Multi-Mode and Variable Density TBMs Latest Trends in Developments

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ABSTRACT: More and more tunnelling projects are planned in challenging ground conditions while at the same time demanding tight control of settlements. Especially in alignments with drastically changing geotechnical properties which can range from soft soils to very hard rock formations the classical TBM technology often operates at the limits of technical and economic feasibility. In the past these conditions often demanded time consuming modifications and even changes of the tunnelling equipment. Recent developments in Multi-Mode TBMs and Variable Density TBMs allow not only a smooth transition between different modes of operation and face support but are also able to safely support the ground pressure in geologies which were very difficult or impossible to handle with traditional TBMs. Multi-Mode TBMs can be incorporating at least two different operation modes, i.e. Slurry and Earth Pressure Balance or Open Mode and Slurry, while Variable Density Machines allow the smooth transition of support medium density from a low density slurry, via high density slurry up to full EPB mode. This paper explains application examples and technical principles of these machine types which have evolved in recent years.

1 INTRODUCTION

Due to rapidly advancing urbanization and rising demands for mobility in metropolitan regions there is a constant rise in tunneling activities. The biggest share is driven by expanding MRT systems. In many cities like Kuala Lumpur, Singapore or Guangzhou there are geological conditions which can be extremely demanding due to their inhomogeneity. For traditional TBMs there are limitations in terms of productivity in these conditions as they might be suitable for a part of the alignment but less suitable for another section. In situations like this additional flexibility can greatly increase performance. Furthermore there are often different methods of face support suitable in different geologies. Therefore adapting the TBM to the optimal method allows optimal face support and settlement control in all locations throughout the project. As some regions feature cavity rich geologies, for example weathered karstic formations, there have been recent developments to adapt the support mediums density to the requirements of these formations. There have been numerous projects with variable methods of face support. They include changes from EPB and Slurry to open machines, as well as changes between EPB and Slurry machines. The Variable Density Machine concept has been used in several projects successfully in recent years. This paper gives an overview on the different concepts and introduces their applicability in various challenging geologies.

2 TBM TYPES AND THE IDEA OF CHANGING THEM

The different types of TBMs are generally chosen according to the prevailing geology in a project. If for example 90% of the tunnel alignment consists of a material which is suitable for using an EPB machine, performance losses will usually be accepted for the remaining 10% which lie within a different geology. But what if either the distribution of different geologies is more balanced or very frequently changing? In this case the solution can either be a conversion once or rather an integrated solution which allows quick or immediate conversion between face support modes. The challenge here is that the face support method is often defining subsequent transport methods for the muck. Therefore the requirements for different modes vary considerably.

2.1 Different TBM Types

TBMs can be classified primarily according to the applied method of supporting the tunnel face. The German Tunneling Committee has published recommendations for selecting and evaluating tunnel boring machines together with their Swiss and Austrian counterparts. For full face excavation shields these recommendation identify five different methods of face support: without support, mechanical support, with compressed air, with slurry pressure and with earth pressure (DAUB 1997). For the discussion of Multi- Mode TBMs there are three relevant types as shown in figure 1.

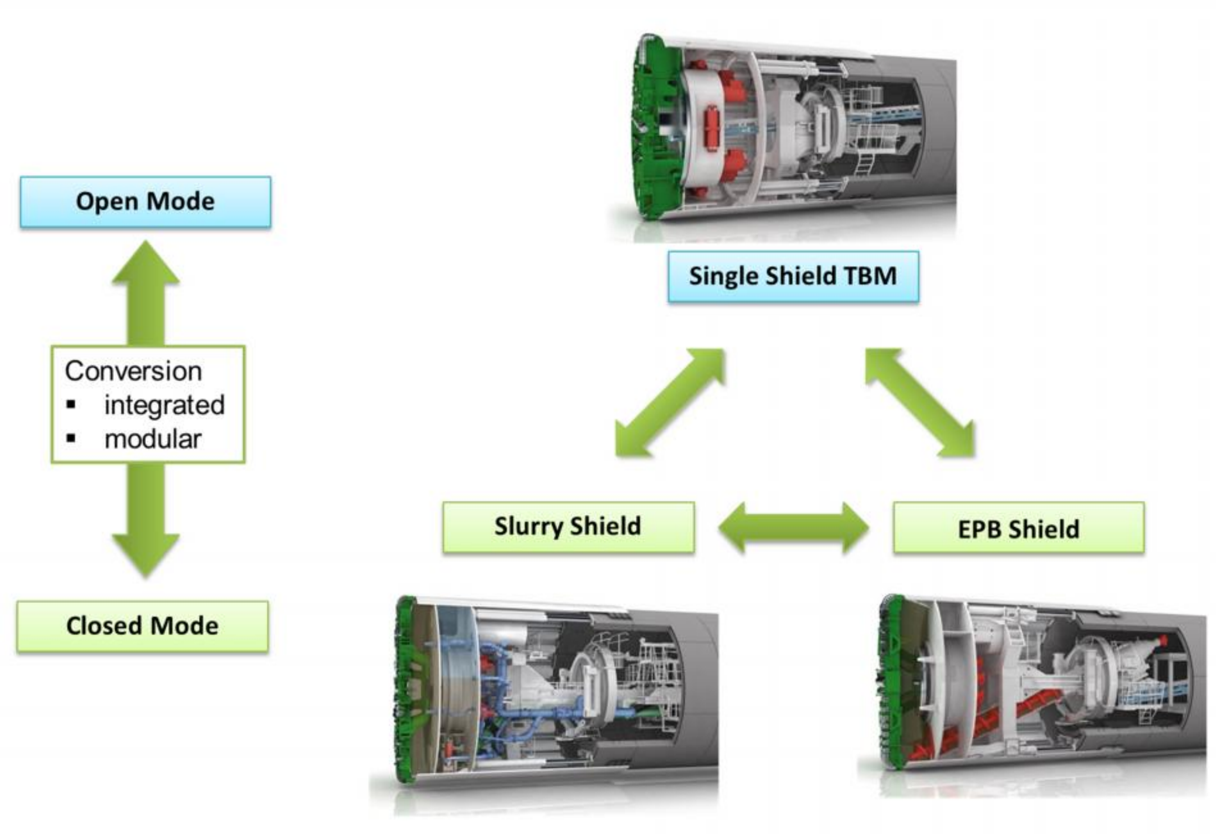

Figure 1. Different possibilities for conversions of TBM types.

These relevant machine types are:

1. The Single shield TBM which is used in ground conditions which do not require active face support. Those are typically non water bearing such as loose to hard rock and dry soils. The shields feature dry belt conveyors for muck removal. The muck is first lifted by pockets in the cutter head and then discharges onto a central collector which feeds it to the machine belt. The machine belt is installed centrally in the TBM and reaches through the maindrive to the front. The machine belt either discharges the muck onto a tunnel belt or into muck skips for the transport to the surface.

2. The Earth Pressure Balance Shield which is applied if the ground contains a sufficiently high amount of fines to allow its usage for face support. The muck is extracted from the chamber via screw conveyor and subsequently transported by belt conveyor to the end of the machine, where it is discharged onto a train or on a tunnel belt. Adequate conditioning of the soil is essential for EPBs as their face support can only be facilitated when the soil properties are plastic enough. This is normally the case in clayey, silty soils.

3. Slurry TBMs utilize a bentonite suspension to support the tunnel face as well as for muck transport. The Bentonite is supplied to the machine and discharged to the surface via a slurry circuit. The bentonite forms a filter cake on the surface of the tunnel face which allows effective support. Often a stone crusher is reducing material size below a threshold that is necessary for pumpability. This stone crusher is installed at the bottom of the working chamber; right in front of the discharge line of the slurry circuit. Slurry TBMs are used when support pressure is required in geologies which do not contain enough fines themselves to enable face support. Therefore the necessary fine particles are supplied in form of bentonite.

Generally all three types have distinct, separate application fields. But there are increasing overlaps between the possible geologies where these shields technically can be used which can be attributed to technical advance. Nonetheless even if different methods are technically applicable, there are still economic boundary conditions which in different situations strongly favor one or the other method.

2.2 Basic idea of Changing between The types of TBM

The general idea of changing operation modes of shields can be traced back to the 80s. Projects like the Grauholztunnel, Socatop or the Channel Tunnel were pioneering these techniques (Maidl 2011). Since those early projects there have been more and more machines in the market which allowed for a conversion of operation modes. The development was initially mainly driven by the European market as European geology was more inhomogeneous. Furthermore the Japanese suppliers seem to have concentrated more on widening the application range of the basic machine types by making adaptions. Today this situation has changed. The Asian market has become one of the driving forces behind technical innovation in Multi-Mode technology.

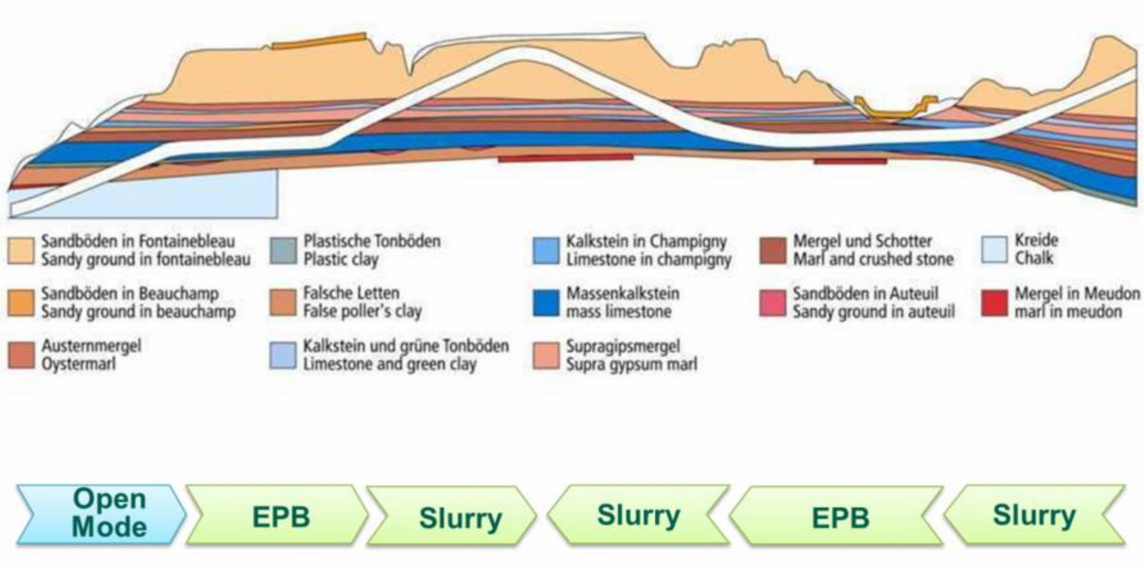

Figure 2. Changing geology conditions of the Socatop Project

The basic comparison which has to be made is between the loss of performance or possible added risk due to not using the most suitable method of face support on one hand and the time and cost for conversions. Especially for longer alignments with a few clearly separated geologic sections even time consuming conversions pay off. Such an example is the alignment of the Socatop tunnel shown in figure 2. Therefore contractors and owners are willing to make the increased initial invest for this technology and we can see more and more Multi-Mode TBMs in the market. Of course there are projects where machines were converted and then no change in geology was encountered. Therefore the conversion was the wrong decision. An example for such a project is the Galleria Aurelia in Rome which was built in the early 80s. In order to plan conversions properly, the ground conditions must be well known. If the ground conditions are characterized by frequent changes of geology, time consuming conversions are not a choice. In this case it is necessary to build integrated solutions, which can be converted without a lot of effort. This is not only due to economic reasons but also necessary to safely support the tunnel face and prevent possible water inflows. The peak of this development is the Variable Density Machine Concept which allows smooth conversion of operation modes at the push of a button.

2.2.1 Convertible Machines

Considering the three different basic principles which were identified as relevant for convertible machines in 2.1 there are three different possibilities, how a convertible machine can be realized. Firstly this can be a conversion between Open Single Shield and Slurry Shield, secondly between Open Single Shield and EPB Shield and thirdly between EPB Shield and Slurry Shield. For all these types there are different synergies between the operation modes and different difficulties to solve as well. Regularly concepts for a universal TBM which features all three operation modes are discussed in literature but economic and practical boundary conditions make this a rather unrealistic scenario.

2.2.2 Variable Density Machines

Variable Density TBMs are sometimes referred to as the “ultimate” Multi Mode TBM as they allow switching operation modes at the push of a button if fully equipped. They utilize a screw conveyor to extract material from the chamber into a slurryfier box where the muck is mixed with bentonite to make it pumpable. Alternatively a belt conveyor can be used for transport. As a slurry circuit exists, it can also circulate through the excavation chamber and therefore regulate the density here. Usually economic considerations will dictate that a Variable Density TBM is rather equipped for one or the other mode to keep the invest low, but the technical possibility for all of this is there.

3 MULTI MODE MACHINES

Multi-Mode TBMs allow the conversion of operation modes. The necessary changes usually affect the cutter head, method of face support, muck transport and sometimes even ringbuilding. The following chapter explains how these changes are facilitated.

3.1 Modular and integrated solutions

There are two general approaches for the design of Multi-Mode TBMs. Either they can be made up of a modular system which means that some components must be removed and others added upon conversion. In this case a shaft is necessary for the conversion. On the other hand one can design an integrated concept, which contains all elements which are necessary for both operation modes and can be switched in the tunnel without major modification work.

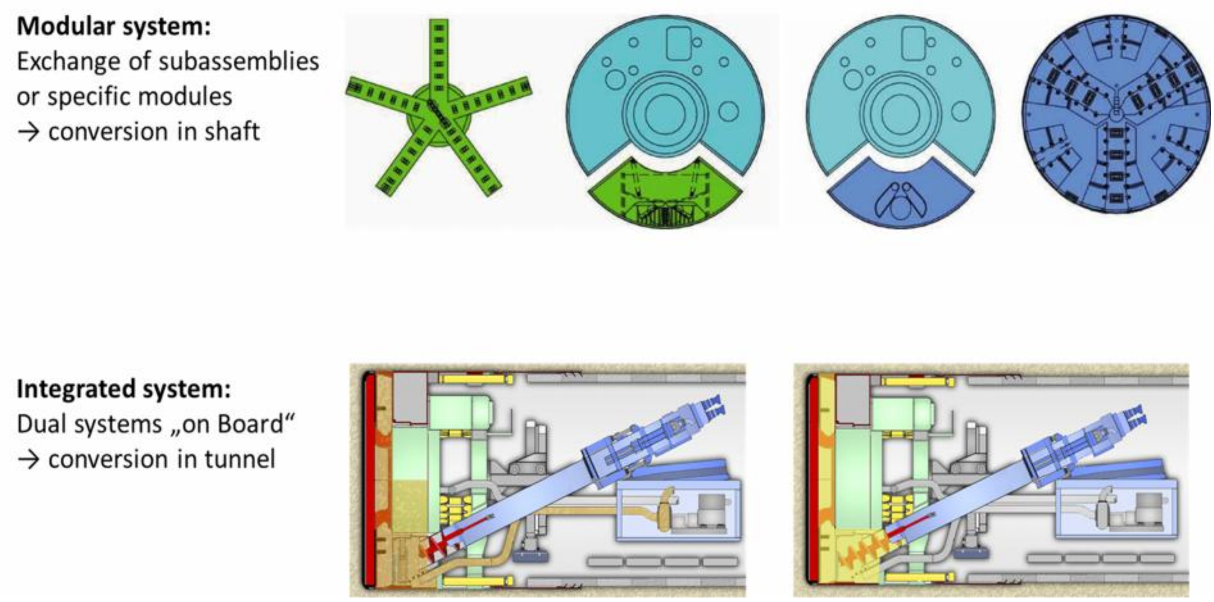

Figure 3. Modular and integrated convertible machine principles

When the first convertible machines were built, generally the amount of work which was necessary for conversions was usually leading to longer standstill periods. But technical advances have led to an increase in the number of integrated concepts which can be converted within the tunnel within a reasonable time. Especially where safety concerns play a role, for example the time to close the excavation chamber of an open machine which might run somewhere where water is expected, integrated concepts are absolutely necessary.

3.2 EPB – Open Mode Convertible

A combination of EPB and Open Shield is appealing if there are long stable sections which don't require active face support as well as sections which require face support and contain a high share of fine soils so that EPB face support is applicable. Generally every EPB shield can be run in open mode as well but only the conversion to an Open Single Shield also bring out the advantages of this machine type in the corresponding geology.

3.2.1 Concept

Earth pressure balance machines use the muck filled excavation chamber to support the face. They can be operated with a fully filled chamber or with a lower filling level of the chamber and compressed air support as shown in figure 4. In case there is no support pressure necessary, every EPB can also be run in open mode with atmospheric pressure in the excavation chamber.

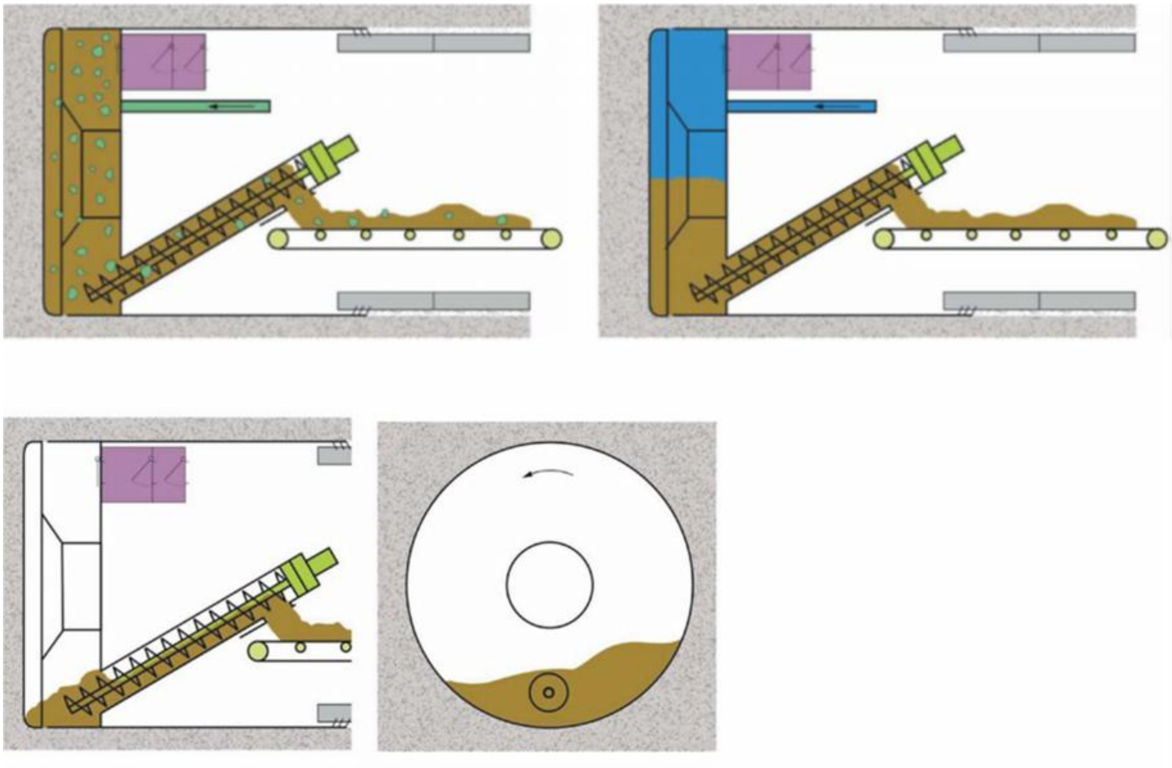

Figure 4. Different Operation Modes of EPB machines

Depending on the ground properties this can be suboptimal. In case the ground conditions are rather abrasive, using the screw to discharge the material will lead to excessive wear as no high plasticity, conditioned soil is present. In this case it makes sense to discuss a full conversion into a single shield.
That means that firstly the screw conveyor has to be exchanged for a belt conveyor in the machine center. Therefore also the rotary coupling must be removed. A muck ring must be installed to guide the material onto the belt and the cutter head must be equipped with pockets which lift the chips onto the muckring. Of course this conversion can only be done, when the geology is dry and there is no clogging. It is possible to keep the all components which are necessary for both operation modes in an integrated machine concept.

3.2.2 Example Projects

The most prominent project where such a combination of Open Shield and EPB has been used is the Channel Tunnel. As there were several fault zones and possibly water bearing zones to cross, the machines which started drilling on the French side have been designed to be operated as EPB TBMs primarily but the screw conveyors could be retracted and belt conveyors could be installed as soon as the stable formations had been reached. Recent projects include the Katzenberg Tunnels in Germany where two EPBs was operated in open mode over longer periods, the Saverne Tunnel in France and the Rio de Janeiro Metro where completely convertible shields have been used. Figure 5 shows an example for the layout of an Open Shield / EPB convertible machine. If well designed, the conversion can be done in less than two week.

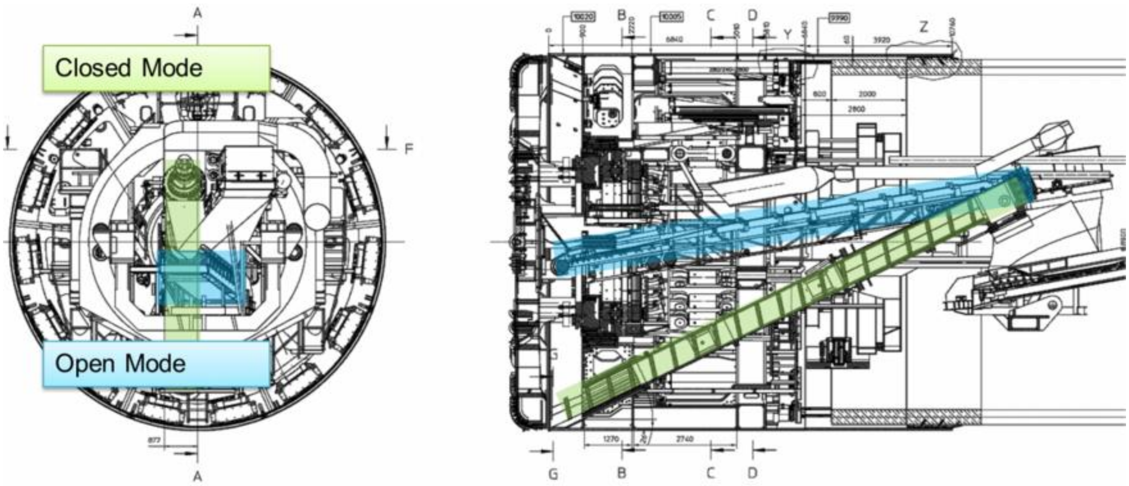

Figure 5. Integrated Convertible EPB / Open Shield TBM for the Saverne Tunnel

3.3 Slurry – Open Mode Convertible

Slurry TBM / Open Mode convertible machines are often used in projects which feature rock geologies with sections of soil or fractured rocks which require the application of face support. Since the muck transport for slurry shields requires a slurry circuit. Two transport systems must be provided. Generally speaking this type of convertible machine is probably the most widely used one as the dry / wet option gives it a very wide application range and the two systems don't compromise each other.

3.3.1 Concept

In order to transform an open machine into a slurry shield, the cutter head center must be closed, the belt retracted and a slurry circuit and stone crusher must be activated. The excavation chamber needs an opening gate in then invert to open or close the way to the working chamber and suction pipe.

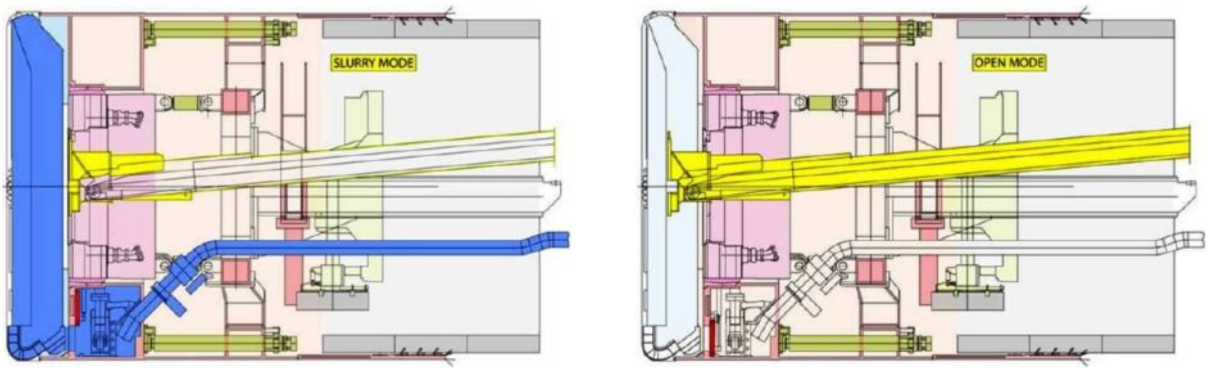

Figure 6. Convertible TBM in Mixshield Mode (left) and Open Mode (right)

Generally the conversion within the machine can be completed within a few hours. After retracting the belt conveyor and closing the center, the excavation chamber can be safely sealed off. In order to restart excavation, the slurry circuit, pressure regulation and separation plant must be in operational condition. Depending on the jobsite, this can be achieved rather quick as well.

3.3.2 Example Projects

There are quite a number of projects where convertible slurry / open machines have been used and are currently used. The pioneering project to mention is the Grauholztunnel built in the early 90s. While a large portion of the tunnel alignment featured fluvial deposits, there was a 2 km section of molasses bedrock to cross. The Alignment is shown in figure 7.

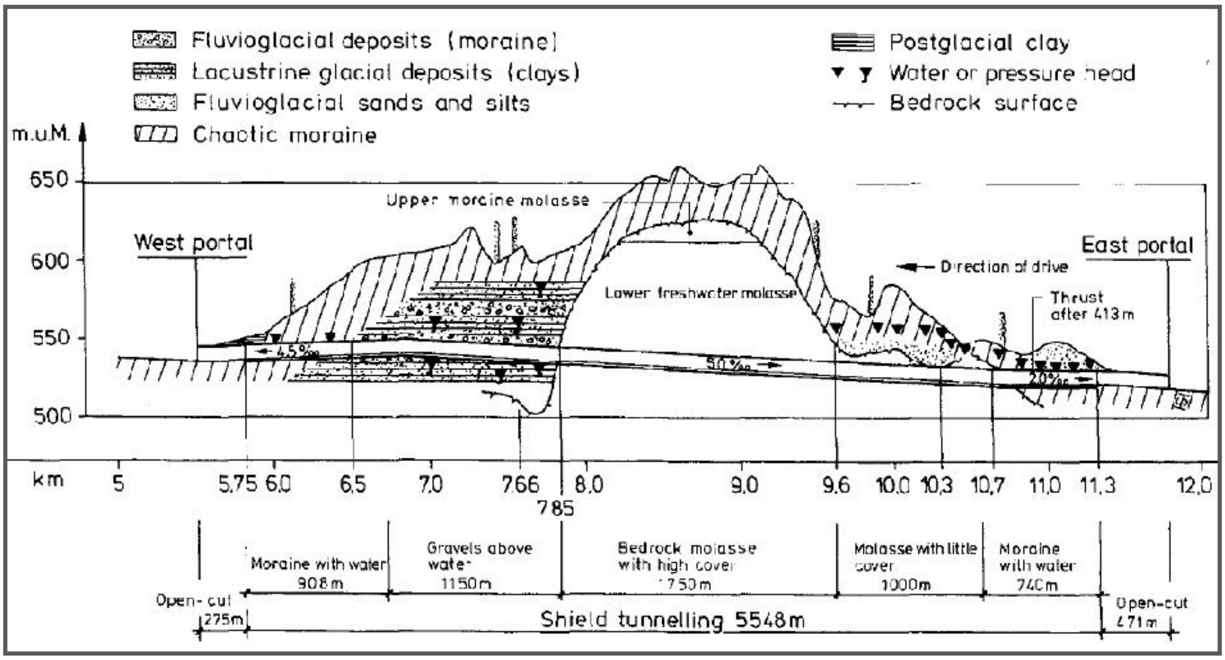

Figure 7. Longitudinal cross section of the Grauholztunnel

The machine has been started in Mixshield mode and later converted to open mode when entering the molasses. After about 1,7km the machine was re-converted into Mixshield mode. After completion of the project the chosen approach could be verified as the best possible solution at the time.

Other convertible projects worth mentioning are the Thalwil-Önzberg Tunnel, which featured a second generation convertible TBM. This machine was on one hand equipped with generally more modern shield technology which had advanced in the meantime and on the other hand incorporated the experience from Grauholz. Recent projects include the Finnetunnel in Germany and the Weinbergtunnel in Switzerland. The Hallandsas project in Sweden which is extremely challenging due to the high pressures of up to 13 bar in slurry mode. Furthermore the one special case where a screw conveyor was installed permanently in the machine center for material transport is the Lake Mead Hydropower Intake Tunnel. Due to the extreme pressures of up to 17bar, the tender required immediate closing of the excavation chamber under all conditions. This is facilitated by a retractable screw conveyor which extracts the material from the chamber when operated in open mode. The screw can be closed with a gate immediately if necessary.

3.4 Slurry – EPB Conversion

The conversion between Slurry shield and EPB is rather difficult as there are several components conflicting with each other. Therefore especially integrated concepts are hard to realize without taking relatively long times for modification into account. A change between those two systems is necessary when the tunnel alignment has sections with too many fines to effectively separate them from bentonite in one area and too little fines to allow earth pressure as a means of face stabilization and pressure control.

3.4.1 Concept

The biggest differences in layout between Mixshields and EPBs lie in the material transport system. Both feature a completely filled, pressurized excavation chamber, since they are built for applying support pressure in different types of geologies, their support mediums have different mechanical properties such as viscosity and density. Therefore the transport systems must be different. A Mixshield generally features a slurry circuit for hydraulic transport of the excavated material. Therefore the density must be low enough and maximum grain size of particles is limited by pipe and pump diameters. This is ensured by placing a mechanical stone crusher in front of the suction pipe. When converting into an EPB, this would be the exact position where a screw conveyor enters the excavation chamber. Therefore the stone crusher is an obstruction and a manual conversion becomes necessary. This has been successfully performed at the Socatop Project in France.

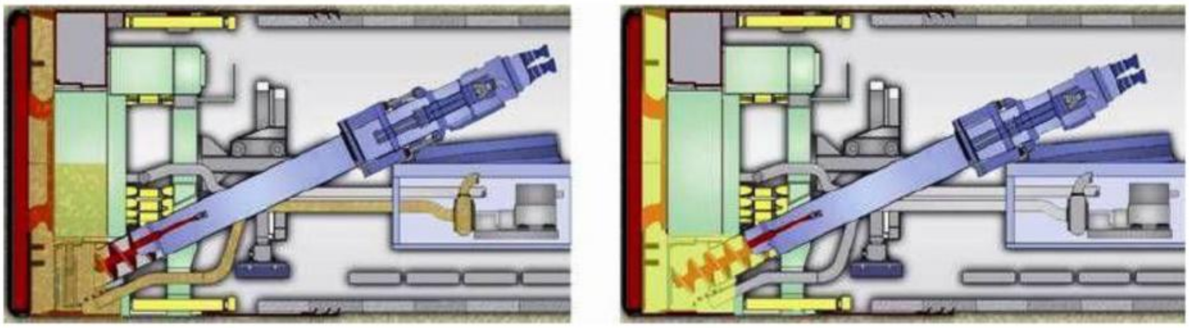

Figure 8. The Socatop TBM in Slurry Mode (left) and EPB Mode (right)

3.4.2 Example Projects

The 10km Socatop project in Paris featured optimal soils for EPB face support on about 60% of the tunnel alignment. The rest was made up by soils which were suitable for slurry shield tunneling. Its alignment is shown in figure 2. This setup with relatively long, uniform sections justified the time consuming conversion.

Another example was the M-1182M project in Singapore. As the machine diameters were smaller, more components had to be shared for the different operation modes. Therefore a Slurry / EPB integrated Multi Mode machine has been designed for this project. The project required cutting through very hard granite as well as Kallang Formation sections with soil. Generally a lot of mixed ground conditions were encountered due to weathered rock near the base rock/soil boundary. The challenges of this project were solved by installing a crusher box with a drum crusher under the screw discharge gate and connecting this box to a slurry circuit. Whether driven in slurry mode or EPB mode, the screw was utilized for the muck transport. The setup allowed world record production rates of up to 210m/week and 630m/month. This was possible since the machine could operate in the optimal mode in all ground conditions.

4 THE VARIABLE DENSITY MACHINE CONCEPT

Especially in alignments with drastically changing geotechnical properties which can range from soft soils to very solid rock formations, the classical TBM technology partly operates at the limits of technical and economic feasibility. In the past these conditions often demanded time consuming modifications and even changes of the tunneling equipment. The Variable Density TBM is Herrenknecht's recent development in Multi-Mode TBM technology. It allows not only a smooth transition between different modes of operation and face support but is also able to safely support the ground pressure in geologies which were very difficult, or impossible to handle with traditional TBMs. While Multi-Mode TBMs can be incorporating at least two different operation modes, i.e. Slurry and Earth Pressure Balance or Open Mode and Slurry Pressure, while Variable Density Machines allow the smooth transition of support medium density from a low density slurry, via high density slurry up to full EPB mode.

4.1 Overview

As can be seen in chapter three, the change from EPB to Slurry machine is mechanically very difficult to achieve as there are many conflicting components which have to be modified. Therefore one of the main development targets for the Variable Density TBM has been achieving a system which can be transformed from a slurry face support into an earth pressure face support in the tunnel without any need for mechanical modification in the excavation chamber or in the gantry and tunnel area.

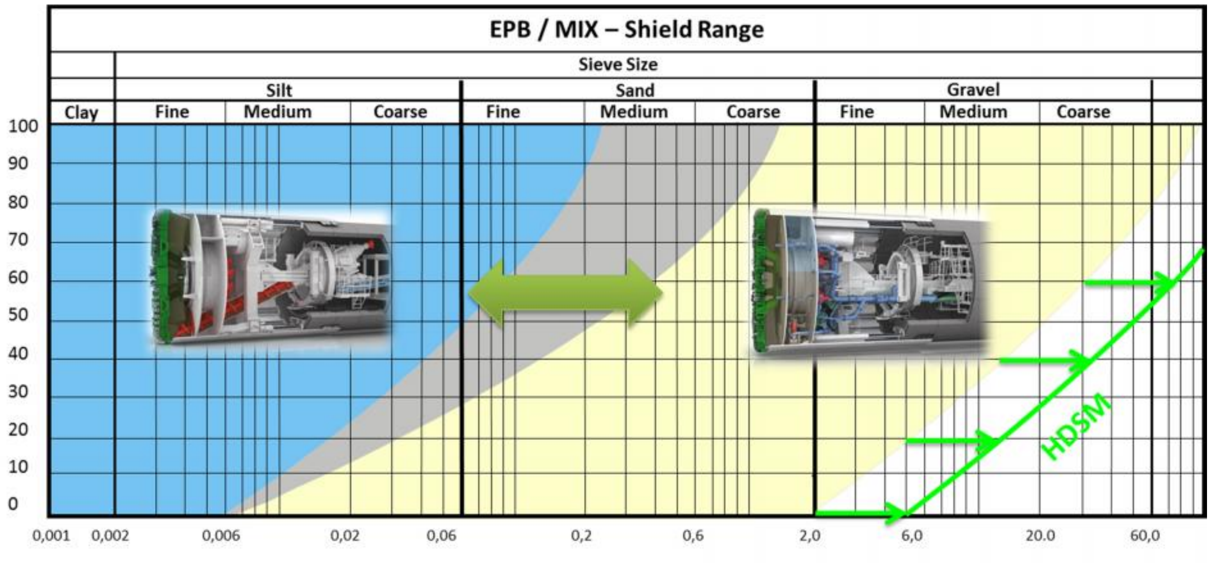

Figure 9. The extended application range of the variable density TBM

By allowing usage of special high density slurry for face support, the Variable Density Machine has an even extended application range to coarser gravel or cavity containing geologies. This can be seen in figure 9. By using a higher density and higher viscosity material for face support, the cavities in between the cobbles can be filled and an effective filter cake can be formed in geologies where normal bentonite could not support the ground. In order to achieve a setup which allows changing from EPB face support to slurry face support without mechanical modifications, the screw conveyor is installed permanently and discharges muck either onto a belt conveyor for EPB mode or into a slurryfier box for slurry and high density mode as well as for EPB mode with hydraulic transport. This slurryfier box is one of the key components of this machine concept. Before being discharged into it, the muck passes a drum sizer which ensures a maximum particle size within it. A jaw crusher can be installed as well if the ground conditions require. Subsequently the box is flushed with bentonite and the muck is transported to the surface using a regular slurry circuit. Fresh bentonite suspension for flushing is pumped to the slurryfier box and excavation chamber. By adjusting the ratio of bentonite between box and chamber, the support mediums density can be gradually changed. Behind the excavation chamber there is a working chamber filled with bentonite and an air bubble for pressure regulation like in a Mixshield. This allows the same quality of face support pressure regulation. One of the key design elements of Variable Density TBMs is the stepping of permissible grain sizes for the different components. Only stones which are small enough to enter the screw may enter through the cutter head openings and what fits into the screw must also fit into the sizer. Therefore matching different opening sizes to each other is crucial for a working machine.

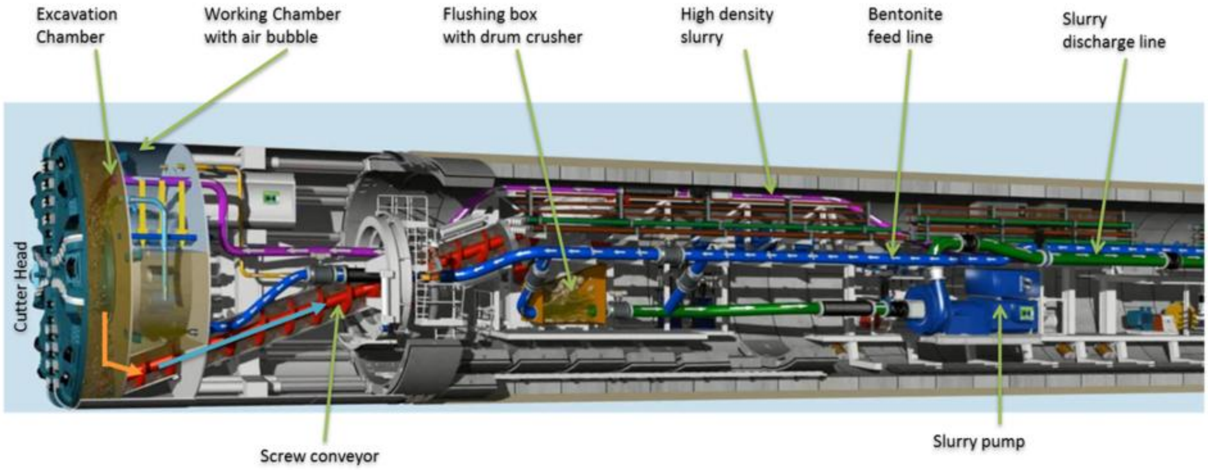

Figure 10. The Variable Density TBM (shown with hydraulic transport)

Figure 10 shows the basic setup of a Variable Density Machine in hydraulic transport mode. Key components like the flushing box, the separate high density slurry line and the air bubble system are highlighted. As mentioned earlier, the machine can be equipped with different material transport modes, which is usually an economic choice. While dry transport is only possible for EPB mode, hydraulic transport is possible in all modes but will cost more energy than belt transport in EPB mode. The different possible options are shown in figure 11. Either the equipment for both transport modes is installed permanently which requires a screw with two discharge points, one for the belt and one for the slurryfier box, or belt conveyor and slurry line are installed upon demand. This mainly depends on the initial investment and the expectations how frequently operation modes are switched. If only few changes are expected, it might not be economic to install the full set of equipment initially.

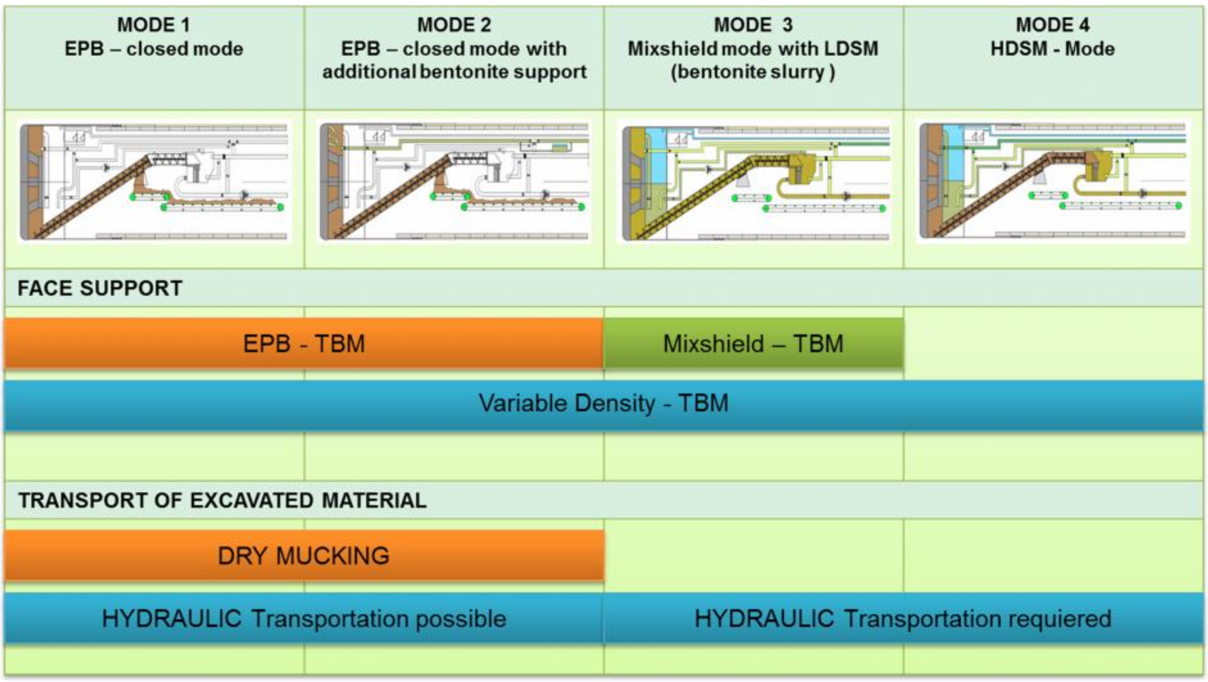

Figure 11. Variable Density TBM Operation modes and muck transport methods.

4.2 Possible Geology Scenarios

Variable Density TBMs have been initially developed for mixed ground conditions as well as for karstic formations. Especially the possibility to use higher density support medium as well as to keep large tanks of reserve slurry on the machine itself guarantee a more stable face support in difficult conditions. This approach allows for the support medium to fill cavities which are encountered without losing the medium pressure in the excavation chamber.

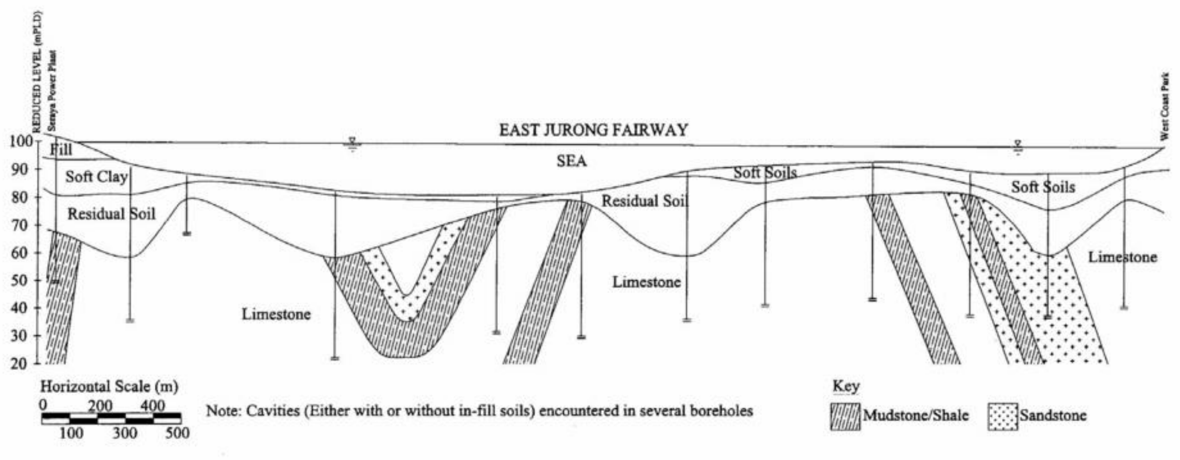

Figure 12. Possible Geology Alignment with Limestone in Jurong Formation

As can be seen in figure 12, several formations interchange in a relatively short distance in some Jurong Formations. While the formation boundaries generally are difficult to tunnel through, as there are often mixed conditions, especially within the limestone areas, cavities have been found in several exploration boreholes. Generally speaking, the application of variable density TBMs could improve the safety standard for face support in these areas significantly.

4.3 Experiences

The first application of the Variable Density TBM has been on the Klang Valley Project in Kuala Lumpur. On previous tunnel construction projects the cavities in Kuala Lumpur’s limestone have posed major challenges and have led to the formation of many settlements and some sinkholes. Approximately 100 incidents were recorded during the SMART project. Fortunately none caused any serious damage or collapse of property, but they did cost time and caused operational challenges, and provided information for the development of the new Variable Density concept. The first two Variable Density Machines have now completed more than 2km of tunneling and without any incidents of either sinkholes or blowouts. This is a considerable achievement through the highly karstic nature of the Kuala Lumpur Limestone formation and a confirmation of the Variable Density concept and technology designed specifically to deal with the challenging geology. Four more machines are used successfully in this project. So far the machines have mainly been used in hydraulic transport mode as the high density slurry support was necessary due to the karst on most stretches of the alignment. Conversion to dry material transportation will be carried out after the machines enter the Kenny Hill formation.

5 CONCLUSIONS

Conventional TBM tunneling has been characterized by a clear separation into different TBM types for different geologies. The experiences of the past twenty years have shown that the lines between the different types are blurring. While initially modular concepts have been prevailing, today there is a clear trend towards integrated solutions which offer optimal face support in all geologies. Especially as more and more projects feature rapidly changing geologies, innovative TBM technology can greatly improve the safety level. Therefore it can be expected that Multi-Mode TBMs and Variable Density Machines will have a far greater market share than today in a decade.

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