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THE MOST COMMONLY USED TBM TYPES AND THEIR SUITABILITY FOR HARD AND SOFT GROUNDS

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Abstract: *Tunnels are underground passages ensuring crucial functions as transportation, conveyance of materials and storage. Among the main advantages of these increasingly widespread structures minimizing traffic jams in overcrowded cities by implementing railway, highway and metro tunnels. Tunnel construction methods are subdivided into two major categories: the classical method and the mechanized method. The classical method consists of the conventional blasting (Drill and blast). In contrast, the mechanized method ensures the excavation of the tunnel by utilizing roadheaders, continuous miners, partial-face excavation machines, hydraulic hammers and TBMs. Today, the continuous evolution of tunneling machines enabled the mechanized method to be an efficient and economically profitable excavation method choice due to the safety, stability and low construction time it provides. In fact, among these tunneling machines, TBMs are widely recognized for their several benefits as ensuring continuous operations and causing less rock damage and less disturbance to the surface. This review paper analyses the conditions under which TBM tunneling is advantageous especially when compared to the classical tunneling method and presents commonly used TBM types and their technical features. This study also highlights the essential parameters to consider in the decision-making process of selecting the appropriate TBM type for a tunneling project and discusses the suitability of each TBM type for hard and soft grounds.*
Keywords: *Soft Rock, Hard Rock, Tunnelling, Rock Excavation, TBM Selection, TBM*

1. Introduction

A tunnel is an artificial underground passageway, completely enclosed except for openings for entrance and exit, commonly at each end [1]. Archeologists emphasize that, in recorded history, the first tunnel ever constructed was in Babylon about 4000 years ago under the Euphrates River to connect the Royal Palace to the Temple of Jupiter on the opposite side of the river. This tunnel was approximately 914 m long, 3.6 m wide and 4.5 m high [2].

Today, tunnels are realized in different cross-sections (rectangular, circular, elliptical, horseshoe or segmental) through various geological, geotechnical and hydrogeological contexts to ensure numerous purposes including transportation and storage. The sector of tunneling keeps evolving by minute to catch up the growing demand for tunnels to cover multiple usages as railways, highways, underground parking lots, sewages and hydropower projects.

Tunneling methods can be subdivided into two main categories. The first category covers the classical method based on blasting (Drill and Blast). However, the second category is represented by the mechanized tunneling method (continuous miners, roadheaders, partial-face excavation machines, hydraulic hammers and TBMs).

Nowadays, the sector of tunneling is facing new challenges. In fact, longer tunnels and higher advance rates are expected. Due to the rapidity, safety and stability it provides, the mechanized tunneling method ensures fulfilling these requirements as an efficient and economically profitable excavation method. TBMs, in particular, ensure achieving safer, less disturbing and longer tunnels.

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In the light of the above considerations, this review paper presents the most commonly used TBM types, their technical specifications and their suitability for hard and soft grounds.

2. Tunnel Excavation Methods

In contrast with the classical excavation method based on blasting, the mechanized tunneling method ensures the excavation of the tunnel by utilizing roadheaders, continuous miners, partial-face excavation machines, Hydraulic hammers and TBMs (Figure.1). Today, the most widespread tunnel excavating techniques are drilling and blasting (D&B) and tunnel boring machines (TBMs) available for both soft and hard grounds.

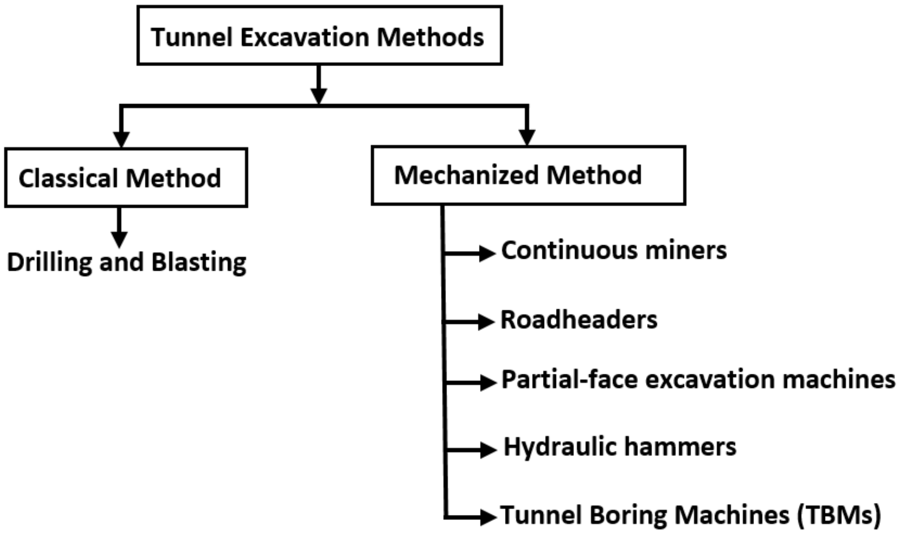

Fig.1. Tunnel excavation methods

Drilling and blasting is an advantageous excavation method for relatively short non circular sectional tunnels in hard grounds. However, despite its unquestionable efficiency, drilling and blasting cannot be used in urban areas and right under buildings where hazardous environmental impacts such as noise, vibration, dust and rock mass collapses may occur which may consequently lead to dangerous unpredictable events.

Under the following condition, a TBM is considered to be an efficient and economically profitable tunneling method:

Table 1 suggests an accurate comparison between D&B and TBM tunneling highlighting the tunnel features, the geological conditions and the environmental restrictions to be considered in the choice of the convenient tunneling method for each project.

Table 1. Comparison between D&B and TBM tunneling [3]., Modified

		Excavation method		
Conditions		**Drilling and blasting**	**TBM**	
			For hard rock	**For soft ground**
Tunnel Features	**Tunnel length**	-Relatively low equipment cost -Excavation cost is not greatly influenced by the length of the tunnel.	-The cost of the TBM is generally high. - Suitable for long tunnels.	-The cost of the TBM is generally high. -Suitable for long tunnels.
	Shape of the cross section	-Basically, the shape of the cross section is arched at the crown. -The shape of the cross section can be changed during the construction.	-Basically, the shape of the cross section is a circle. -After boring other shapes are possible using drilling and blasting in the enlargement.	-Basically, the shape of the cross section is a circle. -Semicircle, multicircle, oval etc. are also possible using special TBMs.
	Size of the cross-section	> 200m^2	The record is held by Big Becky, a Robbins Main Beam TBM with an excavation diameter of 14.4m.	The record is held by Bertha TBM, an EPBM with an excavation diameter of 17.48m.

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Geological Conditions	**Hard rock**	Suitable	Suitable except for extra-hard rock (> 200 MPa)	Not applicable
	Semi-hard rock	Suitable	suitable	Not applicable
	Weak layers (as fractured zones) and aquifer zones	Necessary countermeasures should be taken.	Not suitable for grounds where weak layers or water inflow will be frequently encountered	Applicable
	soil	Not applicable	Not applicable	Most suitable
Environmental conditions	**Noise and ventilation**	-Causes noise and vibration thus not suitable in the surroundings of habitations and important structures. -Necessary measures need to be taken in order to reduce the effects of noise and vibration.	Less noise and vibration compared to drilling and blasting.	Less noise and vibration compared to drilling and blasting and hard rock TBMs.

3. The Major Types and Components of TBMs

This study focuses on the most commonly used TBM types as shown in the figure 2.

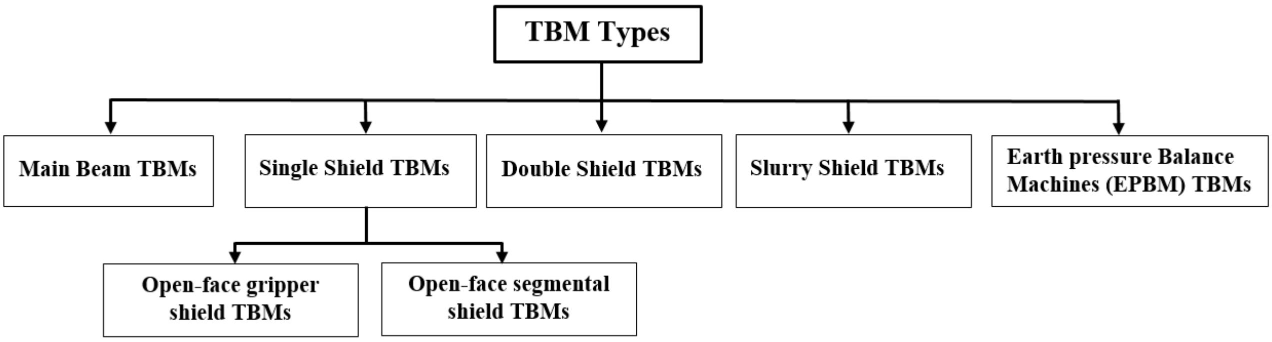

Fig.2. The most commonly used TBM types

Figure 3 displays the common components of a Tunnel Boring Machine (TBM).

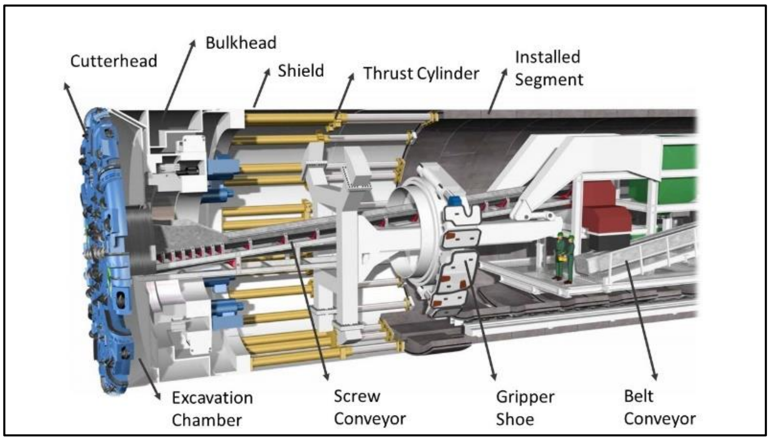

Fig.3. The common components of a TBM [4]

4. The Parameters to Consider in the Decision-Making Process of Selecting the Appropriate TBM Type for a Tunneling Project

A considerable number of parameters affect the choice of the appropriate TBM type for any tunneling project. The decision-making process can be complicated and confusing. However, the choice should never be arbitrary. A deep examination and a careful consideration of all the relevant factors and parameters affecting the efficiency of the TBM in each context are crucial before selecting the appropriate TBM type for a tunneling project. Several researchers studied the parameters affecting the selection of the appropriate TBM type for each tunneling project. Figure 4 summarizes these parameters.

Thus, ‘’the selection of the appropriate tunnel boring machines require a firm understanding of the ground conditions and structural issues’ [5]. That is why site investigation is the key to obtain the relevant parameters of every project site. Such surveys should cover the geological, geotechnical and hydrological aspects of the site. In addition, the environmental aspect should never be ignored.

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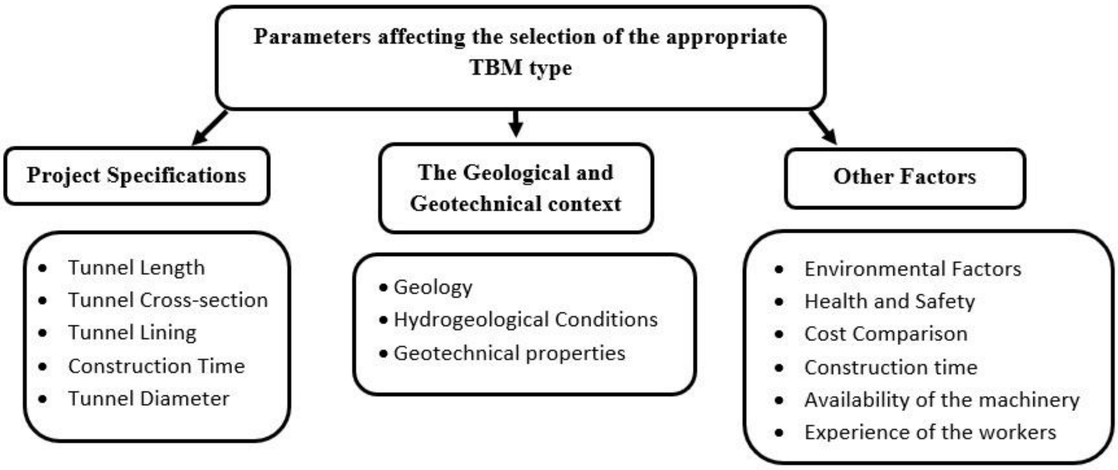

Fig.4. Parameters to consider in the selection of the appropriate TBM type for a tunneling project

5. Technical Features and Selection Criteria of Hard and Soft Ground TBMs

5.1. Hard Rock TBMs

Some crucial features have to be taken into consideration in order to choose the appropriate TBM type for hard grounds. The following TBM types are eligible to excavate in hard grounds:
- Main beam TBMs,
- Open-face gripper shield TBMs,
- Double shield TBMs.

Main Beam / Open Type Gripper TBMs

Main beam TBMs also known as open type gripper TBMs, are marked by the absence of any support form to the rock (neither temporary nor permanent). This TBM type adapted for hard grounds (very strong, strong and moderately strong rocks) with medium to high face stability, is equipped with a rotary head kept in contact with the rock by grippers pushing radially against the wall of the tunnel and thus providing the necessary pressure for the TBM to move forward in the tunnel (Figure.5). Rocks demonstrating lower strengths require increasing the bearing surface of the grippers to protect them from being dipped into the ground.

The excavation process of this TBM can be subdivided into two main operations: excavating while the grippers are stationary followed by regripping to enable the sequential advancement of the machine. The support system of the tunnel is independent of the main beam TBM. A temporary support (shotcrete) can be used but concrete lining is always crucial and indispensable.

It is also important to acknowledge that main beam TBMs are not suitable for excavating in the presence of groundwater, therefore, it is essential to adopt the necessary countermeasures in order to protect them from any water inflows. In fact, probe hole drilling systems installed on this TBM type are crucial to detect the presence of groundwater and soils. Since the configuration of this machine does not allow it to excavate in such conditions, probe drilling allows the workers to take the necessary measures as consolidation, groundwater lowering and drainage before starting the excavation of these zones.

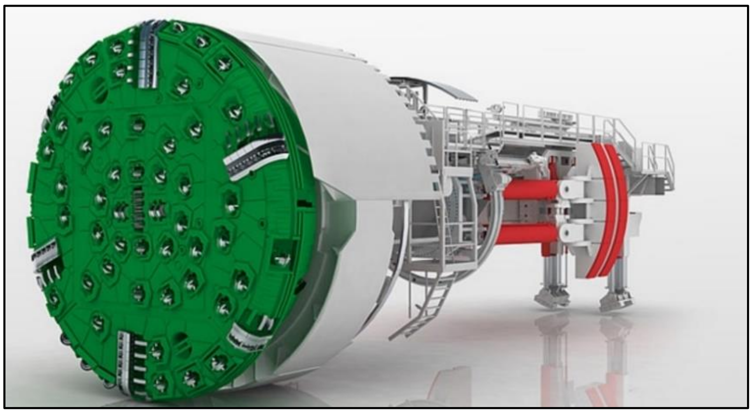

Fig.5. A Main Beam TBM by Herrenknecht [6]

Single shield TBMs: Open-face gripper shield TBMs

Since they provide a passive support to the sides of the tunnel, single shield TBMs play a crucial function in protecting the workers by preventing any accidents involving rock falling. Single shield TBMs can be subdivided into:

- Open-face gripper shield TBMs: adapted for hard grounds,
- Open-face segmental shield TBMs: adapted for soft grounds.

Open-face gripper shield TBMs, similarly to main beam TBMs, use grippers to apply thrust on the face in order to ensure the excavation. The only difference is the presence of a cylindrical shield providing a passive support to the sides of the tunnel during the excavation process (Figure 6). Open-face gripper shield TBMs, are appropriate for the excavation of very strong, strong and moderately strong fractured rock masses. Thus, these TBM types are capable of achieving good advance rates in hard grounds exhibiting geological inconveniences but no groundwater presence. Furthermore, due to their lower cost compared to the double shielded TBMs, open fact gripper shield TBMs are considered to be a good choice for tunneling in hard grounds. However, despite their success, the adaptability of this TBM type is always limited by the capacity of the ground to bear the thrust applied by the grippers.

Such TBM types require mitigation measures to reduce the potential geotechnical risks. “if an open TBM is to be encountering a section with highly hard or abrasive rock, mitigation measures such as choosing larger disc cutters with resistant steel to overcome the high risk should be applied” [7].

Fig.6. An open-face gripper shield TBM by Wirth [3]

Double shield TBMs

Double shield TBMs identified as the most technically sophisticated TBMs, are suitable for rock masses ranging from excellent to poor and especially for unstable grounds displaying fault zones which require high advance rates. This TBM type associating radial grippers with longitudinal thrust rams in one machine require either a lining or a ground strong enough to bear the thrust applied by the grippers. The main advantage of double shield TBMs is the ability to install the lining while excavating at the same time. In fact, double shield TBMs ensure such a continuous work cycle by the means of a double thrust system (longitudinal jacks and grippers) allowing the TBM to move forward during the excavation process while the lining segments are installed (Figure 7). However, it is a long machine thus always exposable to the risk of getting trapped on one hand and hardly accessible when the cutterhead is damaged on the other hand.

Fig. 7. A Double Shield TBM by Seli [8]

5.2. Soft Ground TBMs

The following TBM types are eligible to work in soft grounds:

- Open-face segmental shield TBMs,
- Slurry shield TBMs
- Earth pressure balance TBMs,

Although hypothetically they all display some common characteristics, these TBMs fail to be interchangeable. Each type exhibits some distinct characteristics making it the most efficient TBM type under certain specific conditions within soft grounds. In fact, in soft grounds, a specific consideration of the granulometry, consolidation level, presence of boulders, clay content and water content should be accorded.

Single shield TBMs: Open-face segmental shield TBMs

Open-face segmental shield TBMs provide a passive support to the sides of the tunnel during the excavation process but do not provide any support form to the face of the tunnel. The outstanding feature of this TBM type is the presence of rams consisting of a series of jacks ensuring the thrust forward by reacting longitudinally against the lining of the tunnel erected by an erector integrated in the TBM (Figure.8).

This TBM type is usually suitable for the excavation of consolidated cohesive soils and rocks displaying heterogeneities, groundwater presence and low to very low strengths. However, the absence of a reverse force reaction to release the TBM if it gets trapped and the presence of lining limiting the access to the cutterhead to fix it in case of a damage requiring an intervention are the main drawbacks of this machine.

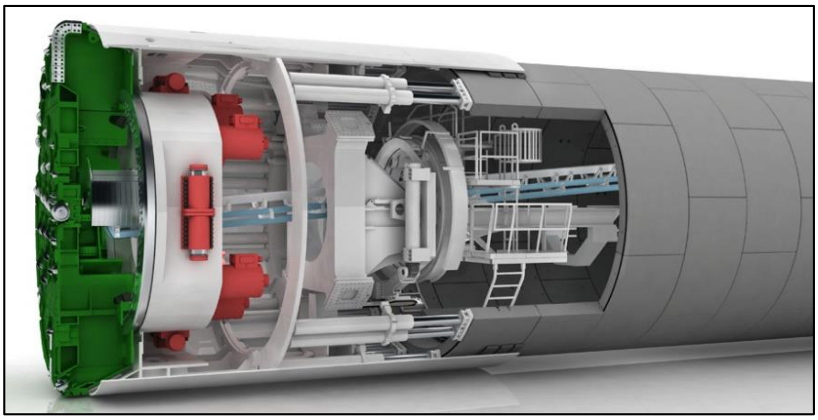

Fig.8. An open-face segmental shield TBM [9]

Slurry Shield TBMs

Slurry shield TBMs provide frontal and peripheral support to the tunnel through a slurry mix (bentonite or clay mixed with water) circulated by slurry pumps (Figure 9). A slurry treatment plant on the surface separates the muck from the slurry mix then recycles the slurry back to the cutterhead. “Openings in the cutterhead (plus possibly a crusher of the first slurry return line suction pump) control the size of spoil removed before it reaches the pumps” [3].

Fig.9. A Slurry Shield TBM by Mitsubishi [11]

Slurry shield TBMs are suitable for soft heterogeneous grounds (granular soils: sand, gravel etc.) displaying high water pressure and high permeability (coefficient of permeability K up to 10-2 m/s). However, "slurry Tunnel Boring Machine is especially used in grounds consisting of gravel and soil mass but it has a limited use in ground masses composed of clay" [10]. In fact, unless polymers are used, grounds exhibiting high clay and silt contents eventually cause the clogging of the TBM. Furthermore, these fine particles generate difficulties in the separation plant and require an expensive separation process. However, slurry shield TBMs are efficient if the presence of boulders is suspected or detected. A crusher can be installed in the cutterhead chamber to allow breaking these boulders before passing through the mucking system.

The last few years have seen a significant progress in the design and technical specifications of slurry shield TBMs. Nowadays, besides excavating in soft grounds, these machines are able to be a part of hard rock tunneling too. However, despite their efficiency and high performance in soft grounds, slurry shield TBMs failed to be as successful as expected in hard grounds. This lack of success in such geological contexts can be explained by the rapid wear of the TBM in hard rock and consequently the higher costs when compared to the alternative excavation methods usually used for the same context.

Earth Pressure Balance Machines (EPBM)

Earth Pressure Balance Machines also offer an immediate peripheral and frontal support to the tunnel. However, unlike slurry shield TBMs, these machines are able of handling the excavated materials by injecting soil conditioning products without the need of using a separation plant. Additionally, these TBMs are capable of holding on soft grounds by maintaining a balance between earth and pressure and using the excavated material to support the face of the tunnel (Figure 10).

Tunneling projects in grounds displaying sporadic discontinuities and high contents of silts or clays require using an Earth Pressure Balance Machine (EPBM). Additionally, utilizing high-density mud or foams allows the excavation of even sands and gravels with this TBM type. However, contrary to slurry shield TBMs, this TBM type is not suitable for highly permeable grounds (coefficient of permeability K > 10-3 m/s).

Throughout the years, EPB machines were put to the test in hard grounds but the results proved the inadaptability of this machines to such geological context. This inadaptability can be explained by the fact that EPB machines require an opening ratio of at least 30% which is not convenient in the presence of blocks and / or layers with joints on one hand and the high wear of the cutterhead and the conveyor in hard grounds on the other hand.

Fig.10. An EPB TBM by Terratec [12]

6. Conclusion

Today, the tunneling sector is constantly evolving to fulfill the increasing demands for tunnels that cover multiple usages. In the light of this expanding need to reach longer, safer and more economically profitable tunnels in less construction time, mechanized tunneling, especially Tunneling Boring machines allowed accomplishing these goals and achieving satisfactory performances.

Thus, numerous factors as the efficiency, time saving and safety allowed TBMs to be the most adequate excavating method in several tunneling projects of critical importance as minimizing traffic jams in overcrowded cities by implementing railway, highway and metro tunnels, excavating diversion tunnels in the construction of dams and even the realization of tunnels destined for the storage and disposal of radioactive waste.

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A deep understanding of the technical specifications of each TBM type and a careful consideration of crucial factors as tunnel features, the geological and geotechnical context and other factors are essential in the decision-making process of selecting the most suitable TBM type for a tunneling project. Today the most widespread TBM types are Main beam, single shield (Gripper and Segmental), double shield, slurry shield and EPBM.

Tunneling in hard rock require using a main bream, gripper shield or a double shield TBM, whereas segmental shield, slurry shield and EPBM types are eligible for tunneling in soft grounds. Although the mentioned TBM types in each category (Hard rock TBMs and soft ground TBMs) display some common characteristics, they all exhibit unique features allowing each type to be the most convenient under specific circumstances.

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