The 2021 World Congress on
Advances in Structural Engineering and Mechanics (ASEM21)
GECE, Seoul, Korea, August 23-26, 2021

Keynote Paper

Latest Developments in Shield TBM Selections & Design for Mechanized Tunneling

Ruben Duhme[1] and *Jeremy Lee[2]

[1] *Herrenknecht Asia Headquarters, Singapore*
[2] *Herrenknecht Korea Branch, Seoul, Korea*
[1] lee.jeremy@herrenknecht.com

ABSTRACT

The development and application of tunnel boring machine (TBM) technology has seen significant advances throughout the last years internationally and in Korea. Especially the closed face tunneling method with shield machines has been successfully used in a number of completed and ongoing projects in Korea. Therefore, the selection of the best suitable type of TBM and its key parameters has grown in importance. This paper highlights the key selection criteria between the TBM types of earth pressure balance machine (EPB) and slurry machine (MIXshield) as well as introduces selection criteria for the innovative Variable Density® machine (Multi-mode). The paper highlights recent successfully completed project experiences with each of these machine types. The evaluated projects in Korea are the Wonju-Gangneung Railway Tunnel using a 8.39m MIXshield and the Goseong Green Power Plant project using a 8.19m EPB machine. The Lyon Metro Line B project in France has used a 9.68m Variable Density® TBM in very challenging ground conditions and is introduced in this paper to highlight the capability of multi-mode machines in such difficult conditions.

1. INTRODUCTION

Many tunneling projects experience problems that could have been prevented by improved selection criteria for the type of TBM. The two types that are traditionally applied are the earth pressure balance machine (EPB) and the slurry machine (MIXshield). In recent years, there are more and more projects that use the innovative and flexible Variable Density® TBM. Several researchers and industry associations have defined application criteria that can be used to guide the TBM selection process for a project. Among these, the German tunneling committee (DAUB) has published one of the most comprehensive guidelines. These guidelines establish a step by step process to evaluate the project geology and select a suitable machine type based on the geology parameters. First and foremost, it is important to provide stable face support and a safe working environment at all times. A number of recent projects in Korea have used closed face tunneling machines and are successfully completed using Herrenknecht TBMs. The projects introduced here are the Wonju-Gangneung Railway Tunnel using a 8.39m MIXshield and the Goseong Green Power Plant project using a 8.19m EPB machine. Furthermore, an overseas project in Lyon, France which has successfully used a Variable Density® TBM in very difficult ground conditions ranging from granite to clays and coarse gravel.

2. MAIN TYPES OF SHIELD TUNNELING MACHINE

The main types of shield tunneling machine have been used for many years in the tunneling industry. All of them have in common that they are providing a face support pressure to stabilize the ground. However, they use different mechanisms to provide and control this pressure, resulting in different mucking systems as well. Following section introduces the basic types.

2.1 Earth Pressure Balance Machine (EPB Shield)

The EPB machine is the most common type of tunneling machine used today. As its name implies, the EPB machine uses the excavated muck to create support pressure for the face. The excavation chamber of the EPB machine is filled with muck that is pressurized by the advancing thrust of the machine. A screw conveyor extracts muck from the chamber. The muck is further transported away by either conveyor belts or muck cars. The pressure is controlled by balancing the advance rate and the extraction rate of the machine.

In order to function, the muck consistency needs to be suitable to create a stable rate of friction in the screw conveyor without water gushing through. This requires a certain amount of fine content in the ground, as well as the employment of conditioning agents such as foam, bentonite or polymer that are injected into the excavation chamber, in front of the cutter head or the screw conveyor and mixed into the excavated soil.

As the principle of an EPB is to develop pressure by creating friction in the screw conveyor and to operate with a full excavation chamber, EPBs are prone to develop high wear rates in abrasive geology. The general layout of an EPB machine is illustrated in following sketch Fig. 1.

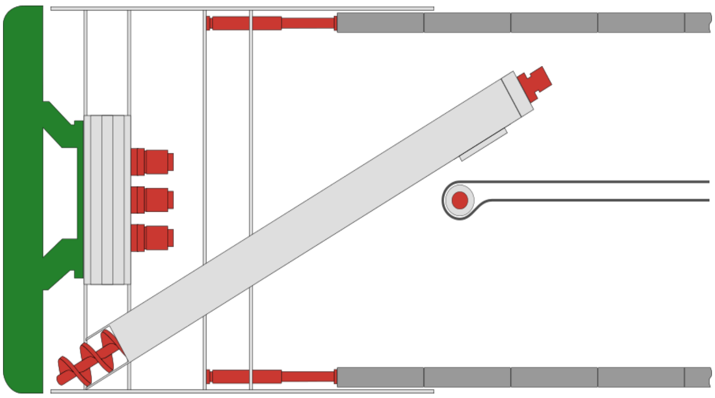


Fig. 1 Schematic sketch of EPB TBM

2.2 Slurry Pressure Machine (MIX Shield)

The Mixshield TBMs have evolved as a further development of Japanese slurry machines to improve support pressure control. Slurry TBMs use a bentonite suspension to support the tunnel face. This leads to the advantage that the process of applying face support becomes independent from the muck consistency. Therefore, Mixshields can safely operate in ground conditions where the face pressure control with EPBs is difficult. However, if encountering very coarse gravel or cavities in the ground, there is a risk of bentonite loss into the ground.

Mixshields are equipped with a double chamber system. Behind the excavation chamber, there is a second chamber that is connected to the front in the shield invert. This chamber is called the working chamber. While the excavation chamber is fully filled with bentonite, the working chamber is only filled by half. In the upper half is a pressurized air bubble. The pressure of the bubble is permanently controlled with a regulation system and its pressure is directly controlling the pressure of the bentonite. This principle allows for a very precise control of the support pressure.

As the face pressure is controlled by bentonite, Mixshield TBMs use a bentonite slurry circuit to discharge the excavated material from the machine. A stone crusher is crushing boulders before entering the suction pipe. A separation plant on the surface is required to recycle the bentonite for circulation. The general layout of an Mixshield machine is illustrated in Fig. 2.

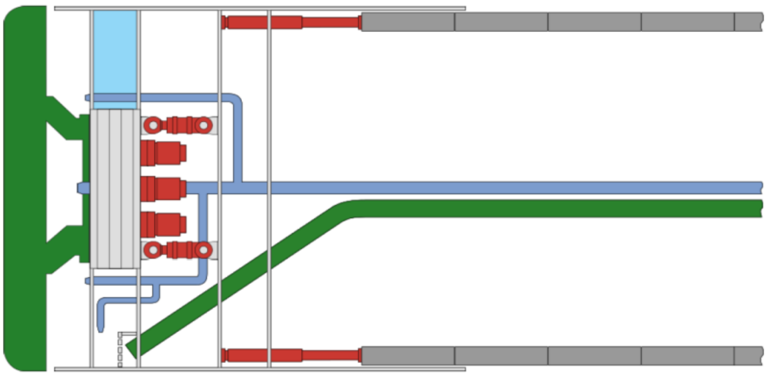


Fig. 2 Schematic sketch of Mixshield TBM

2.3 Variable Density® Machine (Multi-mode Shield)

The *Variable Density®* TBM combines operation principles from EPB machines and Mixshields. There are a few different types of variable density machines with different capabilities, however, the basic principle is combining mucking by screw conveyor with a slurry circuit and air bubble pressure control. The *Variable Density®* machine is equipped with a slurryfier box at the end of the screw. The box contains the stone crusher which crushes boulders before they enter the slurry circuit. The feed flow of bentonite can be adjusted between the excavation chamber and the slurryfier box. By adjusting the amount of bentonite that goes into the excavation chamber, the operator can control the density of the face support medium while at the same time using the air bubble to control its pressure. This principle is why the machine is called the variable density machine. On some variable density machines, additional supply lines for high density bentonite are installed to reach a particular density for a thick but still liquid paste inside the excavation chamber. This provides advantages in conditions such as very low overburden, the presence of cavities or very coarse gravel conditions. The general layout of a *Variable Density®* TBM is illustrated in Fig. 3. The layout shows a belt conveyor below the slurryfier box. Some variable density machines are equipped with such a belt to temporarily switch the machine to EPB mode if this is more economical on some stretches of the project. It also allows for flexible reuse in future projects.

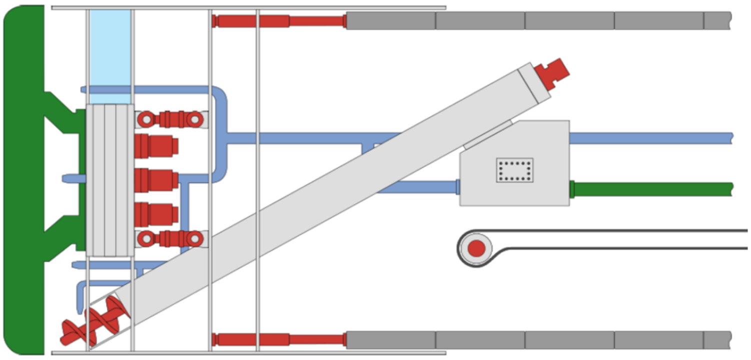


Fig. 3 Schematic sketch of Variable Density® TBM

2.4 Comparison of Machine Types

Below table provides an overview of the three machine types with regards to their face support and mucking characteristics:

Aspect	**EPB TBM**	**Mixshield TBM**	**Variable Density® TBM**
Support Pressure Control	Friction of conditioned muck in the screw conveyor	Control of bentonite pressure by air bubble	Control of bentonite pressure by air bubble
Pressure Control Range	Approx. +/- 0.25 bar	Approx. +/- 0.1 bar	Approx. +/- 0.1 bar
Face Support Medium	Muck Conditioner	Bentonite	Bentonite / Muck / High Density Bentonite
Density Range	1.5t/m³ - 1.7t/m³ (no active control)	1.1t/m³ - 1.25t/m³ (no active control)	1.1t/m³ - 1.9t/m³ (active control)
Rock Handling	Cutterhead Screw Conveyor	Cutterhead Jaw Crusher	Cutterhead Screw Conveyor Jaw Crusher
Primary Mucking	Screw Conveyor	Slurry Circuit	Screw Conveyor
Secondary Mucking	Belt Conveyor	Slurry Circuit	Slurry Circuit (or convert to belt)

3. FACE SUPPORT AND TBM SELECTION

For pressurized tunneling machines, the selection of a machine type that is able to reliably provide face support pressure in the project geology is the key factor to project success. Furthermore, other factors such as the maintainability under pressure, the site logistics and the expected performance play a role. The following section introduces key methods and considerations for TBM selection.

3.1 The DAUB TBM Selection Recommendation

The German Tunnelling Committee regularly elects a scientific committee made of respected industry leaders and academics, called the DAUB (Deutsche Ausschuss für Unterirdisches Bauen e. V.). Among other guidelines and recommendations, the DAUB publishes a recommendation on TBM selection procedures and criteria. The selection procedure divides the alignment into sections with homogenous geological conditions. For each section the possible machine types and system behavior is then evaluated. Fig. 4 shows a graphical representation of the process. For each machine type, the recommendations contain a set of geotechnical parameters for rock and soil with the recommended application range. As more and more countries require contractors to adhere to stricter environmental regulations with regards to muck disposal, the disposal criteria are included. The steps form an iterative process to select the correct TBM type for a project. While some projects feature special situations or requirements that require unusual decisions on the TBM selection, preparing a selection process with a step by step procedure ensures that the rationale for selection is documented in a systematic way. Adhering to a structured selection process including the related documentation supports the project stakeholders cooperation in the long run, as the decision processes become transparent and fact based.

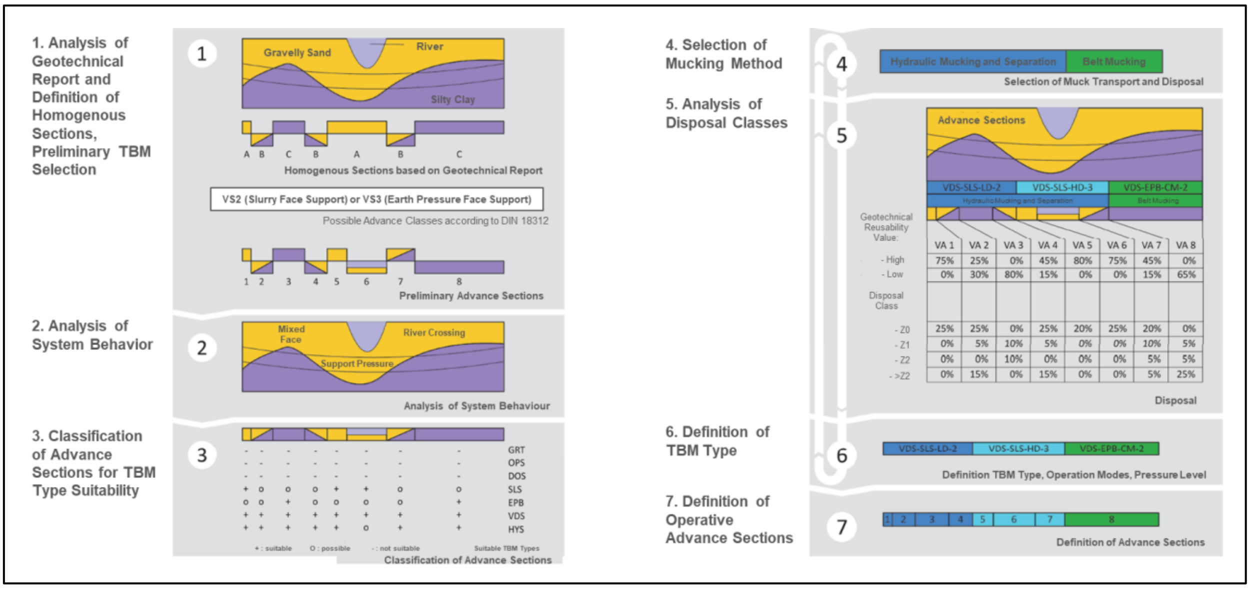


Fig. 4 The DAUB TBM selection process

3.2 Face Support and TBM Type Selection in Soils

The face support mechanisms in soils depend on a number of different geotechnical parameters. The key parameters for the application of EPB machines are the fines content, the permeability and the support pressure. Due to the operation principle, the pressure needs to be controlled in the screw. Therefore the geological parameters must be suitable for this process. Fig. 5 shows the selection criteria for EPB machines in soil based on the DAUB recommendations for TBM selection on the left side. On the right side, the different TBM types are shown with their application ranges across the grain size distribution. EPB machines are suitable for fine grained soils with a minimum of around 30% fines content. Mixshield machines are designed for medium grained soils. Variable density machines can be used in the whole spectrum of grain sizes. They also allow safe face support in coarser ground than Mixshields.

If the type of geology is suitable for EPB application but the support pressure is above around 3-4 bar or the abrasively is very high, it may be more suitable for the project to use a slurry based machine such as Mixshield or variable density machine than using an EPB. For this reason, many river crossing projects use Mixshields as a default.

Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	–	o	o / +	+	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	–	o	+	
Konsistenz (Ic) nach DIN EN ISO 17892-12 [m/s] Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	o	+	+	o	o
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	+	+		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	+		o	–
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	o	o	–

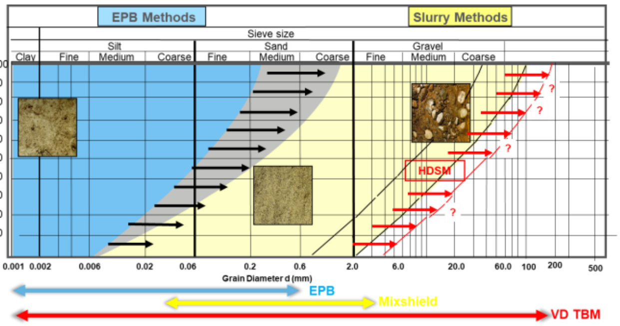


Fig. 5 DAUB selection parameters for EPB in soils (left) and application ranges of different TBM types in soil (right)

3.3 Face Support and TBM Type Selection in Rock and Mixed Face

Many tunneling projects encounter rock and mixed face sections. These sections are typically very difficult with regards to face support as well as with regards to maintenance due to the required tool changes and repairs on the cutterhead. In the past, there have been several projects using EPB machines in rock and mixed face conditions. These projects have generally experienced major difficulties. Fig. 6 summarizes the application results in different conditions ranging from full face soil to full face rock. If the screw needs to provide pressure in rock, the associated friction leads to high wear while it is still difficult or even impossible to maintain pressure. In such conditions the shield needs to be operated with a full excavation chamber leading to high rates of secondary wear as well. Due to the difficulty to reach stable conditions in the excavation chamber, many operators struggle to keep the cutterhead in working order in these conditions as maintenance would require compressed air work. Numerous owners such as Singapore authorities have moved to prescribe Mixshield TBMs for such conditions to reduce project risks. Mixshields have proven to safely handle such mixed face situations.

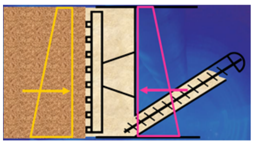
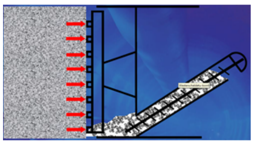
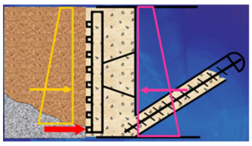
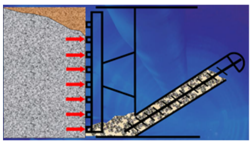
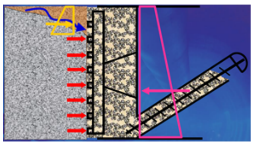
		Excavation Chamber	Screw Conveyor
	Soil Only	• Full chamber full of muck • Conditioning of muck for good face support • No problem to transfer face support to tunnel face	• Conditioned muck forms plug in screw conveyor • No problem to control support pressure
	Rock Only	• No support pressure required • Empty chamber to not have rock chips wear cutterhead too much	• No plug in screw. Just mechanical transport of chips • High wear in screw conveyor
	Mostly Soil Little Rock	• No problem to transfer face support to tunnel face • Impacts destroy cutters at bottom • Frequent interventions	• Conditioned muck forms plug in screw conveyor • No problem to control support pressure
	Mostly Rock Little STABLE soil	• No support pressure required • Empty chamber to not have rock chips wear cutterhead too much • No chance to create support pressure	• No plug in screw. Just mechanical transport of chips • High wear in screw conveyor
	Mostly Rock Little INSTABLE Soil	• Full chamber to transfer pressure • Extreme wear from rock chips • Difficult to create pressure	• Difficult to create plug in screw • Try to create a plug creates extreme wear in screw • Pressure control difficult

Fig. 6 Face support with EPB machines in rock and mixed face

3.4 Special Conditions and Considerations for TBM Selection

More and more projects are planned in very difficult ground conditions. Such conditions can be highly variable geology, high permeabilities, existing cavities or very low overburden. In these conditions, the traditional machine types reach their limitations. To overcome them, the variable density TBM has been developed. By being able to precisely control not only the face support pressure but also the face support medium density and viscosity, it becomes possible to adapt to difficult ground. Fig. 7 shows this situation in low overburden conditions by comparing low density face support medium (LDSM) with high density face support medium (HDSM). By using a higher density medium with precise control of density and pressure, it is possible to safely advance tunnels with very low overburden as the hydrostatic head is reduced and therefore the blowout risk can be eliminated.

In conditions where there is a risk of bentonite loss, such as in coarse gravel or karstic rocks with cavities, a variable density TBM can be equipped with an additional supply of HDSM to compensate the loss with a high viscosity medium that is not lost as easily. For this purpose, additional lines can be installed in the shield. The resulting face support medium is thick and can be extracted with the screw conveyor from the chamber. After mixing with fresh bentonite in the slurryfier box, it is pumpable to be moved to the surface by the slurry circuit. When using variable density machines in ground conditions with sand and clay mixtures, the combined mucking process with slurry flow in the screw has proven to be very efficient and has helped to reach high advance rates. Such effects could be observed for example in Cairo metro.

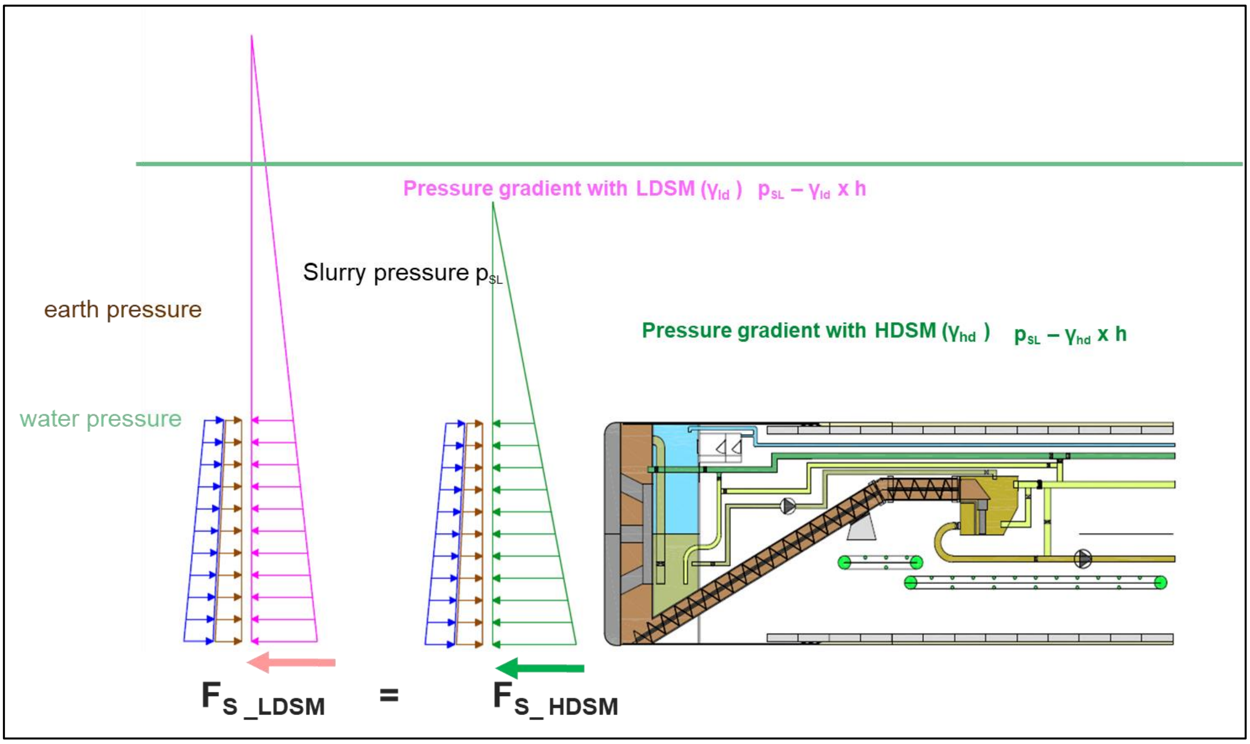


Fig. 7 Face support in low overburden tunneling

4. WONJU-GANGNEUNG RAILWAY TUNNEL

For Wonju Gangneung Railway project Section 11-3, TBM mechanized tunnelling method has being selected instead of the traditional NATM construction method. The project used a 8.39m diameter Mixshield TBM due to the ground conditions with mixed rock geology, gravels and boulders. The following section introduces the project main challenges and the advantages of using Mixshield technology to overcome these challenging ground conditions.

4.1 Project Overview

The total tunnel length is 1,160m and it goes underneath the Namdechon river for 200m stretch of the tunnel. The project main geology consists of fill, granite with different weathering grades (fully weathered, mixed, slightly weathered) and alluvial soils with sand, silt, gravels and boulders. Fig. 8 shows the project tunnel alignment and geology profile. The average size of the boulder is between 40mm to 80mm and the maximum size is 500mm. The maximum granite rock strength is about 85MPa.

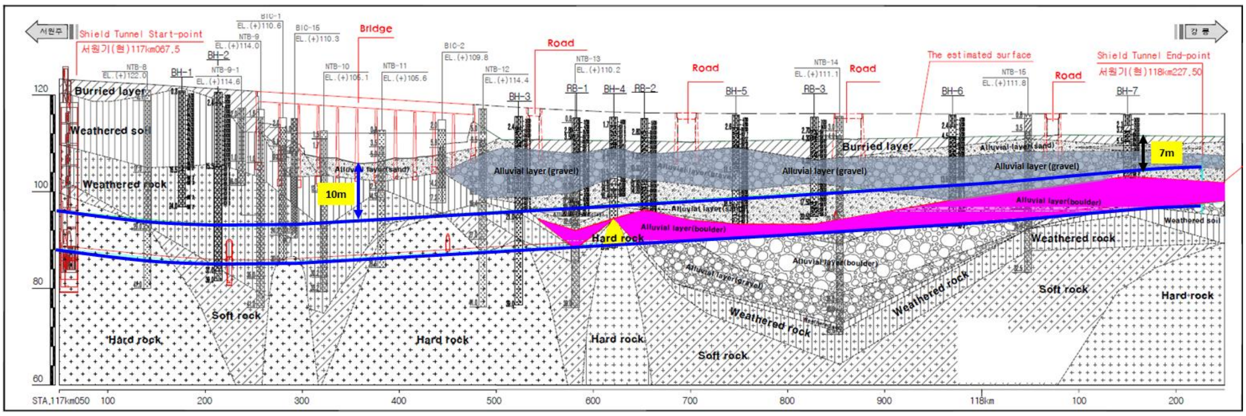


Fig. 8 Project tunnel alignment and geology profile

4.2 Project Challenges

The stability of the tunnel face is extremely challenging, considering the tunnel is underneath a river and bridge, having shallow overburden in one section as well as encountering mixed ground and highly permeable ground (sandy, gravel, boulder) conditions. Unbalanced of overburden pressure and support pressure, will lead to either surface settlement or blowout. Granite and alluvium soils are very abrasive ground conditions which lead to high wear on the cutting tools. For boulder ground conditions, measures must be taken to minimize blockages in the slurry discharge pumps and pipes.

4.3 Mixshield TBM Specifications

The Mixshield TBM is designed based on the project requirements. Fig. 9 shows the key specifications of the machine. Fig. 10 shows the Overview of the actual torque values on the main drive torque configuration curve.

Project specifications	
S-Number	S-962
Project Name	Wonju-Kangneung Railway Tunnel
Location	Wonju-Kangneung
Country	Korea
Diameter	8,390 mm
Total Tunnel Length	1,160 m
Machine Type	Mixshield TBM
Employment	Railway
Max UCS	84.9 MPa
Geology	Granite
Total Machine Length	104 m
Total thrust force	59,464 kN
Maindrive power	1,280 kW
Nominal Torque	4,680 kNm
Overload Torque	6,552 kNm
Breakaway Torque	6,786 kNm

Fig. 9 S-962 TBM Key Specifications

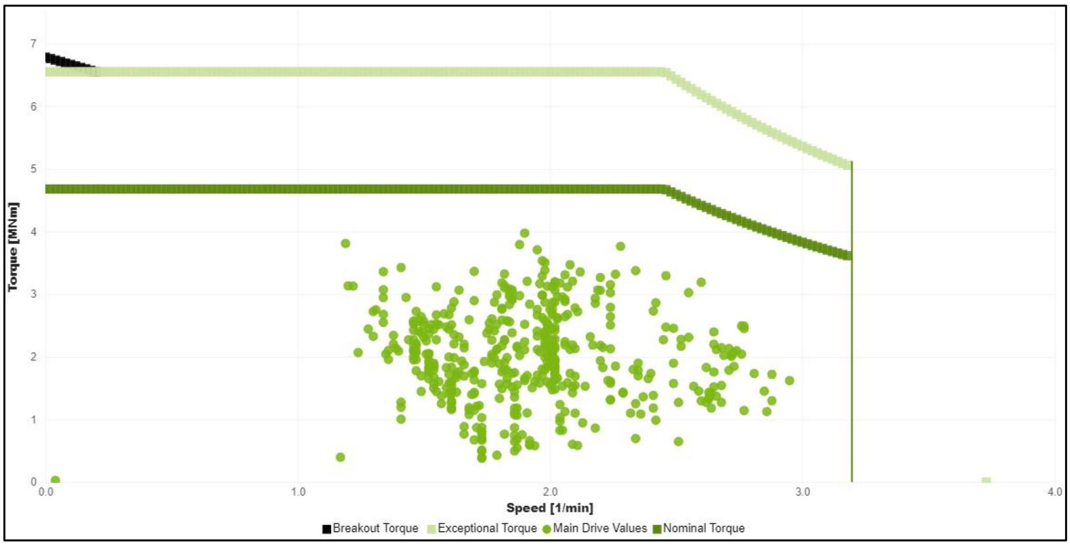


Fig. 10 Overview of the actual torque values on the main drive torque configuration curve

4.4 Mixshield Technology in providing good face support

The Mixshield TBM is fully equipped with compressed air equipment like dual compressed air regulation system for the air cushion in the working chamber and manlock for personnel access to the excavation chamber under compressed air environment. In challenging ground conditions like mixed ground and highly permeable ground (sandy, gravel, boulder) conditions, the Mixshield TBM technology provides a good tunnel face support with bentonite slurry and air cushion by automated compressed air regulation system.

During tunnelling, pre-calculated support pressure is applied. Minimum pressure to avoid instability of the tunnel face which leads to blowout or sink holes. Maximum pressure to avoid breaking up of the face and losing of support fluid (bentonite) to the surface. Therefore, it is crucial for constant monitoring of the support pressure by the TBM operator. Continuous monitoring of the actual backfill grout volume and the quality of the bentonite are being carried out to ensure good control of the face support. Advance grouting from within the TBM has also been carried out to improve the ground conditions ahead of the TBM.

Overall, with the mentioned face pressure control measures, the project was successfully completed with minimum settlement issues. The maximum daily advance was 16.5m and the maximum weekly advance was 70.5m. Fig. 11 shows the successful TBM break-through of the project.

Fig. 11 Successful TBM break-through of the project.

5. GOSEONG GREEN POWER POWER PLANT

For Goseong Green Power Plant project, a 8.19m diameter EPB TBM has being used for the construction of the water intake tunnel. The following section introduces the project main challenges and the key specifications of the EPB TBM in overcoming the challenges.

5.1 Project Overview

The tunnel is driven from the launch shaft on the shore to the intake shaft located 770m into the sea with overburden between 17m and 54m. The project main geology consists of shale, sandstone and andesite of various weathering stages, mainly GI and GIII. The uniaxial compressive rock strength is between 32MPa and 64MPa with a maximum of 95.7MPa. In addition, there are about 40 locations with fractured zones and geological weakness zones. Fig. 12 shows the project tunnel alignment and geology profile.

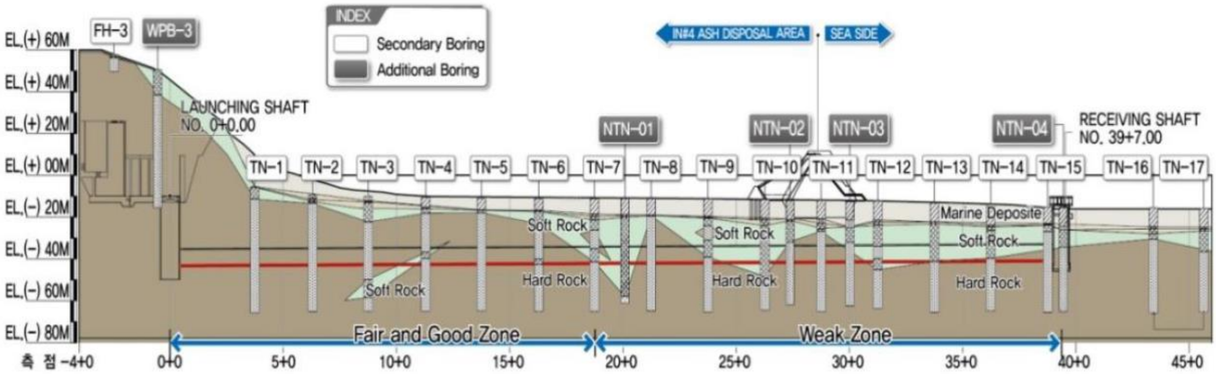


Fig. 12 Project tunnel alignment and geology profile

5.2 Project Challenges

Maintaining of the tunnel face stability between 3bar and 4bar is extremely challenging, considering the tunnel is underneath the sea and the risks of water ingress in the fractured zones. sandstone and andesite rock conditions have high rock strength and they are also of high abrasiveness which lead to high wear on the cutting tools. Hence, cutter intervention with compressed air must be considered. EPB TBM with specific technical features are equipped to meet the project requirements. Fig. 13 shows the key specifications of the machine.

S-Number	S-1104
Project Name	Goseong Green Power Plant
Client	SK E&C
Diameter	8,180mm
Tunnel Length	770m
Machine Type	EPB
Max. Operating pressure	5bar
Total Thrust Force	65,973kN
Main Drive Power	1,920kW
Nominal Torque	7,904kNm
Max. Torque	10,828kNm
Breakout Torque	11,619kNm
Max. Speed	3.5rpm

Fig. 13 S-1104 TBM Key Specifications

5.3 Key Technologies of EPB TBM

The EPB TBM is designed with maximum operating pressure of 5bar which is considered quite high for EPB machine. Specific design considerations are being carried out for the structural design of the shield and bulkhead, tailskin sealing system equipped with 4 rows of wire brushes, screw conveyor design with double discharge gate and the man drive outer lip sealing system with 4 rows and pressurized. In addition, the TBM is fully equipped with compressed air equipment like the compressed air regulation system, manlock and material lock equipment. For the hard rock ground conditions, specific designs on the TBM are also being considered. The TBM is equipped with hard rock cutting wheel which has a configuration of full face 17'' disc cutters with 90mm spacing and electrical main drive of 4m in size with 1,920kW power. Heavy duty screw conveyor of DN900mm with full length wear protection on the pipe as well as on the spiral sections. The subsea tunnel project was successfully completed with customized TBM design and equipment to overcome the challenging project ground conditions. The maximum daily advance was 12m and the maximum weekly advance was 51m. Fig. 14 shows the Overview of the actual torque values on the main drive torque configuration curve. Fig. 15 shows the successful TBM break-through of the project.

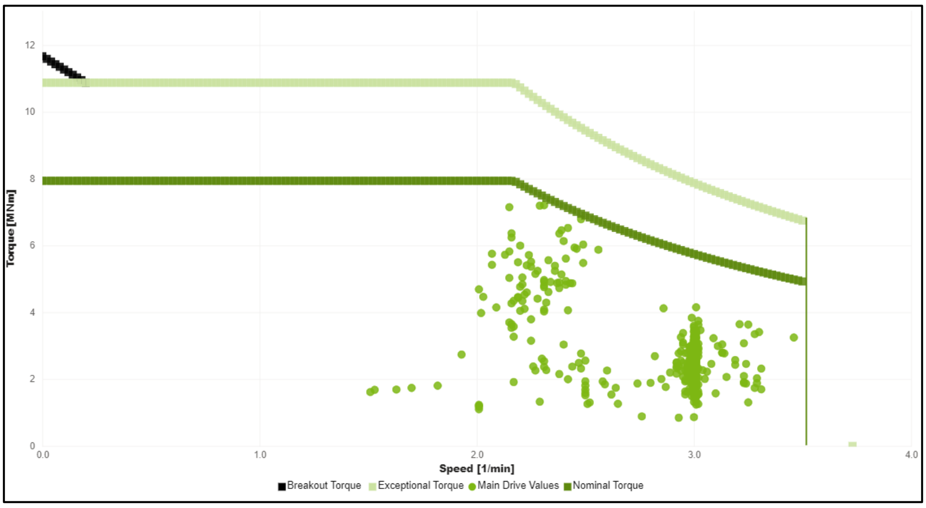


Fig. 14 Overview of the actual torque values on the main drive torque configuration curve.

Fig. 15 Successful TBM break-through of the project.

6. LYON METRO LINE B

For Lyon Metro Line B project, a 9.68m diameter Variable Density® TBM has been used in very challenging ground conditions. The following section introduces the capability of variable density machines in such difficult conditions.

6.1 Project Overview

The tunnel is for the extension of Metro Line B from Orsel shaft to the Hopitaux Lyon Sud, France. Total tunnel length is 2.5km. The main project geology consists of post-glacial alluvium (silt, clay and sand), pre-glacial alluvium (pebbles in sandy clay matrix and sandy gravel) and granite rock conditions. Fig. 16 shows the project tunnel alignment and geology profile.

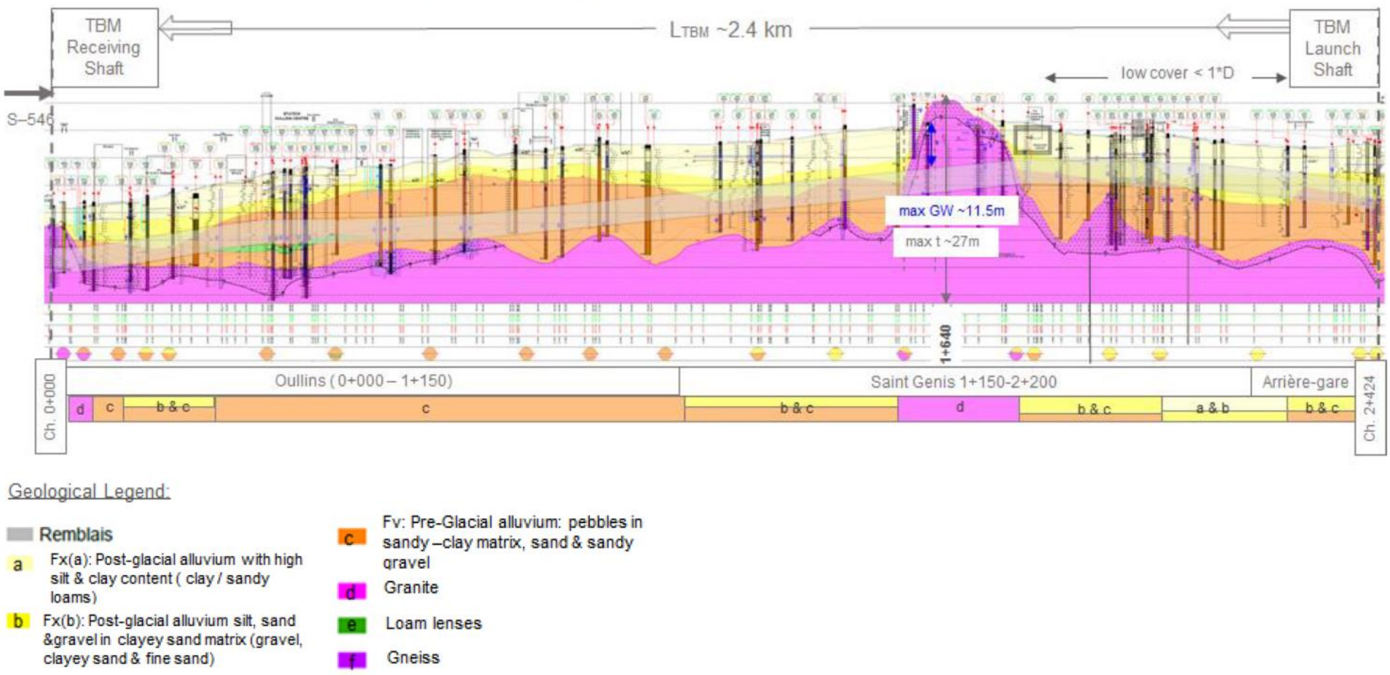


Fig. 16 Project tunnel alignment and geology profile

6.2 Project Challenges

In about 300m stretch of the tunnel alignment, due to the granite rock conditions which are very abrasive, this led to high wear on the cutting tools, slurry pipes and pumps. Fig. 17 shows the key specifications of the machine.

S-Number	S-1204
Project Name	Lyon Metro Line B
Client	GIE Matériel Lyon
Diameter	9,680mm
Tunnel Length	2,424m
Machine Type	Variable Density TBM
Max. Operating pressure	4bar
Total Thrust Force	67,240kN
Main Drive Power	3,500kW
Nominal Torque	14,965kNm
Max. Torque	18,257kNm
Breakout Torque	20,053kNm
Max. Speed	4.0rpm

Fig. 17 S-1204 TBM Key Specifications

6.3 Capabilities of Variable Density® *TBM*

The Variable Density® TBM is equipped with high density face support medium (HDSM). In the coarse gravel ground condition which has a higher risk of bentonite loss, HDSM is being used to compensate the loss with a high viscosity medium that is not lost as easily. The higher density medium provides precise control of density and pressure, which allows safe excavation of the tunnel. This is of critical importance to prevent settlement issues when the tunnel under crosses residential areas on the surface. During intervention, HDSM is also being used to ensure good face stability and hence, providing a safe working environment for the workers. In comparison to low density face support medium (LDSM) mode and EPB mode, the HDSM mode has been mostly used throughout the tunnel excavation.

The tunnel project was successfully completed with the Variable Density® TBM which can precisely control not only the face support pressure but also the face support medium density and viscosity. Hence, it increases the TBM adaptability to difficult ground conditions like the highly permeable sandy and gravel ground conditions. Fig. 18 shows the successful TBM break-through of the project.

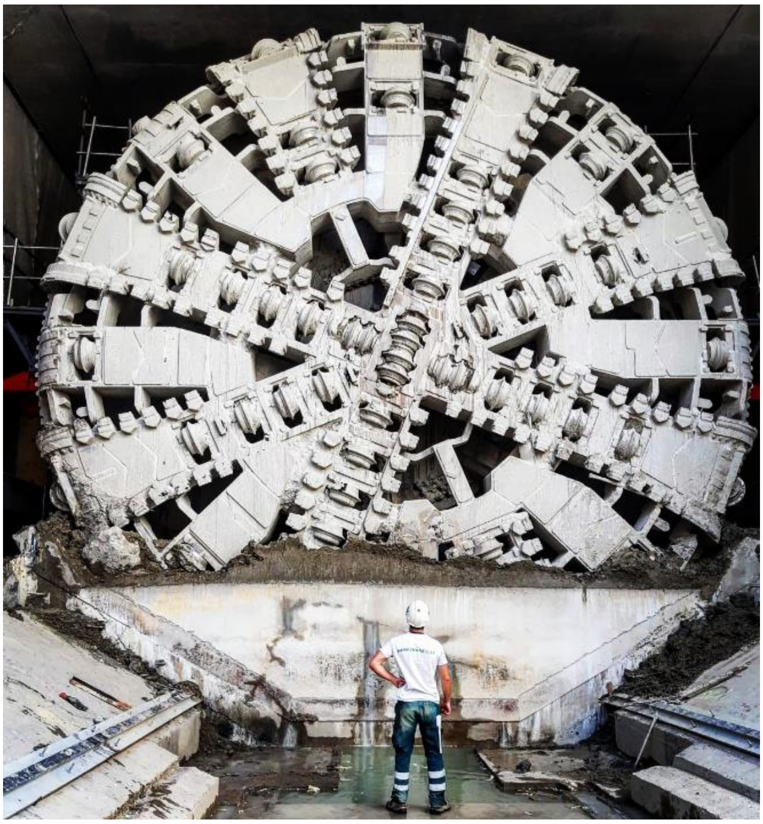


Fig. 18 Successful TBM break-through of the project.

7. CONCLUSIONS

For every tunnel project, detailed analysis of the project and geology risks are being conducted and TBM selection is carried out using the DAUB recommendations. Various TBM types introduced include EPB type, Mixshield type and variable density type. As highlighted in this paper, selection of the right TBM type is of great importance especially for projects with varying ground conditions and of high geological risks. With the appropriate TBM type selected for a specific project, it will minimize the operational risks like surface settlement, sink holes or blow outs. The latest mechanized tunnel trends are leading towards bigger tunnel diameters, deeper tunnels requiring higher operating pressures and longer tunnels with diverse ground conditions. Therefore, it is of even greater importance to have the right TBM selection with customized design suitable for each tunnel project.

REFERENCES

Bäppler, K., Battistoni, F. and Burger, W. (2017), “Variable Density TBM – combining two soft ground TBM technologies”, AFTES The French Tunnelling and Underground Space Association Congress 2017

DAUB, https://www.daub-ita.de/en/start, 2021

Deutscher Ausschuss für unterirdisches Bauen e. V. (DAUB), “DAUB recommendations for TBM selection (Empfehlungen zur Auswahl von Tunnelbohrmaschinen)“, German Tunnelling Committee (ITA-AITES), 2021

Duhme, R. and Brabant, J.D. (2019), “Lessons Learned from TBM Tunneling in Singapore Tropical Weathered Rock Formations”, TBMDigs 2019, Golden.