RESEARCH REPORT

Influence of steering actions by the machine operator on the interpretation of TBM performance data

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Abstract

TBM (Tunnel Boring Machine) performance data are commonly used for interpretation of ground conditions and behavior. This data is highly influenced by the actions of the machine operators during their control of the TBM. Nevertheless interpretation of TBM performance data is often made in retrospect using no or little information about the decisions made by the machine operator. This is despite the fact that in many case histories the comparison between the cumulative footage mined by various operators (day, evening, night shift) shows a clear distinction between various operators.

This study focuses on the machine operator's decisions (including his reasoning) and its impact on the interpretation of machine performance data. This would facilitate a better understanding of actual machine performance in various ground conditions and allows for due consideration of the impact of operator on machine performance. To determine this influence, it is essential to examine the TBM operators work experience, his skills and expertise. Accordingly the main scope of this research was the examination of training, capabilities and responsibilities of the TBM operator relative to the TBM advance. Additional related issues are communication and teamwork between operators and engineers as well as the general setting and organization of the site and investigation of these parameters influence accuracy of TBM data analysis and interpretation.

The thesis consists of a literature review and data collection chapters, that deal with the issues stated above. The literature review sets a framework to gain a better understanding of the subject. This part provides a general description of the main TBM types along with its application ranges and an introduction in the TBM advance from the point of view of the TBM operator. Furthermore an example of a good TBM management is shown and an analysis of incidents with an identification of reasons is given.

The data collection part will be carried out based on Questionnaires and interviews. The Questionnaires have been sent out to various parties including TBM manufacturers, contractors and TBM operators. The analysis of the responses to the Questionnaires, as well as the interviews with the stakeholders, should lead the way to focus on critical issues and offer some suggestions for dealing with the issue of operator training, preferred setting of the site for optimum use of machine, and finally proper analysis of machine performance to eliminate operator sensitivity.

Executive Summary

The following research report was created as part of the Master Thesis on the subject of "Influence of steering actions by the machine operator on the interpretation of TBM performance data". It summarizes the literature research that was done at the Pennsylvania State University , University Park , PA, USA under the supervision of Prof. Jamal Rostami. The experimental part of the work (illustrated on page 5) is currently in progress and will be presented after the completion of the Master Thesis.

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Chapter 1: Introduction

1.1. Structure of the Research

The following Master Thesis includes 5 chapters. The methods used are literature review and experimental research including the data collection and analysis (Chapter 4).
Chapter 1 gives an introduction of the Subject as well as an explanation of research scope, purpose and methodology.

Chapter 2 covers a basic description of the main TBM types, their general application range and specific steering issues in problematic ground conditions.

In Chapter 3 the Control system and Management of a TBM advance is explained using an example of a successfully conducted project. Essential machine data are explained in the case of an EPB TBM and the basic working routine of a TBM operator together with his obligations are summarized. This chapter also covers a listing of incidents happened in the case of Slurry and EPB TBMs and an analysis of their characteristics on the basis of TBM data. Along with this, a brief explanation of the issue of TBM data interpretation is given. The last part of this chapter provides a summary of the literature review.

In Chapter 4 the Questionnaires and Interviews conducted will be explained and evaluated. Differences in the evaluation shall be identified and the significance and usefulness shall be examined. Chapter 4 will be split up in 3 subsections. In the 1st subsection surveys in the USA will be evaluated whereas in the 2nd subsections surveys in Europe will be evaluated. Similarities and differences between these two regions can be indicated in the third subsection.

The results will be discussed and interpreted in Chapter 5. Important statements and findings of the different surveys can be shown and concepts for improvement can be proposed. It will also contain of suggestions of how training of machine operators and communication between them and engineers who interpret machine performance could be adapted. The last part shall contain of a short summary of the research and recommendations for future work.

Figure 1 shows the flow chart of the study and the chapters of the thesis.

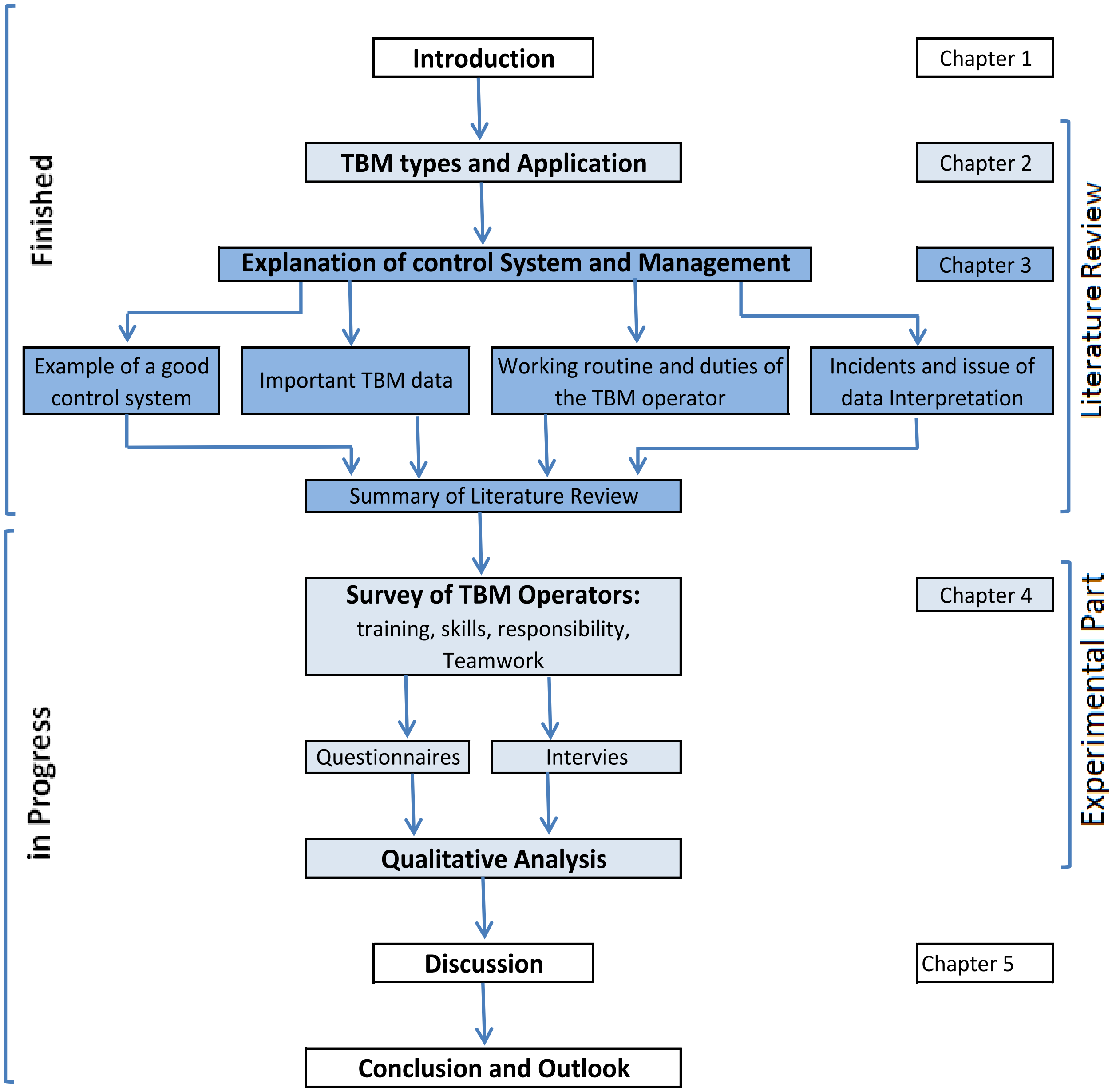


Figure 1 Flowchart of study

1.2. General

During a Tunneling project a high rate of advance is likely to be a key factor of competitiveness. Especially in privately financed tunnels there is a great interest of early revenue and therefore a fast tunnel completion may be even more important than construction costs. A major consideration at this point is the applied excavation method. As tunnels are increasingly becoming longer and are used more frequently in urban regions, the use of Tunnel boring machines (TBMs) is a method of choice. There are different reasons for this trend. Because of the faster tunnel heading, TBMs are much more competitive in long tunnels than drill & blast, as well as in urban regions where disturbance to the surrounding by blasting vibration needs to be limited.

TBMs can be used for nearly every kind of ground and under largely diverse physical conditions. A conventional TBM is a highly engineered unit that has to cope with various duties. It consists of machine parts for cutting, shoving, steering, gripping, exploratory drilling, ground control and support, lining erection, spoil removal, ventilation, and power supply ([1] Bickel et al. 1996). It is the site manager's job to coordinate these elements in accordance with the advance of the tunnel to make the best use of TBM operator's skills in streamlining the production. All these machine parts are interdependent; they must all be able to function at a congruent rate with the tunnel heading.

Operating a tunnel boring machine is not an easy task. The ground is probably the most difficult material to describe in its characteristics and particularities. Hence it is a difficult task to forecast the conditions to be encountered during an excavation progress. Unexpected ground conditions are often a reason for the TBM to be down or underutilized. Because the operator has no direct view of the ground conditions it is an art to handle such situations. A lot of experience and know-how is needed to steer and advance a TBM properly. It is a great responsibility to deal with this since human failure or faults in any part of the TBM can directly result in a delayed tunneling progress and impose cost overruns. To coordinate all these activities special skills and experiences are required, to dedicate time to study and optimize the operation, and evaluate sensitivity of the operations for various parameters. Every TBM is different and after assembling there is always a start-up phase where the operator has to get the feeling for ground and machine. This is called learning phase. The operator has to set up the optimum thrust, rotational torque and cutter wear during this time. ([1] Bickel et al. 1996)

Due to the fact that a TBM is a highly complex machine, that besides excavation is used to determine ground conditions, there are a lot of machine performance data that have to be considered. These data are highly influenced by the actions of the machine operator during steering of the TBM. Nevertheless interpretation of TBM-machine performance data is being made in retrospect using no or little information about the decisions made by the machine operator. It is a hypothesis to assume that by inclusion of information about the machine operators skills and in particular, steering decisions (including his reasoning) the interpretation of machine performance data would be more efficient and enable better understanding of actual ground properties and behavior.

1.3. Purpose of the Research and Scope

The target of this study is to examine the improvement potentials for interpreting TBM machine performance data by taking into account the machine operators decisions and his reasons for setting various operating parameters or for TBM-steering actions.

Interpreting TBM performance data in retrospect based on machine records is a difficult task, especially without any additional information about control measures by the TBM operator, general workflow or occurrences on the tunnel site. It is assumed that interpretation often takes place almost exclusively based on operational data. Recognizing this problem the following Master Thesis was initiated. The focus of the topic is set on the TBM operators. Surveys shall elucidate their education, expertise and responsibilities and show how significant their influence on TBM performance data is.

A literature survey for relevant papers that partially deal with TBM operator training or the influence of operators on performance data in big search engines such as google.com, sciencedirect.com, or onemine.org yields no result, in other words, no systematic study has been performed or reported on this subject. However the significance of a skilled TBM operator is undisputed and a good teamwork and communication is the cornerstone for success. With the progress of TBM technology, larger and increasingly complex projects are constructed by these machines. To cope with this the requirement for skilled tunnel personnel grows. Recent developments such as the Tunneling and Underground Construction Academy (TUCA) in England or the Tunneling Training Academy in Malaysia (TTA) show this increasing demand as well.

In order to examine if there is room for improvement, it is necessary to determine the skills and expertise of TBM Operators and clarify the areas of responsibility of TBM Operators, Manufacturer, Construction Management (CM), and Design engineers, regarding the skill sets and decisions by the TBM operator. Furthermore it is important to examine the teamwork between TBM operators and engineers, since operating a TBM consists of an interaction between decisions made by engineers and TBM operators. The graph below shows the key elements that are important for a successful TBM advance and the main scope of this study, outlined in red.

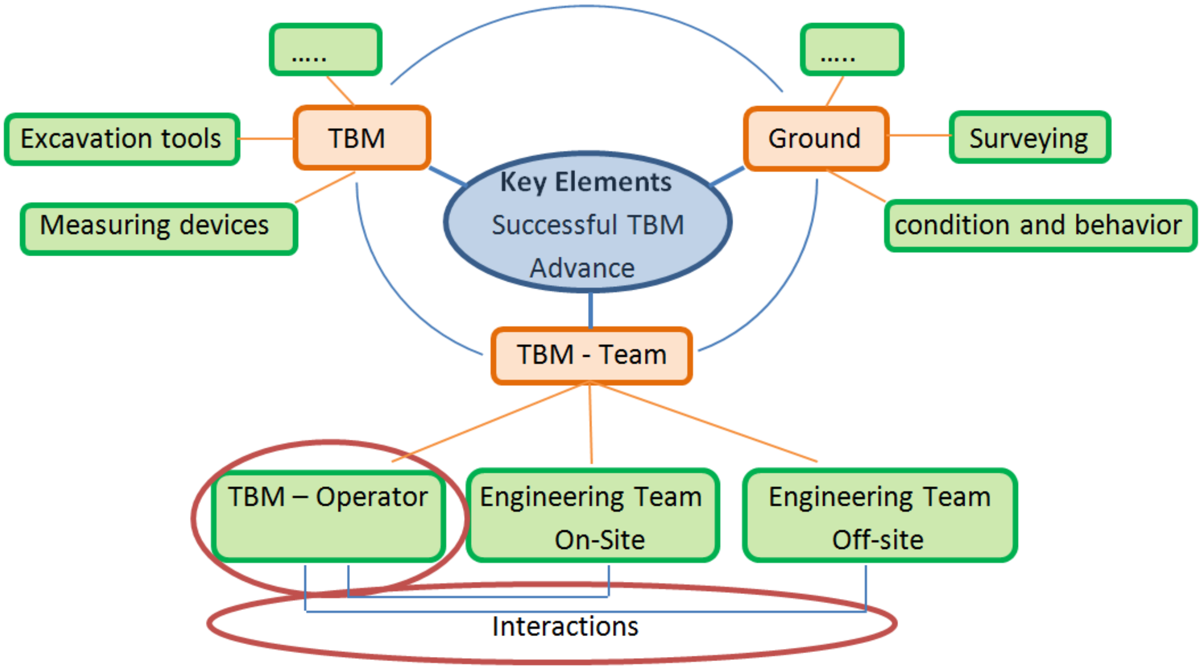


Figure 2 Key Elements for a successful TBM advance

1.4. Survey of state of practice and explanation of its importance

Skills, expertise of TBM operators:

One objective of this investigation is to find out why particular actions are made by the TBM operator (based on which knowledge) and how steering decisions of TBM operators differ. With knowledge about education and know-how of TBM operators it is easier to comprehend the decisions made during the TBM advance and what effect they could have on TBM data. This could provide additional information for the interpretation of performance data. A focal question is, if a general scheme can be identified how TBM operators act and react in specific situations or if it is more based on "trial and error" experiences. In the second case a good teamwork and communication between project participants appears to be essential. Another question is how accurate interpretation could be without knowing about the operator's decisions and how clearly an interpretation of TBM data can be made in general.

Areas of Responsibility:

Knowing that controlling of a TBM is a combination of decisions made by the TBM operator and instructions given by engineers, it is important to clarify their areas of responsibility. The responsibility of the machine operator also affects the importance of his knowledge, the more responsibility he bears, the more skills and expertise he should have. Furthermore the spheres of responsibility of TBM Manufacturer, Construction Management (CM) and Design Engineers regarding the skill sets and decisions by the TBM operator are of interest.

Teamwork between TBM operators and engineers:
Dependent on the knowledge and responsibility of the TBM operator it is important to set up the organizational and interpersonal settings for a good teamwork. Regardless of this, good teamwork and cooperation is always a key factor for success. Especially when advancing a TBM, proper skill sets are always needed from the side of the operator and engineer. The operator knows best about all control functions and how to operate the TBM but can't have the broad range of knowledge about ground and ground support like the engineer.

Beside this major examination, in the course of the research a basic explanation of the main TBM types and application fields is given. An overview of the most important TBM performance data is described in the case of an EPB (Earth Pressure Balance) and a usual workflow along with the duties of the TBM operator is explained. It would exceed the research scope to discuss every type of TBM but an EPB TBM is a good example, since EPB machines nowadays represent the majority of the used soft-ground TBMs. Generally the issue of interpretation of machine performance data is rather common in the case of Soft-ground TBMs such as an EPB Machine compared to Hard-rock TBMs because they have considerably more control options and a large amount of recorded TBM data.

Moreover the issue of TBM Management is taken up since it is associated with teamwork and responsibility on the tunnel site and a methodology is described using an example of a successful application.

1.5. Methodology

The methods used in this study includes literature review, surveys in the form of questionnaires and expert interviews. The literature review shall provide background knowledge of the topic and a basic introduction into the TBM operation.
Questionnaires are prepared in order to obtain a basic knowledge about the subject and develop a preliminary comprehension of the issues. In order to reach an objective evaluation and consider the issue from all perspectives, 3 different Questionnaires have been prepared and sent to various parties including machine manufacturers, contractors, and machine operators. After evaluating the Questionnaires and related analysis relative to the topic, questions for expert interviews have been prepared. The expert interviews are conducted in contact with machine operators, engineers who interpret machine performance data and other specialists in the field of tunneling. These interviews and Questionnaires are carried out in the United States and in Europe. Thereby major differences can be pointed out concerning training and skills of TBM operators, TBM control and site management. Chapter

2: TBM Types and Application

The most common types of TBMs are described in this chapter. In respect to Soft-ground TBMs, only the closed-face tunneling machines are considered and a few TBM types such as Hybrid shield TBMs shall not be mentioned. The basic application fields of the described TBMs are summarized in tabular form and a short distinction between Slurry and EPB TBM is given. Basic steering issues that the TBM operator has to deal with are demonstrated as well.

2.1. Hard-rock TBM

2.1.1. General

Hard rock TBMs are used as its name indicates to excavate rock. Cutter wheels (disc cutters) placed in a certain pattern on the cutter head excavate rock by a rolling crushing action under pressure causing the rock to chip away from the face. The excavated muck gets collected by buckets on the cutter head and transported further to a conveyer belt. As a rough rule of thumb a Hard Rock TBM can be used in rock where the face does not require pressure to support and the walls are competent to stand with minimal ground support requirement. The rock can have comprehensive strength up to 300 Mpa ([2] Maidl et al. 2008), beyond which the TBM performance will be very limited and often contractors resort to Drill & Blast. There are three different types of Hard-rock TBMs based on the ground support requirements. Obviously, the type of machine controls the way the machine is operated and steered. The rock TBM types include the following:

- Main Beam TBM (open type)
- Single Shield TBM
- Double Shield TBM

2.1.2. Main Beam TBM (open type)

This type of TBM has a set of Grippers that clamps against the tunnel wall to shove the machine forward by using the propelling force or thrust from the jacks and the torque from the rotating cutter head. It slides forward on the invert shoe behind the cutter head. When the Gripper is clamped against the tunnel wall, steering is done by moving the main beam in a vertical or horizontal direction before shoving it forward. During the shoving the direction can be adjusted upwards and downwards by the invert shoe and sideways by the side steering shoes. Generally the side steering shoes are used to stabilize the TBM when boring a stroke. Another version of the open type is the Gripper TBM with X-type clamping which uses 2 sets of grippers; however it is far less common in its application.

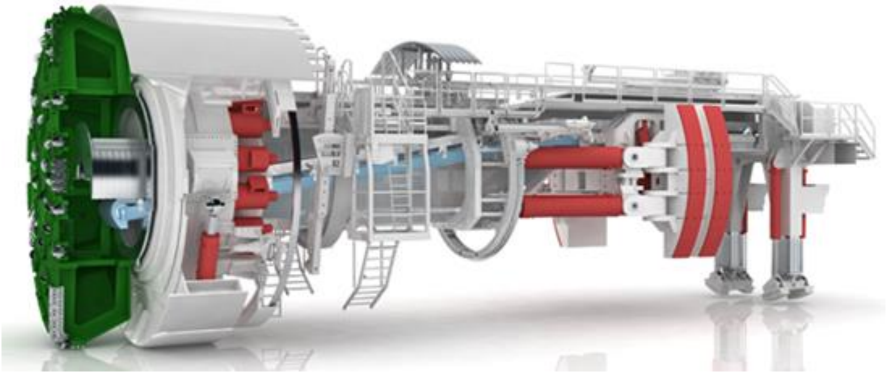


Figure 3 Main Beam TBM (Gripper TBM) © Herrenknecht AG

2.1.4. Single Shield TBM

This kind of TBM moves forward using hydraulic jacks that thrust against prefabricated segment lining. A shield that overlaps on the lining segments provides safety against loose boulders and squeezing rock conditions. To steer the TBM the center of thrust of the propulsion jacks can be adjusted, increasing the jack thrust on one side of the TBM will lead to a direction change to the other side. Some TBMs are also equipped with a movable cutterhead to steer the TBM. Depending on the client's demand, there is the possibility to move the cutterhead forward and backward, shift it up and down or adjust the angle of the cutterhead to the tunnel axis in some machines. The rotating cutterhead causes a slight rolling of the shield. This is counteracted by inclining the propulsion jacks to the opposite rolling direction and usually the direction of rotation can be changed (bi-directional head rotation) to reduce this effect. Steering is primarily done by controlling the jacking force between different set of thrust jacks.

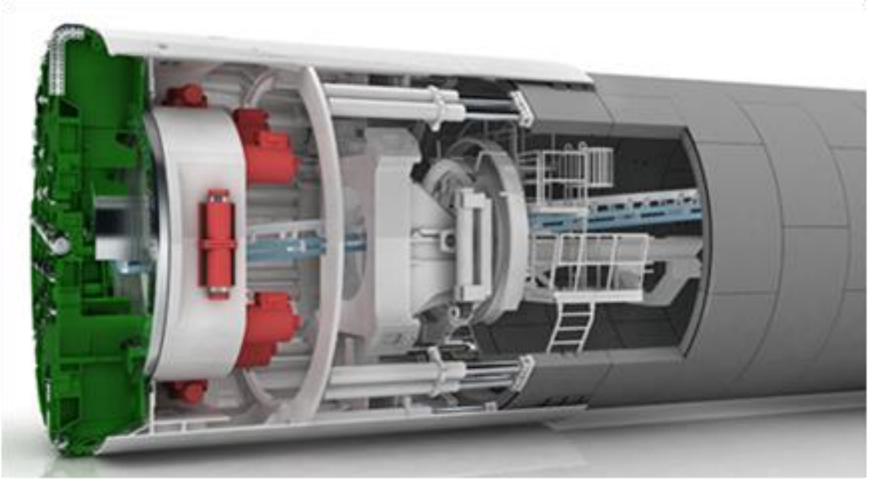


Figure 4 Single Shield TBM © Herrenknecht AG

2.1.5. Double Shield TBM

The double shield TBM combines the elements of a single shield TBM with a gripper TBM. The basic principle here is to advance the tunnel with clamped grippers in competent ground that can support the gripper pressure and when conditions get worse, it can be changed to a single shield arrangement (by locking front and gripper shield) and moving forward by pressing against segmental lining . The main advantage of the double shield machine is the faster advance rate. When shoving forward in stable rock the double shield machine can excavate rock and simultaneously erect the lining which can lead to great time savings compared to the single shield machine.

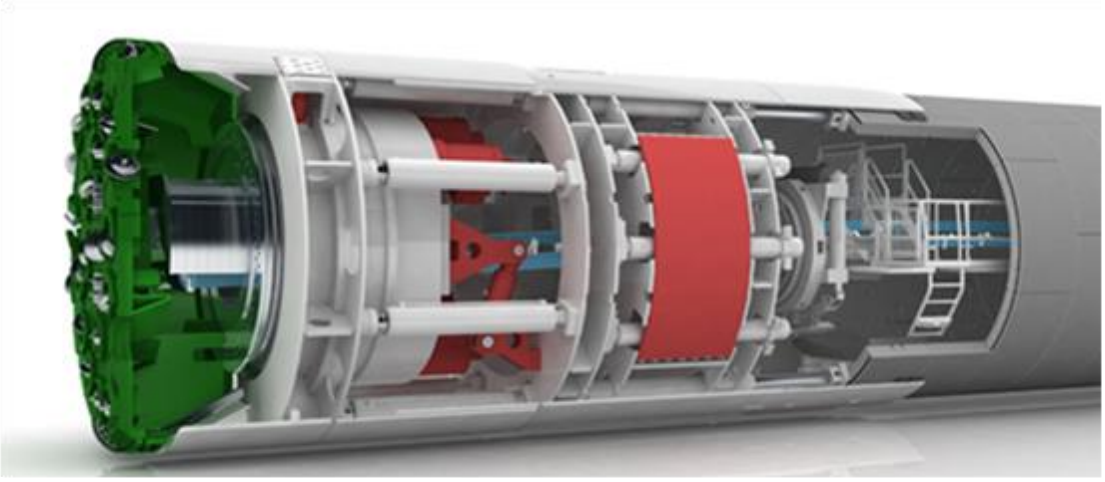


Figure 5 Double Shield TBM © Herrenknecht AG

2.2. Soft-ground TBMs

Two main types of Soft-ground TBMs shall be mentioned in this work. EBP (Earth Pressure Balance) and Slurry TBMs are the most important and most commonly used types of shielded machines with active face pressure to avoid ground settlement in soil and soft ground. When it comes to guidance the principle of a Soft-ground TBM is the same as the Single-shield TBMs. Major differences in excavating ground compared to Hard-rock TBMs can be seen in the cutting tools and the face support. The cutting tools are excavating ground by a ripping action (i.e. drag type tools as compared to disc cutters for rock TBMs) using carbide teeth. When condition changes are expected such as occurring rock boulders at the face, the cutter wheel is usually equipped with additional disc cutters. Soft-ground mostly requires face support. This is where the two mentioned types of soft-ground TBMs have their major differences.

2.2.1. Earth Pressure Balance TBM (EPB)

The principle of an EBP shield is that the excavated ground is used directly as a support medium to counteract the pressure of the face and prevent water seepage into the face and face collapse. The excavation chamber is completely sealed through a bulkhead and a screw conveyer. The screw conveyer regulates the spoil removal and the pressure inside the excavation chamber. To support the face and regulate the pressure properly the muck has to convert into a plastic paste. Therefore water, foam, polymer, bentonite or a combination of these additives are added to make the soil more plastic and flowable.

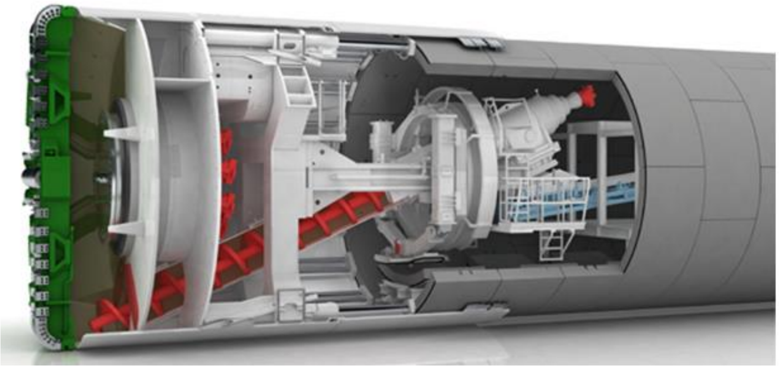


Figure 6 EPB (Earth Pressure Balance) TBM © Herrenknecht AG

2.2.2. Slurry TBM

The Slurry TBM supports the face with bentonite slurry, that is pumped into the excavation chamber through a pipe system. The slurry is a mixture of water, bentonite and excavated ground. In some cases polymers are used to replace bentonite. The excavation chamber is divided centrally by the front bulkhead in front and rear part. A submerged wall opening in the front bulkhead connects these two chambers. In the rear part an air cushion situated on the top regulates the pressure of the bentonite slurry by adapting the air pressure. The air cushion also acts as a buffer to sudden pressure changings.

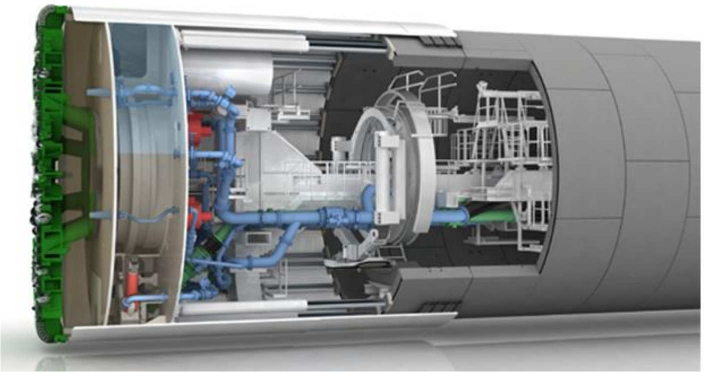


Figure 7 Slurry TBM "Mixshield" © Herrenknecht AG

2.3. Application fields

	TBM - Type	**Ground Type**	
Hard-rock TBM	Open type (X-type, Single bracing)	rock	competent to slightly fractured
	Single shield TBM	rock	fractured, low stand up time
	Double shield TBM	rock	fractured, low stand up time
Soft-ground TBM	EPB TBM	soft-ground	cohesive fine grains
	Slurry TBM	soft-ground	Incohesive coarse grains

Figure 8 basic application field of the different TBM types

The table above shows the usual application field of the described TBM types. However this is just a general overview and the different TBM types can also be used for ground that is out of the usual application range. For example a Soft-ground TBM could be a good choice in groundwater bearing rock to avoid penetration of water into the heading. ([6] BTS and ICE 2005)

Decision between EPB and Slurry TBM

Generally soft-ground TBMs are used for poor ground conditions, sands, silts, soft clays below the water table. When comparing the two main types Slurry and EPB traditionally EPB TBMs are used as described in the table above for finer grained soils and SPB for coarser grained soils. However the application field increased with the development of additives so that the criteria of decision between those two types is not necessarily the type of soil ([3] Lovat 2006).

Tunneling projects such as the Turin metro line 1 (2000 – 2005) have shown that an EPB TBM can operate even outside the theoretical range of a Soft-ground TBM. Large boulders and cobbles, gravel, a view sand and almost no fine-grains were encountered at this project.

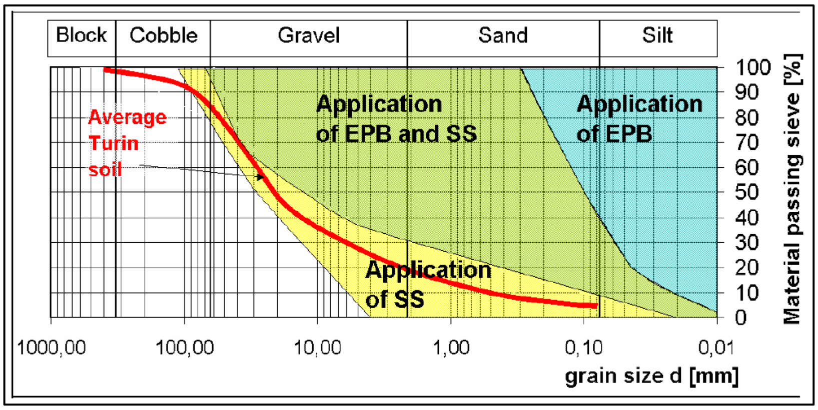


Figure 9 application field EPB and Slurry TBM (SS for Slurry Shield) with grain size curve of Torino soil ([4] Carrieri et al. 2006)

2.4. Steering and control issues

„*Steering a TBM is an art, and one not easy to practice off-site*.“ ([1] Bickel et al. 1996)

Single Shield TBM

Steering of a shield TBM can be very site sensitive. For example, lifting the cutterhead results in a rise of the TBM axis in stable rock. If conditions are worse, for example molasse marl or broken sandstone it has the opposite effect, because weak layers get sheared off by the cutting edge. “*The slow lifting of the shield TBM can only be achieved by producing resistance at the top of the shield by extending steering fins*.” ([2] Maidl et al. 2008)

Shielded TBM (including EPB and Slurry)

Another steering issue occurs when the ground changes inside the cutterhead range. The TBM will always tend to drift away into the softer area because the pressure increases on the cutters that are facing it the harder ground. Usually this can be countered with increasing the force on the propulsion jacks on the side of the harder ground and decreasing it on the other side. If the TBM is equipped with a movable cutterhead or movable Forward shield it can be aligned to support this steering measure.

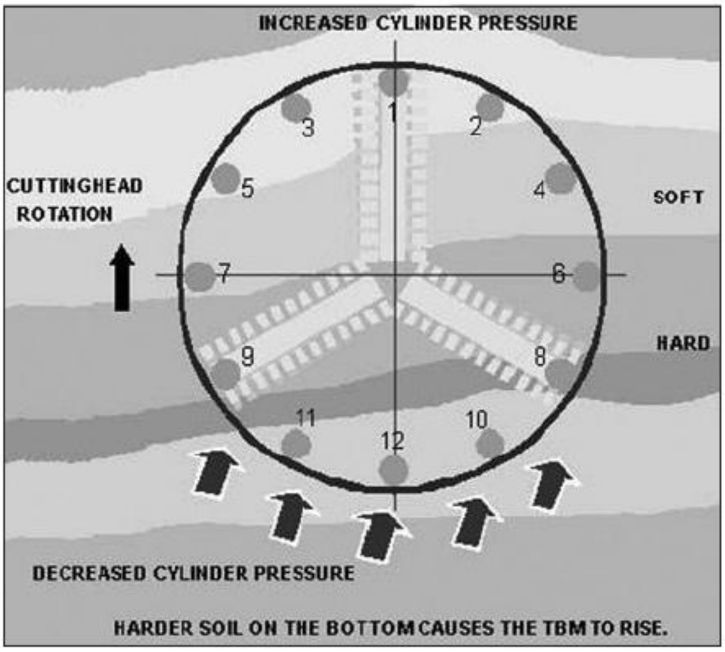


Figure 10 Impact of ground conditions on steering (Lovat) ([5] Redmond and Romero 2011)

Double Shield TBM

Since the shield of this TBM type is considerably longer compared to the single shield TBM it has to deal with higher cladding friction and there is higher chance for the TBM to get trapped. A critical part of the TBM is certainly the telescope shield joint. This is the area between front and rear shield that allows for articulation between the shields within a few degrees. This articulation also allows the machine to be able to negotiate turns along the alignment. Fallen rock between the shields can make it difficult to move the shields or ground material can even clog the telescope joint. ([13] Grandori et al. 1990)

Chapter 3: Control System and Management

"*The correct choice of machine operated without the correct management and operating controls is as bad as choosing the wrong type of machine for the project*" ([4] BTS and ICE 2006)

To ensure a smooth TBM advance and avoid severe incidents, the monitoring of TBM data as well as an accurate managing and control of these data is an essential part and sets a prerequisite for a successful tunneling progress. This chapter provides an overview of the important parameter and how control systems can work successfully in the case of an EPB TBM. The responsibility of the TBM operator shall be pointed out by explaining his working routine, important control actions and an example of an incident that appeared because of insufficient control of face support. Furthermore the issue of interpretation of TBM data is mentioned and suggestions for possible improvements are discussed.

3.1. Successful TBM management

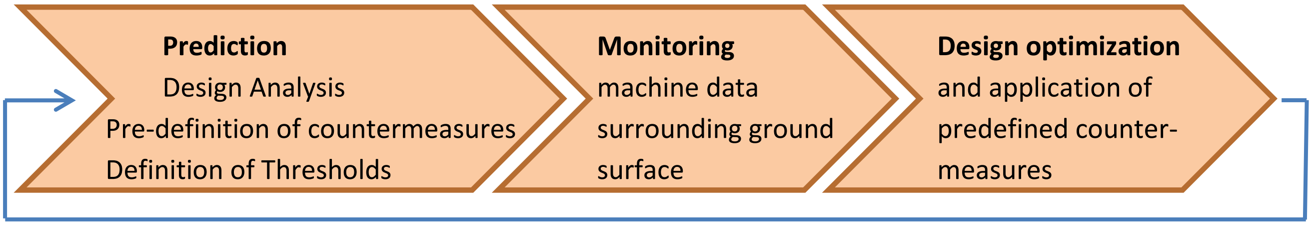
Modern TBMs are usually equipped with a direct connection to the surface to provide a data for engineer's to recognize needs for maintenance or adjustments in performance. In critical situations technicians are able to act quickly and contingency procedures can be treated under permanent supervision ([7] Guglielmetti et al. 2008). This system also acts as a source of information in retrospect to identify eventual reasons of incidents happened during the excavation progress.

The highest requirements regarding ground control are surely encountered in urban areas where surface subsidence must be prevented entirely. In order to avoid this and to control construction risks, a system has been developed called PAT (Plan for Advance of Tunnel)

PAT (Plan for Advance of Tunnel)

The PAT is a live document that implements a concept that provides a dynamic link between design and construction and enables the management of prevailing risks. It is a procedure where risk scenarios and mitigation plans can be updated throughout the excavation progress. The model is based on the initial design documents, previous PAT stretches and input data ([7] Guglielmetti et al. 2008).

Pat Scheme:



The example “Nodo di Bologna”

An example for a successful application of the PAT system is the “Nodo di Bologna” tunnel construction (Italian High Speed Railway System). This project was accomplished in a sensitive urban area where the impacts on the surface had to be minimized.

The main elements of the excavation control system:

- Detailed TBM advance plan (PAT) for each 300 meter section with definition of all necessary parameters and design issues. During the excavation the main TBM parameters, ground conditions and effects on surface were back-analyzed and the procedures were customized.
- Permanent site team with supervising tunnel engineer during all time for checking TBM data and reflecting of excavation procedures.
- Technical Desk for daily and weekly reviewing and analyzing of TBM reports

The fundamental parameters controlled during excavation:

- Face support pressure
- Muck “Apparent Density” and extracted muck weight
- Tail Void Grouting volume and pressure

The TBM operator controlled the advance speed and the screw conveyor rotation speed to stay inside the previously set upper and lower levels, so called “Attention Thresholds”. When the “Alarm Thresholds” would be reached the excavation would stop automatically.

Monitoring System

The required information was delivered to a web-platform and technicians could get access to data in real time. The client and consultant were able to check the soil behavior around the excavated area and almost 200 EPB parameters were recorded every 5 seconds. ([8] Marchionni and Guglielmetti 2007)

3.2. Important data in case of an EPB TBM

Every type of TBM is different in handling and controlling and there is a huge amount of processing data. The described case of an EPB in this section gives an overview of important TBM data and should be a representative example for TBM control. The whole research is mainly aimed at Soft-ground TBMs due to the fact that they are more complicated in its structure and handling. As the machines are more complex and the ground they deal with needs to be treated and investigated cautiously, the issue of interpretation of TBM data is more common in comparison to Hard-rock TBMs.

The main monitored parameters for excavation control of an EPB TBM

- Face support pressure: Keeping the maintenance of the face support pressure on the correct level is crucial in order to ensure the face stability.
- Weight and volume of removed muck: To avoid an under or over-excavation it is important to record weight and volume during all time.
- Density of muck in the plenum: In order to indicate the consistency of the paste inside the plenum and to guarantee its capability to offer adequate face support pressure, the density needs to be monitored. Furthermore the density is an indicator of the plenum filling rate.
- Volume and pressure of backfill grout: To prevent deformation and surface settlements it is important to measure and control the Segments backfill grout.

3.3. Control actions and working routine of the TBM operator in case of an EPB TBM

3.3.1. Working routine and recorded data

The TBM operator’s start-up routine for one stroke consists of the following:

- Start-up of electrical motors and hydraulic groups
- Start-up of foam or/and other used additives, injection into plenum and/or screw conveyor
- Start of cutterhead rotation
- Pressurization of thrust jacks
- Start of screw conveyor → begin of excavation progress

In course of the TBM movement the operator is always aware of the difference between theoretical tunnel axis and TBM axis. To steer the TBM and keep the alignment difference at a minimum, the operator controls the center of thrust of the propulsion jacks and if possible, he aligns the cutterhead and shield direction.

When the propulsion jacks are extended to its limit, the machine operator stops the additive inflow, except when it’s needed for upholding the face pressure. He reduces the cutterhead rotation speed, the thrust on the jacks and the screw conveyor rotation until its stoppage, finally he shuts the rear gate of the conveyor. ([7] Guglielmetti et al. 2008)

Besides this major activity during a stroke the machine operator always has to be attentive and observe several machine data to check them on potential irregularities. There are over 200 data visualized on the operation screens. The machine operator has to assume responsibility for observing these data and take suitable controlling measures when it’s needed. To illustrate how big the amount of data is, the most essential once are listed below:

Essential machine data of an EPB TBM: ([14] Breunig, 2013)

- Cutterhead torque and rotation speed
- Screw conveyor torque and rotation speed
- Propulsive force and velocity
- Penetration
- Pressure force of cutting wheels (if main bearing is displaceable)
- Shield rolling and position (surveying)
- Extracted muck quantity control
- Support pressure in plenum
- Mortar pressure and quantity of backfill grout
- Parameter of additives for ground conditioning
- temperature of oil and cooling water
- grouting quantity of grease lubrication (propulsion and tail seal)

3.3.2. Control actions

Concerning the ground control, the EPB Machine Operator is basically responsible for the following operations.

- Regulating the Face-support pressure
- Control of weight and volume of the extracted material
- ground conditioning, according to the instruction received from the Machine Superintendent
- Control if any abnormal situations

If any abnormal situation occurs during the TBM advance the Machine operator has to inform the machine superintendent immediately. The machine superintendent usually has to inform the project manager about the initiated countermeasures. Generally there is an operational range for parameters like face-support pressure, extracted muck weight and apparent density. The limits of these operational ranges are visualized thresholds which the machine operator uses to control the TBM. If it is not possible to remain inside these ranges the machine operator has to advise the machine superintendent. If the alarm thresholds are exceeded the TBM operator has to stop the machine instantly. ([7] Guglielmetti et al. 2008)

The BTS (British Tunneling Society) and the ICE (Institution of Civil Engineers) suggests that the operator has to immediately shut down the excavation, advance the cutterhead hard against the tunnel face to maintain support pressure and wait for further instructions when he realizes any anomaly. ([6] BTS and ICE 2005)

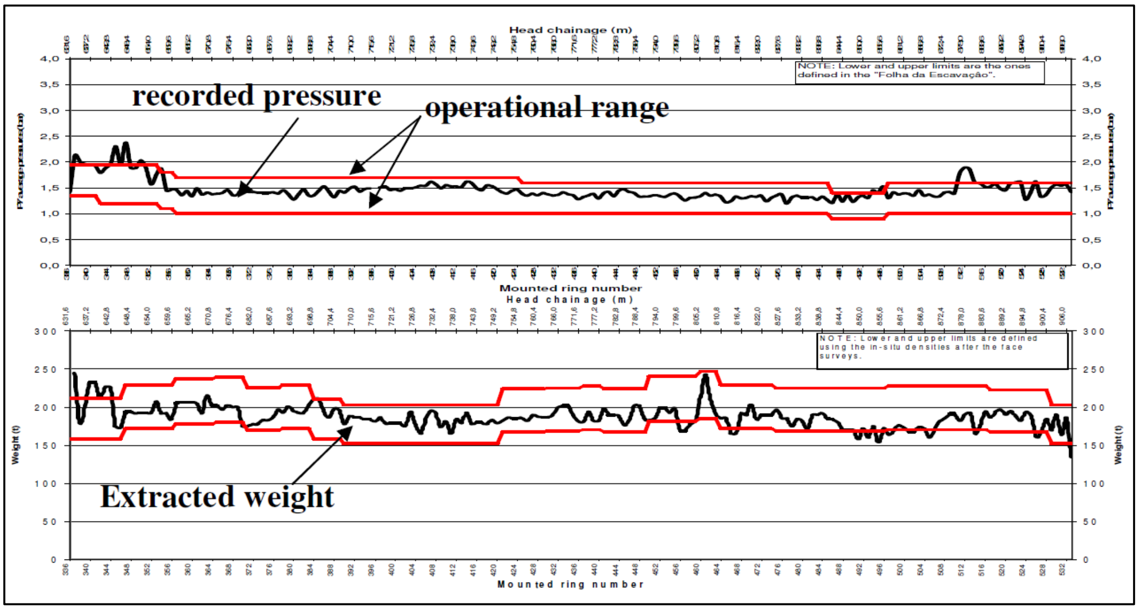


Figure 11 Attention thresholds to control face support pressure and extracted muck weight ([9] Guglielmetti 2012)

Regulating the face support pressure:

If the face support pressure decreases under the lower limit (attention thresholds) the operator reduces the rotational speed of the screw conveyor to stabilize the pressure and vice versa. This procedure assumes that the pressure sensors are calibrated properly for an exact measurement. It is also important to check the relation between face support pressure and ground condition variations. During a stoppage usually a face pressure drop will occur which has to be controlled and suitable countermeasures must be initiated when needed. In some cases also an increasing pressure could occur during stoppage, which could indicate a face collapse, water inflow or an insufficient support pressure. In any case the TBM operator has to increase the support pressure. When restarting the excavation progress it is very important to check other parameters such as torque, thrust or any subsidence on the surface. ([7] Guglielmetti et al. 2008)

The following graphic shows the influence of a pressure compensation system at the Metro do Porto Project in Portugal. Bentonite-Slurry was added to the excavation chamber automatically when a certain minimum value of face support pressure was reached. Usually the TBM operator is responsible for these countermeasures.

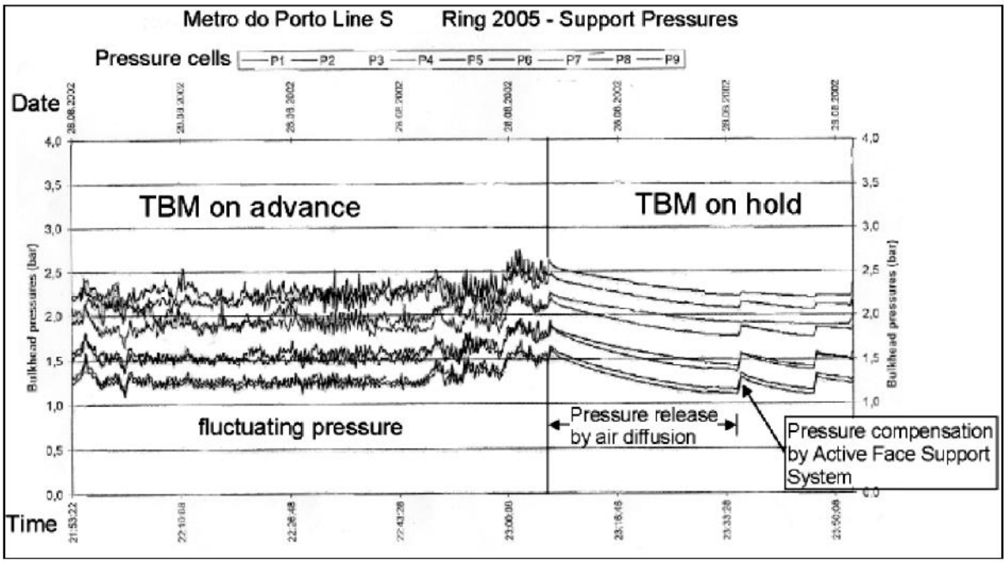


Figure 12 Difference in face support pressure during advance and stoppage. ([11] Babendererde et al. 2005)

This picture below shows a surface settlement caused by insufficient face support of a Slurry TBM during stoppage at the Tunnel Radfeld/Wiesing.

Figure 13 (a) Surface settlement

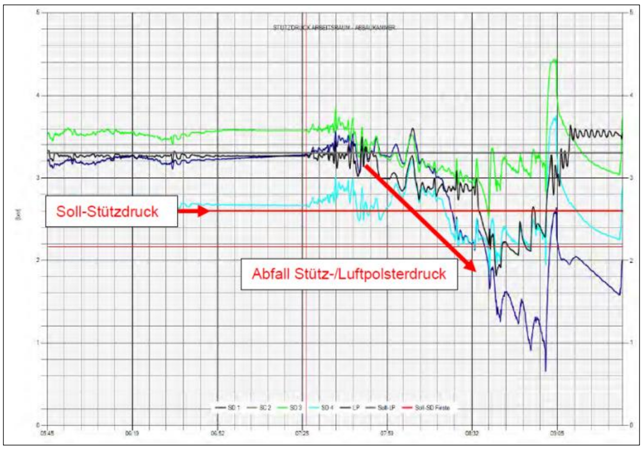


Figure 13 (b) face support pressure drop during stoppage

([10] Maidl and Labda 2010)

This brief insight in controlling the face support gives an example of the TBM operator’s responsibility. Especially during stoppage and intervention phases the operator has to be attentive to prevent an incident like the one described above. Furthermore it is important to see the trend of all the data and what it could possibly indicate for the present and further ground conditions and TBM advance. Therefore a well-educated TBM operator with know-how and “common sense” is crucial. It may be argued that a good cooperation between TBM operators and engineers is essential as well to ensure an effective detection of faults or changing ground conditions and prevent serious incidents.

3.3. Analysis of Incidents and issue of interpreting TBM data

The Closed-Face Working Group made an attempt to collect data of incidents that happened in the case of Slurry and EPB TBMs in order to identify common factors of incidents (collapses or excessive settlements) and prevent future occurrences. Data of 14 incidents of Slurry TBMs and 47 incidents of EPB TBMs all over the world were collected. The higher number of EPB TBM incidents results from the larger application of EPB TBMs in comparison to Slurry TBMs and is no indicator of safety. ([6] BTS and ICE 2005)

Collected data of incident characteristics

Incident features	**Slurry TBM**	**EPB TBM**
Total number of incidents	**14**	**47**
Problem during maintenance or TBM problems	4	8
Ground obstructions	1	4
Over-excavation	8	16
System obstructions/other	-	4
Unknown cause	-	6
Mixed-face ground conditions	5	13
Human error	4	15
Inappropriate technical decisions	-	13
Exit/entry to launch/reception shafts	-	9

Figure 13 incident characteristics ([6] BTS and ICE 2005)

When evaluating the data above it should be pointed out that not all of the incidents can be assigned to only one specific cause. For example in the case of the EPB TBM incidents, 15 out of 16 over-excavation characteristics could be attributed to human factor and in particular to operator or technical error ([6] BTS and ICE 2005). It is noticeable that the majority of all incidents are caused by human errors, unexpected ground conditions or a combination of these factors. In fact statistically more than 30% of all EPB TBM incidents and more than 25% of all Slurry TBM incidents are directly attributed to human errors. However, the amount of data is too small to make a precise and reliable statement and either way it is hardly possible to attribute an incident to a specific issue every time. Nevertheless this statistic demonstrates that the human factor is a fundamental part during the TBM advance and especially the TBM operator and his supervising team can be considered as its key elements.

Generally interpreting TBM-data is not an easy task, since there are many factors that influence these data. A precise analysis can only be drawn if the person who does the interpretation is aware of all failures and influences. There are often inaccuracies in measurements and it is not uncommon when operational data aren’t completely conclusively. Another thing that might have an influence is the steering of the TBM operators. Steering and controlling of a TBM is done mainly based on their own experiences and according to this, each operator has a different style of handling the TBM. Without the consideration of their actions an accurate interpretation is more difficult.

3.4. Summary

As shown in this chapter the TBM operator has a great responsibility in operating and controlling the TBM. In order to avoid technical or human failure the described System "PAT" in combination with a real time data analyzing and permanent site support team has been proved to be successful. This is an approach that reduces the responsibility of the machine operator and at the same time allows specialists to get access to important data without delays in order to make the right decisions at the right time and react effectively in contingency situations.

At the current state of the art, TBMs can be equipped with seismic control systems which should provide information about the encountered ground conditions. Applied alternatives are acoustic and electrical waves ([12] Mooney et al. 2012). Theoretically these systems are beneficial, however they are expensive and need specialized knowledge in order to interpret the produced data correctly.

The field of TBM monitoring has significant room for advancement and at present, the technology hasn't replaced the significance of human expertise yet. This expertise consists of a combination between individual know-how and team competence. In terms of controlling the TBM, essential members of this team can be seen in 3 persons: the tunnel engineer, the tunnel foreman and the TBM operator. In any case the TBM operator knows best about operating the TBM, and with the input of engineer and tunnel foreman he finally decides about control measures.

It is a widely recognized experience that every operator has his individual way of steering that can sometimes be identified like a person's fingerprint ([14] Breunig, 2013). TBM operators communication with each other and their team about general steering issues, occurrences and further procedures could be a benefit for the interpretation of TBM data as well as controlling of a TBM. These communications can improve their understanding of operating issues and mitigation plans and subsequently improve their skills to operate the TBM in a more efficient and productive way.

Ongoing Research

The Questionnaires and interviews that are prepared and distributed to various stakeholders in tunneling industry in course of this research are primarily for examination of the training of machine operators, their skills, expertise and their responsibility for operating the machine. This information can be the basis for further analysis of the conditions and site organization on the tunnel site to increase machine productivity, reduce downtime through proper use of machines by experienced operators. Both parts will be discussed later and conclusions and ideas of improvement can be drawn.

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