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Difficult ground conditions? Use the right chemicals! Chances–limits–requirements ☆

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ABSTRACT

The optimum solution for a successful TBM drive in general and especially in difficult ground conditions can only be reached by combining adequate mechanical solutions together with the use of suitable chemicals as well as working with experienced TBM drivers.

Especially in EPB tunneling, the correct choice and use of well adapted soil conditioners can make a considerable difference for the success of a tunneling project – both in highly permeable grounds as well as in sticky clays. Originally difficult ground conditions can be transformed into (easier) manageable ones.

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0. Introduction

More and more TBMs are working in mixed face conditions due to their large diameter or increase demands in tunnel construction (alignment restrictions) – but also due to the fact that tunneling is nowadays possible through almost all geological conditions.

The above statement generally being correct – it shall be highlighted that the TBM itself, the soil conditioning system and the soil conditioners used have to scope with these increased requirements. Interesting jobsite examples in this aspect would be Kuala Lumpur Metro System, Miami Port Tunnel or Kaiser Wilhelm Tunnel Cochem.

The following aspects are given from a chemical supplier's point of view – to the best of our knowledge and making no complete claim instead the purpose is to highlight important facts and examples.

1. TBM design – the mechanical contribution

Nowadays the critical geological areas of a TBM project shall be well detectable by combining the tunnel alignment with the

geological profile. Soil permeability, Atterberg limits, overburden, mixed face conditions, water pressure, fault zones and earlier experiences from nearby tunnels, all these parameters are normally known before excavation begins.

Consequently, the TBM shall be equipped with the necessary configuration with additional flexibility towards the soil conditioning system and the pre-injection system. The TBM must have a suitable cutterhead design in order to allow a good muck flow through both the cutterhead and the working chamber.

The final decision regarding the TBM design shall be made by experienced contractors or consultants and not only by the TBM supplier.

1.1. Cutterhead design/torque

The soft ground/hard rock repartition of the tunnel alignment has to be considered when designing the cutterhead, amongst other factors, a balance of hard rock and soft ground excavation tools is needed. Clayey soils generally require a more open cutterhead (especially in the center region: defining only opening ratios is not sufficient) than gravelly sands (where mechanical stabilization may have positive effects). The opening dimensions also have to correlate with the excavation screw design. All these criteria can be contradictory – often resulting in a quite general shield design. Subsequently decisive factors for successful TBM tunneling are:

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1. Generally open cutterhead center (not only when tunneling through clayey soils).
2. Wide disk windows in order to allow material flowing through the remaining opening.
3. Sufficient amount of independent foam injection ports (with a 1 to 1 connection to a foam generator) at the cutterhead in order to allow the chemicals and water to be present at the point where they are most needed (even if the consequence is a more complex rotary union).

A plugged cutterhead results in a difficult material flow through the cutterhead and also limits the flow through the working chamber, increasing the muck temperature and tool wear – ultimately reducing the lifetime of the main bearing seal system or the risk of failure.

The cutterhead torque is another very important factor, especially when driving through clayey soil with high EPB pressures. Without sufficient torque, the TBMs are often driven

1. In compressed air mode – resulting in increased settlement and surface collapse risk as well as increased difficulties to control the ground water properly.
2. With a very liquid muck – resulting in transportation and disposal difficulties.
3. Very slow advance speed – therefore not matching the foreseen progress rates resulting in project delays.

In general all these results are not positive for TBM tunneling and for the given project in detail – highlighting the cutterhead torque as a decisive factor for successful TBM tunneling (see Fig. 2).

1.2. Injection ports – amount and placement

The amount of foam injection ports at the cutterhead restricts the amount of soil conditioner and water that can be injected during TBM advance. Limited amount of soil conditioner and/or water will result in increased muck consistency (increased torque values) or reduced TBM speed.

The positioning of the injection ports is of high importance too – they shall be well distributed over the cutterhead (cutterhead shall not turn for an extended period of time without close injection of soil conditioners) and take special care of high risk areas such as the cutterhead center (necessity of multiple ports). Furthermore,

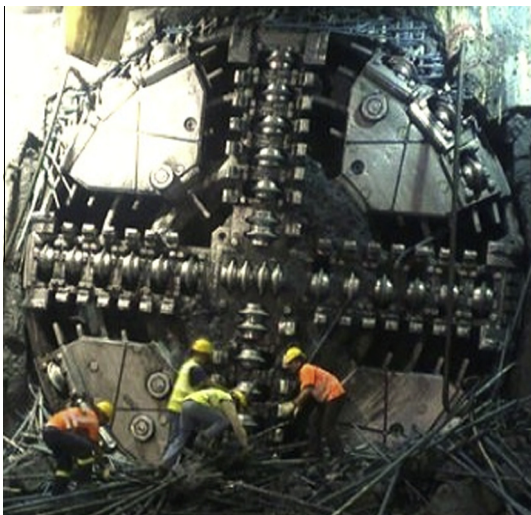


Fig. 1. Example of a plugged cutterhead center, closed disk windows, insufficient number of foam injection ports (Malaysia 2014).

consideration should be taken that an injection port may get clogged – there is a need for redundant design at critical areas so that the TBM can continue tunneling for a while without getting any problems: TBMs are unfortunately seldom stopped when a foam injection port gets clogged.

1.3. Soil conditioning system – as flexible as possible

It is a known fact that modern soil conditioners can change the behavior of a soil quite drastically, let it be highly clogging clay soil or highly permeable sandy/gravelly soil: soil conditioning plays an important role regarding the overall project success. Therefore it is essential that the TBM is equipped with the necessary tools to effectively allow and control the application of these modern soil conditioners:

1. Two dosing pumps (one for foam and one for polymer, can also be used for redundancy purposes).
2. Two water booster pumps (for independent and sufficient water supply, redundancy purposes).
3. Static mixer (efficient mixing of foam concentration and polymers with water), no installation of intermediate foam/polymer solution tanks).
4. Efficient foam generators (especially at low FIR ratios, continuous foam flow, no free air release) (Storry et al., 2013).
5. Efficient non-return valves (not destroying the foam).
6. Efficient foam nozzles (not destroying the foam, not easy to get plugged by the soil).

Special interest shall be paid to the interface between the soil conditioning system and the TBM driver. The on-site experience generally shows the necessity for:

1. Separate and easy to use foam screen (as user interface for the TBM driver, see Fig. 3).
2. Water/foam selectors (for an automatic switch between foam and or water injection).
3. Quick rider (for a quick FIR change of all foam lines, avoiding switch-off of foam lines).
4. Color code for rapid identification of functionality and anomalies.

1.4. Pre-injection – be prepared for the unforeseen

Some TBM projects do require a separate pre-injection concept and the necessary installation on-site, regardless of the TBM type. Especially for multi-mode TBMs operating through fault zones or extremely difficult geology, pre-injection becomes a more and more vital issue. Important questions are

1. Necessity of umbrella type only or 360° pattern?
2. Injection through shield only or also through the cutterhead?
3. Possible length of the drilling rods.
4. Drilling angle.
5. Separate drilling installation or system based on the erector? (see Fig. 4).
6. One component pump (cements, nanosilica) or two component pumps (PU).

2. Soil conditioning – the chemical contribution

2.1. Foams

Foams are the backbone structure of the soil conditioning system. When foams are well distributed inside the conditioned soil, they are responsible for its compressibility, its reduced inner

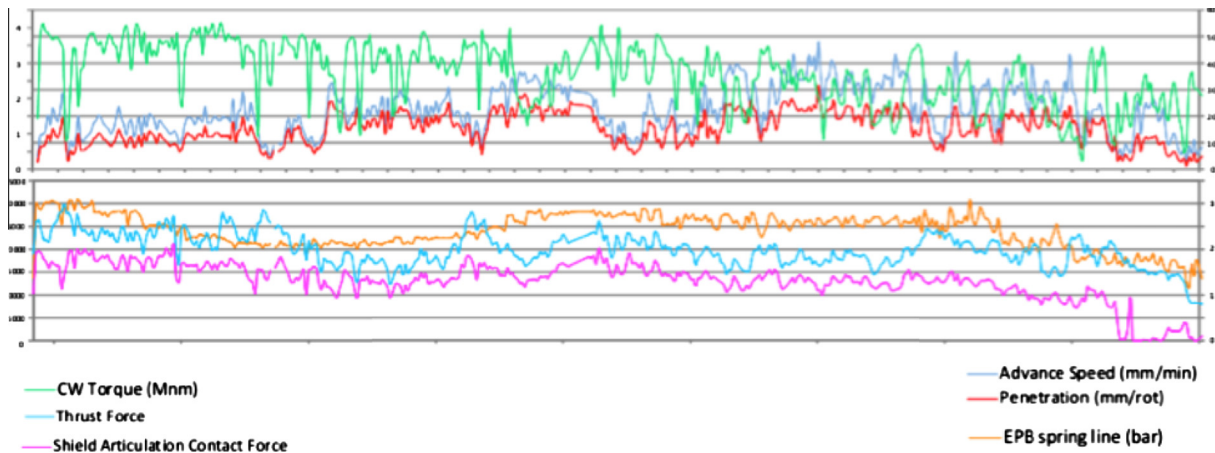


Fig. 2. Example of an increasing cutterhead torque (green) and decreasing TBM speed (dark blue) due to clayey soil and clay clogging phenomena – with torque values at the TBM design limit (Malaysia 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

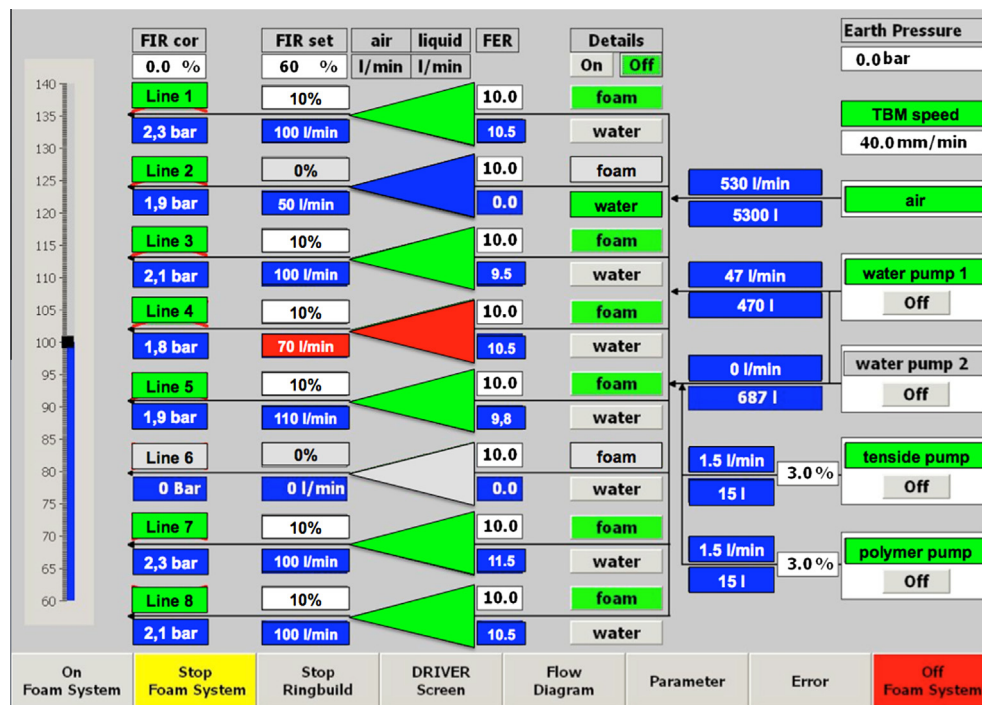


Fig. 3. Example of a highly flexible 6-line EPB system with water/foam selector and quick rider (FIR adaption of all foam ports), NORMET design.

friction and for the creation of a homogeneous and impermeable soil paste inside the working chamber (see Fig. 5).

The interaction of the foam with the soil is also important – consequently there are different types of foams used for sandy soils and clayey soils.

Regarding the environmental compatibility, foams shall be non-toxic for aquatic organisms and highly biodegradable.

2.2. Polymers

In case of water bearing and/or highly permeable grounds, it will not be sufficient to work with foams only: the use of polymers is recommended. Polymers used in TBM tunneling can be structuring polymers (increasing the muck cohesion, forming a polymer network) or water binding polymers (see Fig. 6).

Regarding the environmental compatibility, polymers shall be non-toxic for aquatic organisms and either highly biodegradable or inert.

2.3. Anti-clay agents

TBM drives through clay require in most cases the use of special anti-clay agents. The use of foam only is clearly not sufficient to treat the clay as necessary: reducing its adhesion to metal surfaces (cutterhead & working chamber) and reducing the re-agglomeration of clay chips.

Anti-clay agents shall avoid cutterhead clogging and closing of the openings (especially cutterhead center, disk windows) and reduce the cutterhead torque in closed mode. Consequently the TBM speed can be drastically increased using anti-clay agents.

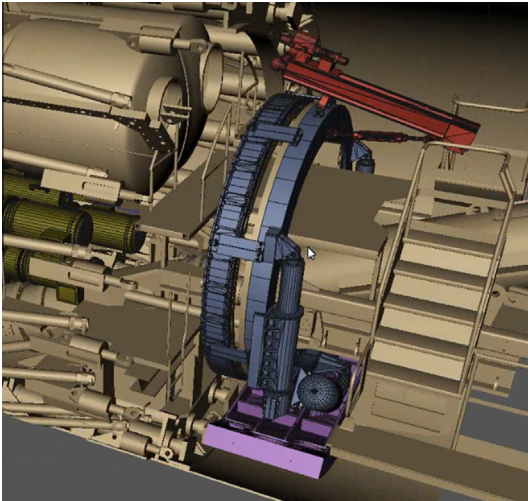


Fig. 4. Example of a drilling rig mounted on the segment erector.

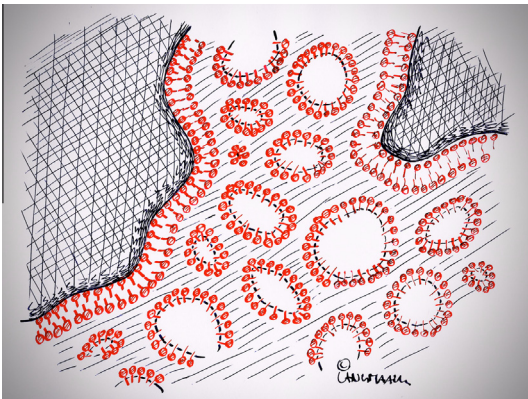


Fig. 5. Foam and foam-soil interaction.

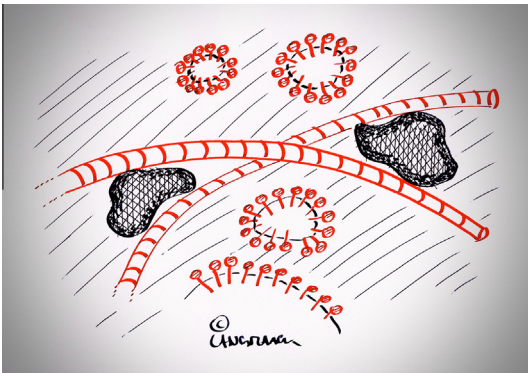


Fig. 6. Long chain polymers.

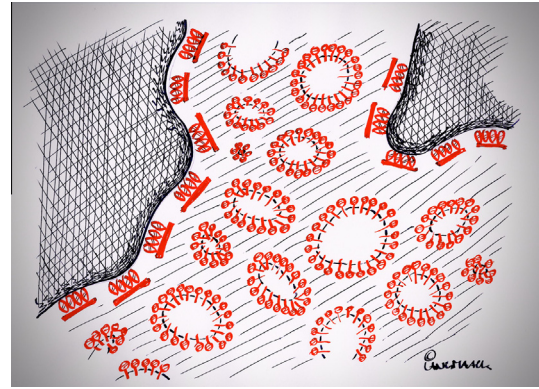


Fig. 7. Foam and anti-clay agents.

3. Site examples

3.1. Clay clogging – Kuala Lumpur, Malaysia (Langmaack et al., 2015)

Malaysia's first Mass Rapid Transit (MRT) project was officially launched on July 8th 2011. The total length of 51 km stretches across Klang Valley, with 9.5 km running underground with seven stations across the busiest city center of Kuala Lumpur. MRT is expected to be in operation by end of 2016. The project was awarded to MMC Gamuda KVMRT Sdn Bhd (see Fig. 8).

The geological conditions of the Klang Valley made tunneling beneath Kuala Lumpur extremely challenging – cutting through two totally different geological formations: The Kenny Hill Formation (consisting of sedimentary rocks) & Kuala Lumpur limestone formation (with erratic karst features).

The project was divided therefore into four launching shafts with two totally different TBM types for each geological formation: EPB TBMs for the Kenny Hill Formation (see Fig. 9) and Variable Density (VD) TBMs for the limestone formation.

The following soil conditioning system setup was generally used in Kuala Lumpur (see Fig. 10):

- Foam Nozzle F1: Foam + polymer
- Foam Nozzle F2: Water
- Foam Nozzle F3: Foam + polymer
- Foam Nozzle F4: Water
- Foam Nozzle F5: Foam + polymer

Regarding the original five injection port design, quite often only three ports remain for the injection of soil conditioners – the remaining two injection ports are used for the necessary water injection. This setup is clearly insufficient as shown already in Fig. 1. Furthermore, it also illustrates that only one injection port for the whole cutterhead center area is clearly insufficient.

The efficiency of an adapted/modified design is shown in Fig. 11 – comparing two parallel drives with quite similar TBMs: First drive (top) with the original EPB TBM and the second drive (bottom) with a modified VD TBM operating in EPB mode. The cutterhead torque drops from around 4 MNm (design limit) down to 1.5–2 MNm.

3.2. Mixed face conditions – Delhi Metro phase III, India (Cooper et al., 2016)

The following example from Delhi Metro illustrates extremely well how important a proper soil conditioning can be for a TBM project.

Simultaneously, the necessary amount of water to reach plastic clay behavior shall be reduced to a minimum for disposal reasons (see Fig. 7).

Regarding the environmental compatibility, anti-clay agents shall be non-toxic for aquatic organisms and either highly biodegradable or inert.

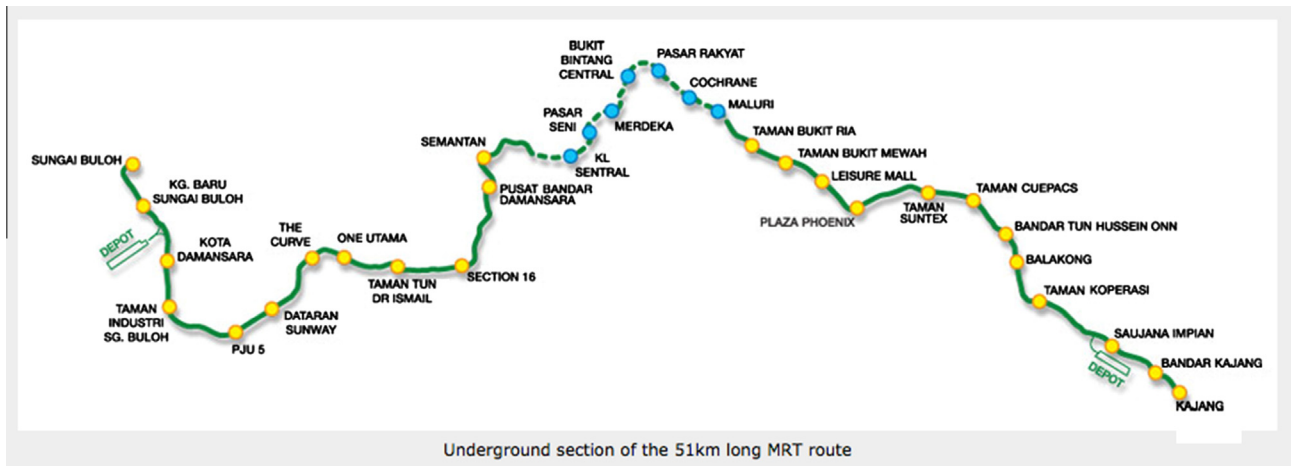


Fig. 8. Overview of the MRT route including underground section (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) source: T&T 201.

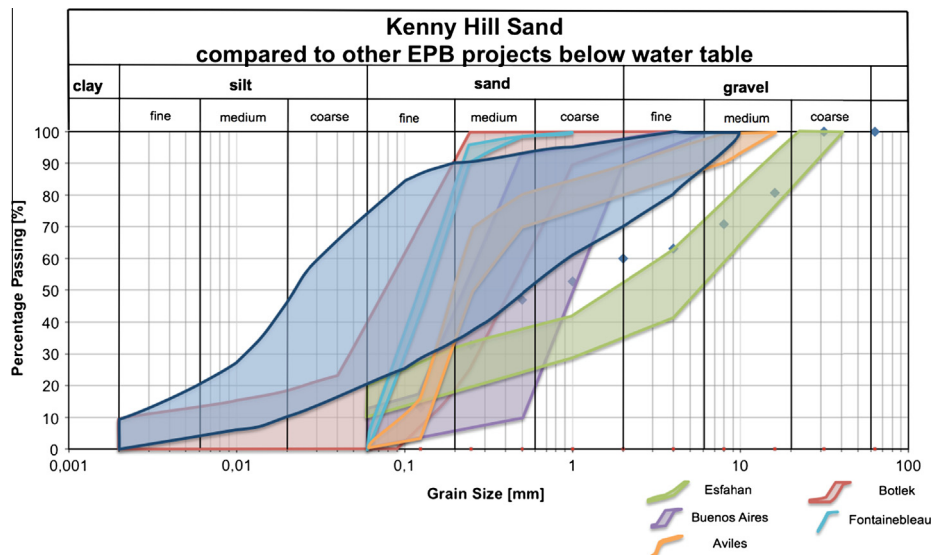


Fig. 9. Grain size distribution of Kenny Hill Formation compared to other TBM projects.

The TBM could be steered well till advance (Ring) No. 455. Ring No. 456 was driven into a silty sand with high water pressure and no-one noticed that the machine started sinking (within the limit of tolerances).

The TBM operators initially recognized that the machine was still responding with modified thrust pressures at the bottom group C at 340 bar and 85 pressure at top group A.

The Geological Interpretation Report indicated that the machine sunk further down in poorly graded fine to medium sand with high water pressure and a top band of stiff clay above tunnel axis (see Fig. 12). Until now, all mechanical efforts failed to put the TBM right on track. Finally it was decided to use the copy cutter above the TBM axis half portion and inject Bentonite Slurry to avoid settlement due to extra cutting. From Advance No. 491 to Advance No. 517 the copy cutter was used above the TBM axis, but still the TBM continued its sinking process to 648 mm below the designed alignment. The magnitude (PITCH) of the machine increased from -3 to -4 mm (advance Nos. 456–490) to -4 to -10.6 mm (advance No. 491 to advance No. 517).

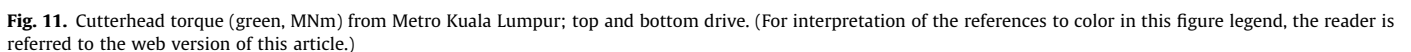
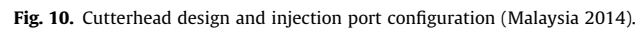
At that point it was clear, that all mechanical ways to get the TBM back on track, failed. Furthermore, the point of no return (from alignment point of view) was dramatically approaching.

The only two remaining options were

1. Massively modify and adapt the soil conditioning system.
2. Stop the TBM and pre-grout respectively to stabilize the running sand in front of the TBM (costly and time consuming).

Decision was made to check the effects of a modified soil conditioning system – with the necessity of immediate results due to the given and unfortunately very close point of no return.

After implementing the agreed modification of the soil conditioning system – especially with the selection of polymers, the way of using them and their concentration – the TBM responded positively during the following 11 rings (until advance No. 537, chainage 2664) and finally tilted upwards, reaching a pitch of $+0.3$ mm/m (see Fig. 13). But the TBM position was still located 1106 mm below the foreseen alignment.



The double track Kaiser Wilhelm Rail Tunnel, which opened back in 1879, is located on the Coblenz-Perl Moselle rail route between Ediger-Eller and Cochem, which is an important

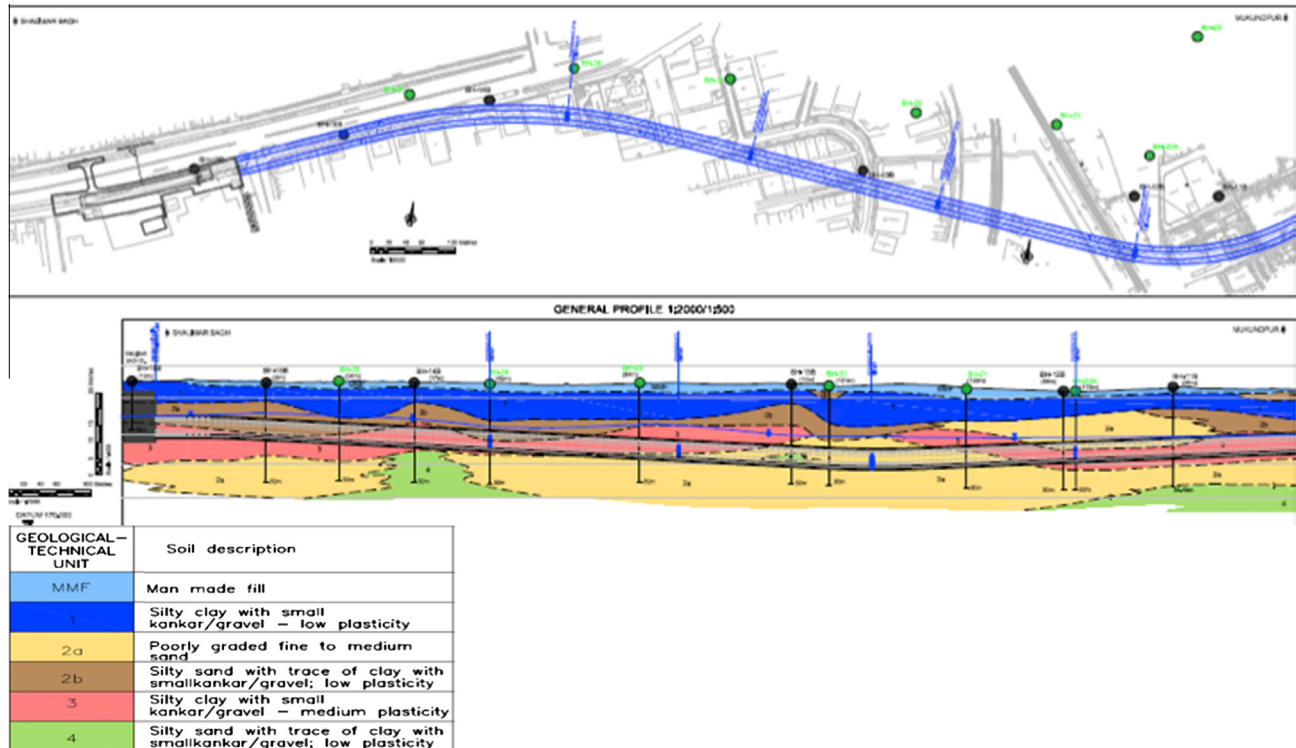


Fig. 12. Geological cross section.



Fig. 13. Running silty sand with no cohesion. Increased cohesion and decreased permeability with the use of polymer.

component of the Trans-European Network (TEN) for conventional traffic. The mechanised TBM drive building the 4242 m long New Kaiser Wilhelm Tunnel was successfully concluded with the breakthrough on November 7th, 2011.

The TBM was designed to cope with the relatively stable solid rock zones encountered along the majority of the alignment, to be driven in open mode. However at the same time it was necessary to apply an active face support to overcome fault zones and the soft ground zone in up-town Cochem. Consequently, the TBM was equipped with a screw conveyor, which at any time depending on the geo-technical demands could be converted from open mode to pressurised closed mode and vice versa.

Technically the most difficult part of the TBM drive in tunneling terms was the EPB-Section located uptown Cochem (Fig. 14), especially when switching from hard rock open mode into full EPB mode already in the hard rock section (below house No. 28).

Buildings had to be undercut with a minimum distance of 3.2 m from the tunnel roof with a TBM diameter of 10.54 m and minimum settlements allowance. This was the first time in the world

that this driving method was applied for under-tunneling a built-up area with such small overburden. Additional problems aroused due to the presence of mixed face conditions in this area: on the one hand the prevailing rock face and on the other soft ground (see Fig. 14).

The transition from rock to soft ground and vice versa could be accomplished resulting in low surface settlement rates thanks to the proper and sensitive application of the open and closed operating modes. The TBM data were continuously compared with the surface deformation behavior. There was no need for chamber inspections with lowering of the earth pressure level.

The following preventive measures were adopted:

- Servicing and inspecting the complete driving installation, in particular the cutting wheel, screw conveyor, foam lances for adding soil conditioning additives and calibrating the belt weighing system.
- Installation of additional cutters to cope with the slope debris and slope loam layers.

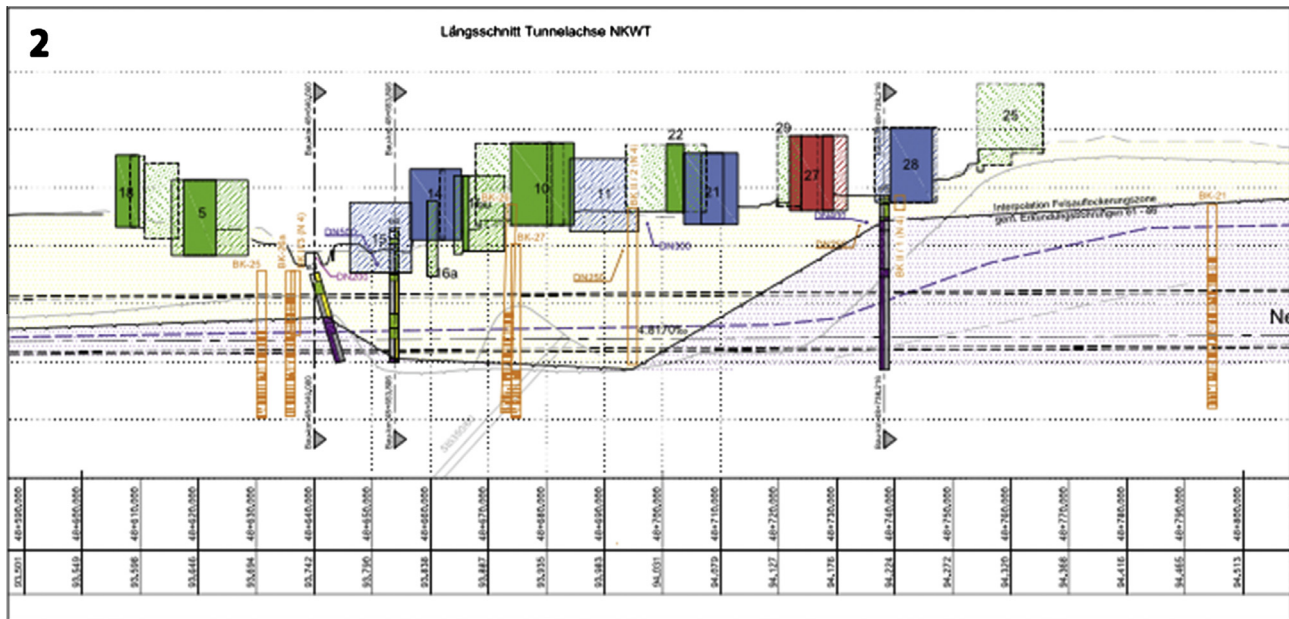


Fig. 14. Longitudinal section uptown cochem, driving direction: from right to left.

- Replacement of the grill bars.
- Replacement of the standard disks by special disks with double seal, high-grade steel and lubricant filled in order to prevent disk blockages.
- Installation of an automatic compressed air release valve at the top section of the working chamber.
- Testing the compressed air lock.

Extensive test series of the soil conditioning system were carried out in advance – also to study the possible reduction of clogging phenomena and to be able to adapt the earth paste optimally. Furthermore, two site test sections were defined under real driving conditions in order to evaluate and proof the laboratory findings and to ensure a proper EPB driving mode even under geotechnical unfavourable conditions (mixed face conditions of soft ground and solid rock).

Laboratory tests revealed that an anti-clay agent was able to safely fulfil all the required demands, compared with a high concentrated Bentonite suspension (HD-Slurry) injected at the cutterhead (see Fig. 15).

The ground could be plasticized to a sufficient extent so that the TBM working chamber could be completely filled and the necessary pressure be built up and maintained. This requirement was proven both in solid rock as well as soft ground (see Fig. 16). 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. Openings on top of the working chamber for a controlled compressed air release were installed to ensure the quickest possible change from open to EPB mode with a completely filled working chamber (see Fig. 17).

4. Conclusion and recommendation

More and more (EPB) TBM tunnel projects face difficult ground conditions, unfavorable zones and mixed face conditions. Large diameter shields furthermore increase the percentage of tunneling with mixed face conditions.

Only the intelligent combination of mechanical and chemical solutions will ensure a successful, safe and efficient execution of TBM tunneling projects in the future.

The above-mentioned statements require actions from both the TBM manufacturers

- Intelligent engineering solutions from the mechanical TBM side.
- Review of the actual design in order to increase efficiency and user friendliness.
- Efficient integration of the chemical products & possibilities into the TBM design.



Fig. 15. Cochem shale (borehole sample) and conditioned soil with anti clay agent and fine filler suspension.

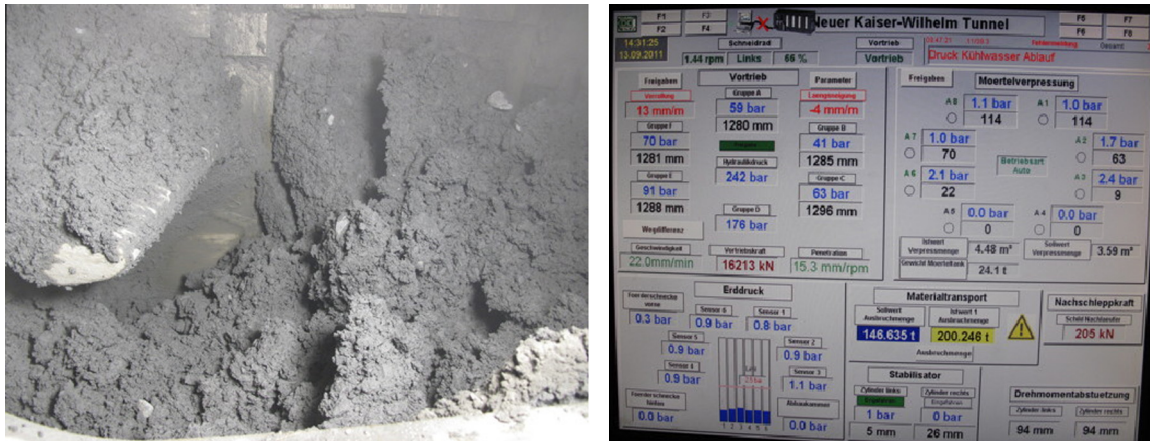


Fig. 16. Well conditioned soil inside the TBM working chamber and TBM screenshot.

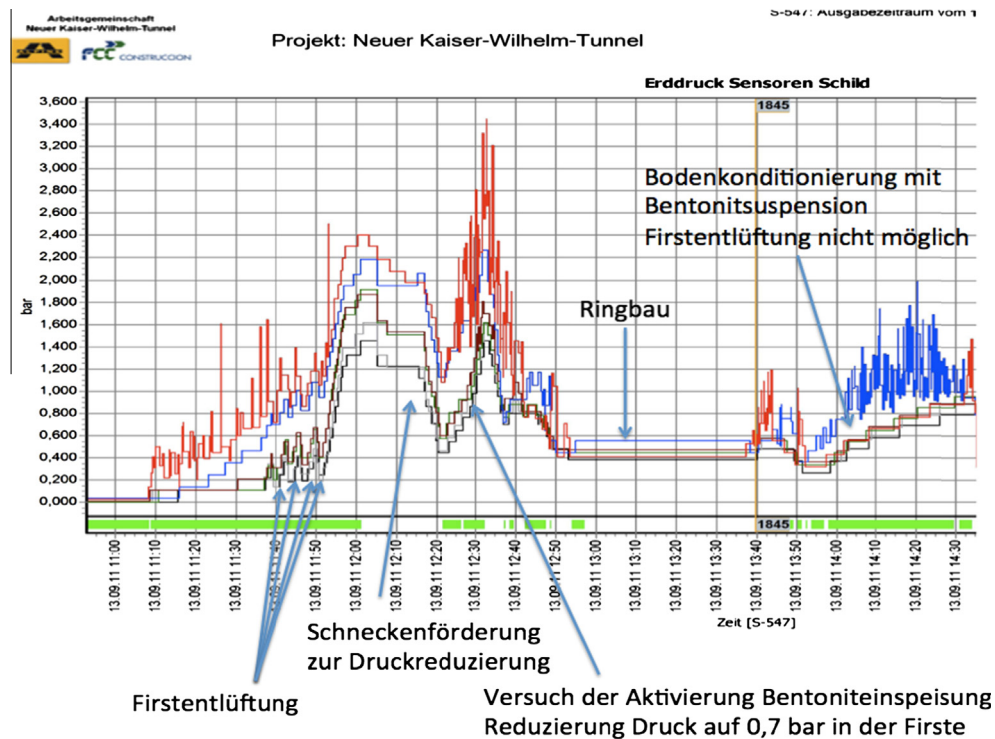


Fig. 17. EPB pressure readings during the first trial.

And the chemical companies

- Ensure the use of ecofriendly additives only.
- Develop new systems instead of making products only cheaper, increase efficiency of existing technologies.
- Offer real on-site support.
- Better convey the message to TBM manufacturers, construction companies and consultants regarding the benefits of correctly used additives and new developments.

In order to combine the available options and reach the overall optimum for mechanized tunneling.

Furthermore, (experienced) contractors need to focus more on the exact and detailed TBM specification reflecting the needs for a specific project – implicating the openness to new chemical solutions: If nothing new is tried out, no development will be realized.

To a large extent this involves also the universities, consultants and project owners.

Consultants and project owners shall try to

- Keep track with the new developments (mechanical and chemical).
- Be open to implement the new possibilities.
- Avoid to ban the use of product groups/techniques without any substantial reason.

Universities need to

- Be interested to drive TBM research forward (mechanical and chemical).
- Teach modern tunneling with all its facets (more detailed than actually) together with industry lecturers.

- Attract young engineers/chemists.

Let's build tomorrows tunnel together!

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