1 *Laboratory tests for enabling EPB mode in hard rock conditions*

For achieving the optimal earth paste extensive test series related to soil conditioning as well as for reducing clogging phenomena were carried out in advance for achieving the optimal earth paste. The rock sample used was Cochem shale from a borehole (see picture 7).

Picture 7: Cochem shale (borehole)

The laboratory tests were performed with a concrete mixer to enable using grain sizes above 50mm for testing, which was necessary for reducing scale problems and for significant results.

The initial tests demonstrated the good reaction of the foaming anti-clay agent with the fine to medium sized soil particles – where as it was impossible to create a sufficient homogeneous earth paste (see chapter 1).

Therefore, a fine filler suspension was used in addition to the foaming anti clay agent.

Picture 8: Cochem shale conditioned with foaming anti clay agent and additional fine filler suspension

Picture 8 illustrates, that the additional fine filler suspension and the foaming anti clay additive finally offered the desired soil homogeneity and plasticity. Overdosing of the fine filler suspension had no negative and especially no clogging effects.

4.2 *TBM advance into transition zone*

After successful laboratory trials and identification of the necessary soil conditioning agents and their quantities, on-site test sections were defined, they should evaluate and prove the laboratory findings under driving conditions, and to ensure a proper EPB driving mode even under geotechnical unfavourable conditions.

The following preventive measures were adopted at the TBM itself:

- Servicing and inspecting the complete driving installation in particular the cutting wheel, screw conveyor and foam lances for adding soil conditioning additives and calibrating the belt weighing system.
- Replacement of the grill bars.
- Replacement of the standard discs by discs with double seal, lubricant filled and high-grade steel to generally reduce risk of blockages and wear.
- Installation of an automatic compressed air release valve at the top section of the working chamber
- Testing the compressed air lock.

The aim of the site test was to create an EPB-mode within full face hard rock conditions, as illustrated in picture 9.

Picture 9: Hard rock geology before the start of the EPB testing operation

To validate the laboratory findings, the testing started with the injection of the foaming anti clay agent in open mode. It was possible to increase the filling height of the working chamber to 50% but already reaching 100% of the possible cutter head motor power consumption. This result well underlined the necessity of an additional fine filler injection,

which had already been discovered during laboratory testing.
Consequently, the foaming anti-clay agent was combined with an injection of Bentonite suspension (approx. 25 l/min or 1,5 Vol% of the in-situ soil). The use of Bentonite suspension was decided due to availability reasons.

Picture 10: EPB like soil paste after conditioning process on the TBM

Picture 10 confirmed the results of the soil conditioning activities in open mode: plastic and homogeneous soil /rock behaviour as necessary for an EPB drive. After the satisfactory application of the soil conditioners, it was decided to increase the filling height in the working chamber again, as illustrated in figure 2.

Picture 11: Well conditioned soil inside the TBM working chamber

The ground was successfully plasticized and ready to fill the excavation chamber. The filling of the excavation chamber was finally successful and the necessary pressure could be maintained. At the same time adhesion and cohesion effects were sufficiently reduced. To monitor the temperature development in the earth paste, two temperature sensors were additionally installed in the working chamber. For controlled compressed air release, valves were installed at the top of the working chamber ensuring the quickest possible change from open to EPB mode with a completely filled working chamber.

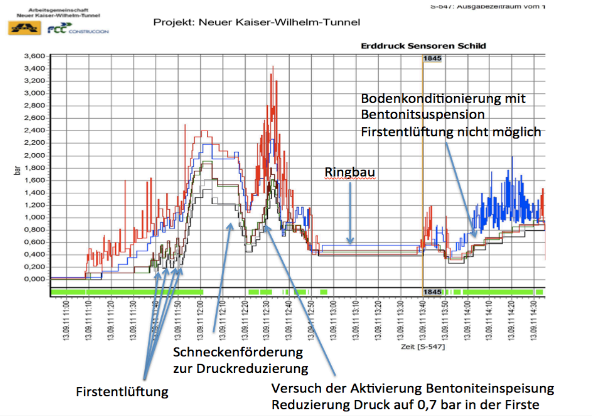


Figure 2: EPB pressure readings during the first trial

The TBM data records in figure 2 illustrate, that is was possible to achieve full EPB mode within less than 1 ring. The necessity of the air release valve at working chamber crown level is also quite clearly visible. The power uptake of the cutterhead motors reached only 50-60% at 1 bar EPB pressure, leaving enough potential for further increase.

One of the remaining fears was the potential clogging of the conditioned soil. Therefore, the soil inside the working chamber was completely excavated after the trials. Picture 12 shows a perfectly clean chamber without soil agglomerations.

Picture 12: clean chamber after finishing EPB mode

4.3 *Lessons learnt*

It is possible to run a TBM with fully pressurized EPB mode already in a full face rock section.

It is essential to choose the correct soil conditioners, soil conditioning parameters and to update the TBM accordingly with a suitable soil conditioning system including fine filler injection and air release valves.

Once the basic parameters are determined, the complete switchover from open mode to full EPB mode can be successfully realised within 20-30 minutes.

5 SOFT GROUND CONDITIONS / TBM DRIVE EXPERIENCE

Especially after long drives in open mode, it is quite difficult for the TBM team to understand the fundamental difference of the EPB advance mode – this includes the necessary monitoring of a couple of essential parameters.

5.1 *Advance in soft ground conditions*

The first and most fundamental difference of tunneling in the soft ground sections is that the working chamber needs always to be filled with soil paste. In addition, the soil pressure in the working chamber has to be maintained all times at a certain level, following the pre-calculated earth pressure values. The TBM crew needs to learn that no exception of the rule can be made without direct consequence to surface settlements.

Directly related to the pressurized driving mode is the soil conditioning. The TBM can only advance with a completely filled and pressurized working chamber, when suitable soil conditioners are used. It is essential to pre-define suitable ones by using laboratory tests. The use of soil conditioning agents on the TBM implicates also the installation of a suitable soil conditioning system (dosing unit and foaming unit) and suitable rotary union. The use of the soil conditioners has always to be adapted to the soil – changing soil conditions require also a change of the soil conditioning parameters.

In order to avoid settlements, it is furthermore essential to control the quantity of the excavated muck and to control the quantity and pressure of the annulus grout.

It is therefore recommended to create a guideline for the TBM driver with the main parameters to look at and how to react in case of deviation:

- Cutterhead power consumption
- EPB pressure & repartition
- Excavated soil quantity and consistency
- Annulus grout quantity and pressure

5.2 *Lessons learnt*

It is not only the switch from hard rock to soft ground which needs special attention – it is generally a fundamental change of habits which needs to take place during the whole soft ground tunneling section:

- Always respect the calculated the lower and upper earth pressure limit, orientation closer to the upper limit
- Crosslink the annulus grout pressures and quantities with the amount of excavated soil
- Detect soil changes and adapt the soil conditioning continuously. Don't rely only on the geological predictions!

Furthermore it is necessary to regularly verify if secondary grouting is necessary, especially when 2k grouts are used.

6 CONCLUSION

During the above-mentioned project and the related engineering, it was demonstrated that hard rock can plasticized. The hard rock with appropriate conditioning additives can be pressurized and maintain the required face pressure in closed mode. By this, the limits of EPB tunnelling have been pushed further.

Transition zones or mixed face areas with hard rock and very soft ground on top can safely be crossed with EPB or Slurry TBMs. Maintaining the face pressure is key for safe tunnelling without exorbitant settlements.

Proper data acquisition and data interpretation entitled the project to overcome critical situations.

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