# Use of "Command Chair" Simulator Technology to Optimize Modern TBM Performance

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TBM operator cabs and controls are often a long way down the list of priorities when it comes to the overall design of a Tunnel Boring Machine. However, their proper design and inclusion of the latest technology can mean the difference between a successful project and an unsuccessful one.

On soft ground machines the industry often puts operators in control of machines with little or no practical experience of that particular machine or the control systems. This practice can, in some cases, lead to major incidents such as ground heave or sinkholes in densely populated urban zones causing major disruption, downtime and untold damages and cost.

This paper will discuss the advances and developments in TBM operator controls and the use of "command chair" technology as both a training tool in the form of a boring machine simulator and as a way of controlling modern-day TBMs.

## INTRODUCTION

For a long time now personnel entering construction sites have been required to carry out safety induction courses. These courses can range from a simple one-day course explaining basic safety principles to induction courses that can last a full week and cover a wide range of topics.

For personnel operating machinery or driving vehicles on site there are additional courses to be undertaken that include theoretical and practical training. In a lot of cases specialist training companies are hired to certify operatives of machinery, and personnel are issued with licenses or given approval to operate the said machine.

Boring in and around major world cities is often done under sensitive structures, roads and rivers. The potential for an incident caused by sinkholes or ground heave cannot be underestimated. Damage to structures or disruption to daily life can lead to multi-million dollar claims against contractors and untold damage to the reputation of the client and contractor.

It seems remarkable therefore that in today's world with tunnel boring machines operating in highly populated urban environments, TBM operators or pilots as they are sometimes known are hired based on, in the main, experience alone. In a lot of cases these operators are trained by personnel from the tunnel boring machine suppliers or by their peers whom, it can be said, have little or no formal training themselves.

Whilst this approach to TBM operator selection has served the industry well enough until now, albeit with numerous catastrophic failures, it would appear that with the technology available to us, the number of perceived higher risk projects being undertaken and the requirements of clients to adhere to much stricter operating parameters of machines, the time has come to introduce a more formal TBM operator training program.

## OPERATOR TRAINING TOOLS

Currently there aren't many tools available for TBM operators to learn about the functions of the machine they are going to take control of. In the first instance the operator gets access to the tunnel boring machine manual. In most cases they are then put in an operator room or cab. The manual might explain the function of each control and the interlocks in any particular system on the machine, but it doesn't really tell the operator how to operate the machine to achieve safe, optimum production or how to overcome situations relating to changing ground conditions they encounter. A lot of the understanding of how the machine responds to operator inputs can only be gained during actual boring and this is where the fundamental problems lie.

Operator cabs in the modern day can, upon entering them for the first time, appear to be very sophisticated (they often are). They can also be daunting and personnel can in some cases be completely overwhelmed with the number of controls and information being presented to them. Couple this with the information being given to the operator in the form of verbal communication and it is easy to see how this can lead to simple mistakes that if not caught in time can escalate very quickly and lead to serious conditions and in the worst cases fatalities.

So how to improve the training? Commercial pilots are given classroom theoretical training and put in simulators for months before taking control of a modern airplane. The simulators give them the chance to not only learn the controls of a plane but also respond to most situations they may come across in real life situations.

Would it be possible therefore to come up with a tunnel boring machine operator training program that included theoretical classroom training and practical training on a TBM simulator?

### ITA-CET Endorsed Training Program for Certified TBM Operators

Since the year 2000, the International Tunneling Association committee on education and training (ITA-CET) has identified education and training as one of the most important challenges and needs of the association and officially established the ITA-CET Committee during the ITA General Assembly in Prague, in May 2007.[1] ITA-CET's role is to promote education and training throughout the tunnelling and underground space association and assist in its coordination.

In regards to theoretical training for tunnel boring machine operators at the time of writing the ITA-CET is currently working in conjunction with one of the major tunnel boring machine manufacturers to develop a classroom training course that will lead to TBM operators being given some formal classroom training.

The course is foreseen to consist of 80 hours of theoretical training over a 10 day period covering a wide range of topics related to tunnel boring machine operations.

## EPB SIMULATOR

As an enhancement to the theoretical course an earth pressure balance TBM (EPBM) simulator is also being developed by the Colorado School of mines (CSU) with input from a US tunnel boring machine manufacturer to serve as an additional valuable tool in the training and certification of EPBM operators. The EPBM simulator may also be used to train all tunnel engineers on TBM / ground interaction issues. The simulator may be implemented in multiple ways, i.e., as a stand-alone system operating on a PC or by linking the system with an actual boring machine operator cab. At the present time the simulator is simply being used as a stand-alone system operating on a personal computer.

There are an endless number of scenarios that can be created for EPBM operator training, depending on any particular project a machine is deployed on with known ground conditions. At the moment five (5) conditions / scenarios have been developed. These scenarios focus on EPBM operations during excavation and standstill (ring building) within each scenario. Geological parameters and tunnel depth can be modified (see Figure 1). Ring building will not be simulated. The current scenarios are as follows.

### Scenario 1. Boring in Sand

At the commencement of a stroke the operator initiates and completes excavation of one 1.5 m ring advance. Excavation is straight (no curvature) and operation throughout ring build & waiting time (standstill for ring building for example) is simulated with regards to control of the chamber pressure for the ground conditions encountered.

### Scenario 2. Boring in Clay

Again the operator initiates and completes excavation of one 1.5 m ring advance. Excavation is straight (no curvature) and operation throughout ring build & waiting time or standstill is simulated related to control of the chamber pressure for the ground conditions encountered.

The simulation administrator and/or user can adjust the following parameters:

- Geometry: (tunnel depth)
- The ground water table depth
- Soil parameters.

Some preset values will be provided that span the ranges of behavior, e.g., normally consolidated soft clay to heavily over consolidated stiff clay.

### Scenario 3. Boring Through Transitional Geology

The operator initiates and completes excavation of one 1.5 m ring advance that transitions from sand to clay or clay to sand (both conditions programmable). Excavation is straight (no curvature) and operation throughout ring build & waiting time or standstill is simulated related to control of the chamber pressure in relation to the ground conditions encountered.

The simulation administrator and / or user can adjust the parameters of the clay and the sand (as described in scenarios 1 and 2), and prescribe at what distance into the ring the transition occurs.

### Scenario 4. Boring in Mixed Face Conditions

The operator initiates and completes excavation of up to five 1.5 m ring advances in mixed face conditions—clay over sand or sand over clay (both conditions programmable). Excavation is straight (no curvature) and operation throughout ring build &

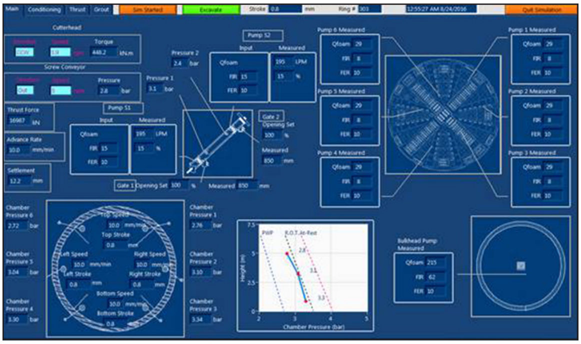

Figure 1. Screenshot of the EPB simulator operating on a PC

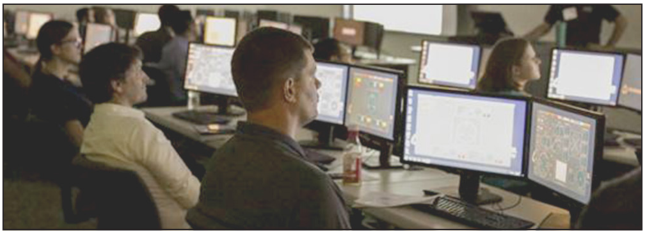

Figure 2. Students working with the simulator

waiting time or standstill is simulated, as well as control of the chamber pressure in relation to the ground conditions encountered.

The interface between the two soils changes with each advance hence the simulation of five excavation cycles.

The simulation administrator and / or user can adjust the parameters of the clay and the sand (as described in scenarios 1 and 2), prescribe whether sand over clay or clay over sand, and prescribe the depth of the interface with respect to the face.

### Scenario 5. Boring in Homogeneous Conditions

Beginning from standstill (during ring build), the operator initiates and completes excavation of up to five 1.5 m ring advances in homogeneous clay or sand (both conditions programmable). Excavation is through vertical and horizontal curves.

The simulation administrator and/or user can adjust the geometry and soil parameters as indicated above, and can prescribe the horizontal and vertical curvature.[2]

The heart of the simulator is the suite of input-output relationships, algorithms and scenarios that relates actual operator inputs to produce 'reasonable' outputs. The simulator is still in the early stages of trials, but has recently been used in an industry course offered by CSU in June 2016 (see Figure 2).

## INTERFACING THE SIMULATOR WITH THE COMMAND CHAIR

The next and perhaps most important phase of this program is implementing these simulator algorithms into any particular TBM training operator cabin. This requires the involvement of TBM and software suppliers. Further, the rendering of inputs and


**Figure 3. An example of a simulator for operator training[3]**

outputs can be done with any existing TBM supplier software, albeit with some work required to ensure both programs align correctly (see Figure 3—an example of a simulator from the excavator industry).

## COMMAND CHAIR TECHNOLOGY

Operator cabs have evolved considerably from the early days of tunnel boring machines. On hard rock, open gripper style machines it was not uncommon for manufacturers to simply put a soft cushion on top of the lubrication tank. The operator had a simple bank of hydraulic controls and stop / start stations for controlling the necessary systems to allow the machine to operate.

Over the years there have been lots of improvements to operator control rooms. On most modern machines operator control rooms comparisons have been described as being like ‘spaceships’ amongst other things.

It is a fact however that operators of tunnel boring machines now have a large amount of systems to control and are receiving so much data from systems that we now consider data acquisition systems as the norm.

Operators are not only controlling the boring machine, they are sometimes responsible for grouting systems, foam systems and other additional systems that may be installed on the machine. This has led to operator cabins becoming much larger than they might need to be. Larger operator cabins are always the central meeting station on a boring machine and it is not uncommon to see 5 or 6 people crammed into a cab. This can lead to many distractions for the operator that as previously mentioned could cause the operator to make mistakes more easily than if he was left alone to concentrate on his work.

## COMMAND CHAIR DESIGN & LOCATION

Working hours on boring machines are often long and carried out in hot, humid environments. More often than not operators are now controlling machines from sound proofed, air conditioned control cabs but one of the biggest complaints from TBM operators is the comfort of the chair they have to sit in. Many will have witnessed operators sat on stools, plastic chairs or been forced to stand up for long periods to control the machine. No particular thought went into the ergonomics of the chair for the operator either.

Furthermore, as previously stated operator stations are becoming so big that they are often placed on the boring machine back-up with little or no thought being given to what the operator sees visually. We rely on CCTV systems when in some cases it would be better for the operator to have a first-hand view of the situation. We could argue that as per a ship or other large machinery the operator should be sat in a location that gives him an overview of some of the more critical functions or areas of the boring machine. Should he for example be able to see the material on the conveyor belt or be able to see the ring build area (particularly the top 120 degrees of the machine)? In effect the operator should be located on the 'bridge' of the boring machine for the best view.

With this in mind, and with consideration to providing training to operators on the controls, a more compactly designed operator station or command chair needed to be developed. The chair essentially needs to be removable from the cab to allow on or offsite training and needs to be a self-contained unit with all systems necessary to control the boring machine included within the design of the chair.

Taking all the above into consideration, designers with input from onshore and offshore command chair manufacturers, and field service personnel (those who actually operate the machine), came up with an innovative design based around a helmsman's chair (see Figure 4).

The two panels on either side of the operator have been designed with modular control panels that are interchangeable based on the type of machine the chair will be installed on (see Figure 5).

A detailed explanation of all the functions on each of the modular control panels is beyond the scope of this paper, but suffice it to say that each modular panel is specific to that type of machine and is designed to be instinctive for the operator to start and control the machine. Functions on the control panels have been reduced to the absolute minimum with all other functions to control, monitor or stop and start systems being transferred to two touchscreen panels also incorporated in the command chair (see Figures 6–8).

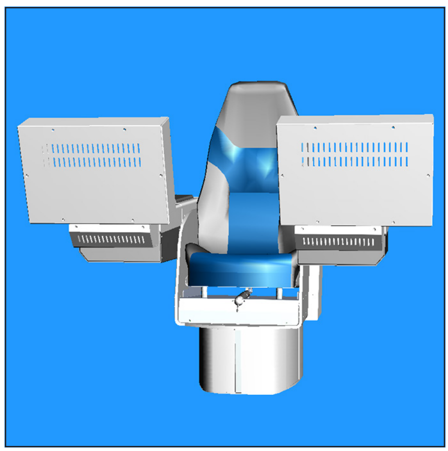

**Figure 4. Preliminary 3D design concept**

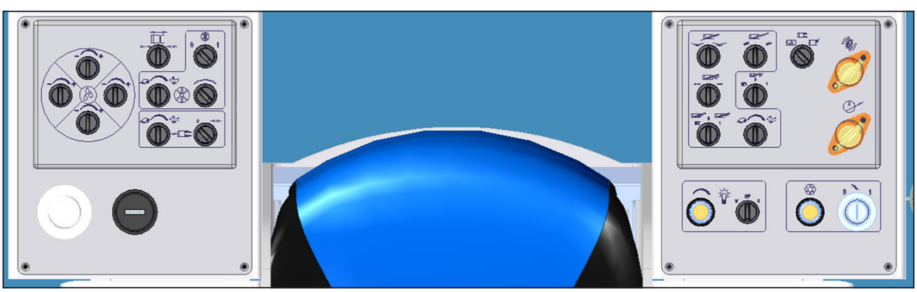

**Figure 5. Overview of the modular control panel concept for an EPB machine**

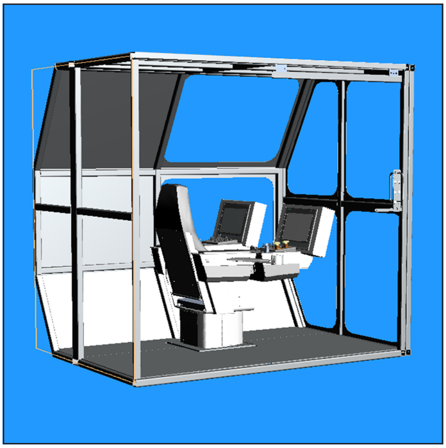

Figure 6. Command chair incorporated into a cabin

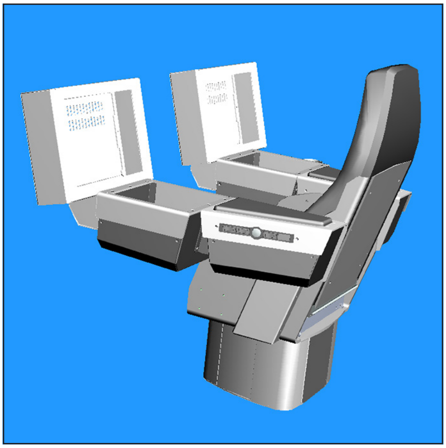

Figure 7. Side view of command chair concept[4]

## SIMULATORS FOR HARD ROCK BORING MACHINES

At this stage the simulator has only been developed for soft ground (EPB) applications. In the future programs and scenarios will be added for Slurry and Hard Rock applications.

We may actually question the need for simulators for hard rock boring conditions, but there are scenarios related to ground collapses and squeezing ground that operators would benefit from by being put through their paces on a simulator. Hard rock ground conditions and incidents related to them can lead to months of downtime on a machine whilst bypass tunnels are constructed to free blocked machines.

Figure 8. Actual commmand chair[5]

Recent projects in Turkey and Austria where machines were down for 6 months and 3 months, respectively, have shown that simulator training would have been an invaluable training aid and may well have given the operator the ability to recognize what was happening with changing ground conditions. Familiarity with how to act could have given them options to stop and treat the ground or modify the machine (for example go into an overcutting mode) before getting the machine into a very difficult situation.

## FUTURE USE OF THE COMMAND CHAIR

As the concept of the command chair is relatively new it is currently being introduced on several machines. These include projects in Nepal on a hard rock double shield machine, in India on EPB machines, and in Japan for slurry machines. These projects will come online in late 2017.

## Developments Going Forward

There are several ideas currently being considered on how to best utilize the command chair and simulator technology in future. With the ever improving connectivity of machines via high speed internet there may in some circumstances be a valid case to argue for remote operation of boring machines outside a tunnel. Whilst this has been done in the past, most control cabins due to their size and cost have not been replicated outside a tunnel. Command chairs do not require operator cabs and can be easily installed in an office environment. Having the ability to operate a machine utilizing identical controls as those on the machine rather than from a keyboard can only give boring machine pilots more confidence in understanding that a remotely operated machine will respond to their inputs just as if they were actually on the machine themselves.

Additionally, due to the incorporation of highly sophisticated data acquisition systems it is only a matter of time before a real time database of every project and all the ground conditions encountered can be stored on the simulator to give operators first-hand experience of actual conditions on any particular machine encountered.

# CONCLUSIONS

Tunnel boring machine operator training and formal recognition of training by means of certification or licensing will become the norm in the not too distant future and is a goal the industry should be working towards.

Providing operator instructors and experienced or new boring machine pilots with sufficient tools in the form of courses, lectures, operating manuals and practical training on simulators that replicate the controls on the machine (i.e., by use of the command chair technology) can only serve to improve industry standards and hopefully reduce unwanted incidents of sinkholes, ground heave or machines being out of action for lengthy periods of time.

Having pilots familiar with machines and the control thereof before a project starts will be invaluable in terms of commencing boring and reducing learning curves on machine functions.

By incorporating information from data acquisition systems from all types of machines in any ground encountered into the simulator it is only a matter of time before a comprehensive database of rock or soil conditions can be drawn from to further enhance operator training.

# REFERENCES

[1] https://www.ita-aites.org/en/wg-committees/committees/ita-cet.

[2] Mike Mooney, Director: Center for Underground Tunneling and SmartGeo, Colorado School of Mines.

[3] http://www.catsimulators.com/.

[4] Courtesy of The Robbins Company, Solon, OH, USA.

[5] http://norsap.com/.