PRINCIPLES OF THE TUNNEL FACE SUPPORT IN SHIELD TUNNELLING – HISTORICAL PERSPECTIVE AND PRESENT DAY

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ABSTRACT: The construction of tunnels using a shield, as an independent discipline within underground engineering, is entering its third century of existence this year. It has now been two hundred years since the first tunneling shield—designed by Marc Brunel—came into being and was deployed for the excavation of the Thames Tunnel. Since that pioneering achievement, the technology has transformed from a simple protective steel envelope into sophisticated mechanical systems. What tunneling shields have retained in common over the past two centuries, however, is the need to determine how the tunnel face will be supported in the given geological environment. How the various methods of face support developed, and especially how the approaches to them have changed, is the subject of the following article.

1. HISTORICAL PATHWAY TO THE CURRENT STATE OF TECHNOLOGY

Builders who sought to connect the opposite banks of London's River Thames between the parishes of Saint John of Wapping and Saint Mary Rotherhithe faced an almost insoluble task at the beginning of the nineteenth century. A bridge connection seemed the logical solution, but the extraordinarily dense river traffic—unimaginable by today's standards—and the need for a very high clearance practically ruled out this option. Work on a tunnel therefore began. After several shaft floods and, later, collapses of the tunnel itself caused by running sands, the works were abandoned and the project was deemed unfeasible with the methods available at that time. A fresh idea and a design solution previously unknown and unrealized were therefore required

At this moment, Marc Brunel entered the scene—an engineer of French origin, a man of remarkable life circumstances, and above all a figure of innovative thinking, technical and design skill, and immense courage to undertake a risky and highly uncertain task. Inspired by the marine organism known as the shipworm, he designed the tunnelling shield—a movable steel structure within which a total of 36 miners could work simultaneously, gradually breaking the ground at the tunnel face while continuously installing wooden supports

After eighteen long years marked by countless difficulties, Brunel completed the tunnel and, without realizing it, opened a symbolic gateway for his successors, who continued—and still continue—to develop his original idea.

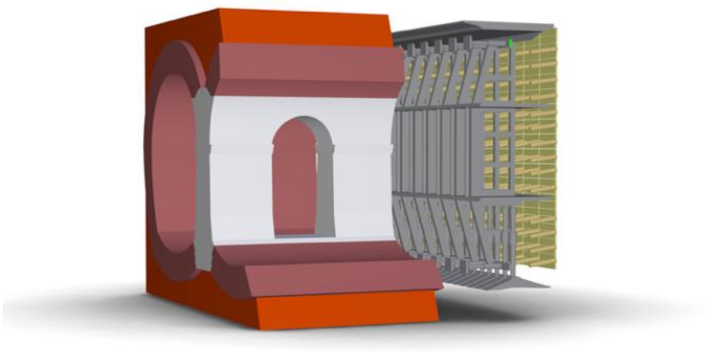


Figure 1: Visualization of the Brunel's shield and a part of the Thames Tunnel

One of Marc Brunel's notable successors was James Henry Greathead, who designed a circular tunneling shield for the excavation of London's Tower Subway, which opened in 1870. In 1886, Greathead was appointed engineer of a new project—the City & South London Railway—for which he improved his original shield. He not only enlarged it but also equipped it with a hydraulic system and compressed air. His shield, with only minor modifications, remained in use until the 1940s.

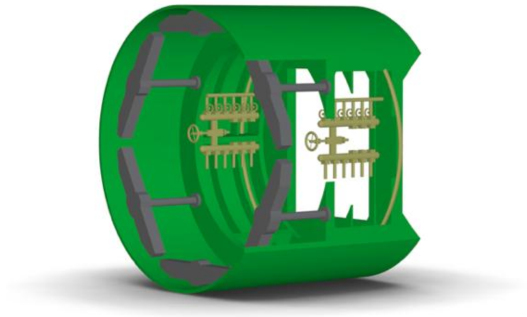


Figure 2: Visualization of the Greathead's tunnelling shield

Compressed air was used quite extensively in underground construction and, in certain specific cases (e.g., TBM cutter tool changes), is still used today. Despite its undeniable advantages, compressed air also carries many risks. In 1880, a blowout occurred during the excavation of a tunnel intended to connect New Jersey and Manhattan beneath the Hudson River (MCCRAY J., 2025). The incident claimed twenty lives. During the construction of the New York Subway in 1916, an almost unbelievable event occurred when, as a result of a blowout near the Brooklyn Bridge, three workers were shot through the riverbed by air pressure—one of whom miraculously survived with barely any injuries (New York Times, 1916).

Compressed air can also force contaminants from polluted soil into the atmosphere during underground works, as happened in Baltimore during the excavation of Metro Section C (EDWARDS C., MERRILL K., 1995), when vapors from petroleum products were released into the air. Beyond these extraordinary incidents, working under compressed air is hazardous for workers if prescribed procedures and decompression times are not followed, not to mention that work in compressed-air conditions is physically far more demanding than comparable work under atmospheric conditions.

The complications associated with compressed-air operations led designers to develop new methods of supporting the tunnel face using fluids instead of air. John Barlett, who was considering how to excavate tunnels in non-cohesive soils and water-bearing strata, was inspired by a visit to the construction of the first line of the Milan Metro. There, diaphragm walls supported by bentonite slurry were widely used, and during his return flight Barlett imagined how this method could be adapted for tunneling machines. The initial contours of a design began to form in his mind, later materializing into the concept of the bentonite shield, which he patented in 1964.

Figure 3: Visualization of John Barlett's bentonite shield

Another significant contribution to face-support methods emerged in the 1970s. In the Land of the Rising Sun, the concept of the earth-pressure shield was developed—a machine that supports the tunnel face using conditioned excavated material. The first shield of this type was used for sewer construction in Tokyo in 1974.

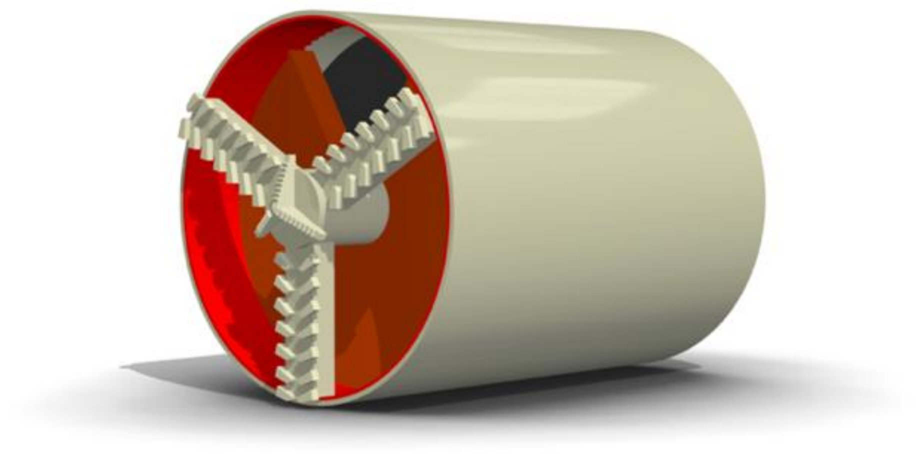


Figure 4: Visualization of Earth Pressure Balance shield (Tokyo 1974)

The above-mentioned principles of face support are one of the fundamental criteria for the classification of tunnelling shields. Table 1, based on (Recommendations and Guidelines 2000), presents the categorization of shields according to two primary criteria: whether they are designed for partial-face excavation (abbreviation **T**) or for full-face excavation (abbreviation **V**). A secondary criterion is the specific principle by which they are able to support the tunnel face during excavation.

Table 1: Categories of tunnelling shields (ITA-AITES, 2000)

Shielded Machines			
Shield Machines with full face		**Shield Machines with part heading**	
Face without support	SM-V1	Face without support	SM-T1
Face with mechanical support	SM-V2	Face with partial support	SM-T2
Face with compressed air application	SM-V3	Face with compressed air application	SM-T3
Face with fluid support	SM-V4	Face with fluid support	SM-T4
Face with earth pressure balance support	SM-V5		

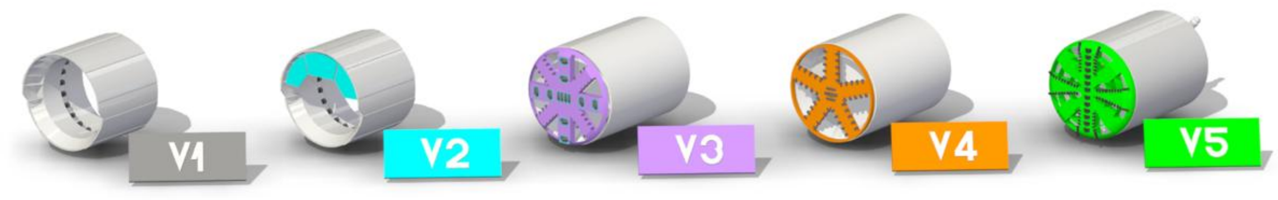


Figure 5: Overview of the basic principles of tunnel face support in shield tunnelling

2. MECHANICAL INTEPRETATION OF SHIELD TUNNELING

At the close of the twentieth century and the onset of the twenty-first, the development of mechanized tunnelling methods underwent significant expansion. The number of tunnels excavated with full-face tunnelling machines increased markedly, their diameters grew, and the range of geological environments in which these machines could operate broadened. As a result, Tunnel Shields became more versatile and frequently integrated multiple methods of face support.

Considering the substantial advances in mechanical engineering, in computer-based control systems, and above all the fact that the tunneling shield is not merely a tool for performing excavation—as is the case with conventional tunneling methods—but rather constitutes the very essence and defining element of the excavation process, it is unsurprising that the conceptual approach to face support has shifted. Gradually, the mechanical-engineering perspective has come to dominate over the geotechnical viewpoint, a trend that is also reflected in the terminology used to describe the various excavation regimes.

This can be demonstrated, for example, by document (Recommendations for the Selection 2022 revised 2025) from 2025, which modifies the designation given in Table 1 and refers directly to tunnel boring machines rather than to the principles of face support. It is noteworthy that EPB machines are described as being capable of excavation only in closed mode. However, in the detailed description of the EPB principle in the same document, it is stated that *in stable ground conditions the earth pressure balance machine can also be operated without pressurization, with a partially filled excavation chamber. This operating mode, without active support of the tunnel face, is referred to as open mode.*

Table 2: Classification of tunnelling shields (DAUB 2022, rev. ,2025)

Name	Short	Operation Mode			Excavation Classes
		Open	Closed	Transition	
Slurry Shield	SLS	---	X	---	VS2
Earth Pressure Balance Shield	EPB	---	X	---	VS3
Variable-Density-Shield	VDS	X	X	X	VS2/VS3
Hybrid Shield	HYB	X	X	X	VS2/VS3

3. EARTH PRESSURE BALANCE SHIELDS

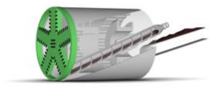
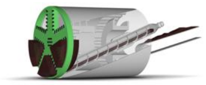
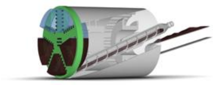
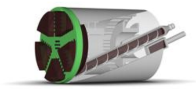
The earth pressure shield is a tunnelling machine, capable of operating in several different modes. For example, (HERRENKNECHT M., THEWES M., BUDACH CH., 2011) lists six such modes. It is precisely here that the difference between the mechanical and geotechnical perspectives becomes evident. Whereas for the mechanical interpretation the key question is HOW—that is, how the support pressure is generated, how the muck is removed from the excavation chamber, and subsequently transported through the tunnel—the geotechnical viewpoint focuses on WHAT: namely, what the supporting medium is and what pressure pattern it creates.

Table 1 compares the excavation modes of the earth pressure shield as presented in (HERRENKNECHT M., THEWES M., BUDACH CH., 2011) with their geotechnical interpretation. Excavation in Open Mode theoretically represents tunneling without face support (the limitations of this approach will be discussed in Section 4), corresponding to category V1 (according to the Table 1). Closed Mode, by contrast, represents excavation with earth pressure balance support. If the chamber is only partially filled, this constitutes a combination of modes V1 and V5.

Modern EPB machines also enables to excavate by using compressed air. This regime is described with varying terminology—such as “half open mode” (HERRENKNECHT M., THEWES M., BUDACH CH., 2011) or “semi closed mode” (BABENDERERDE S., HOEK E., MARINOS P.G., CARDOSO A.S., 2005). In practice, it corresponds to the situation in which an EPB shield operates in mode V3, i.e., compressed air face support. The associated pressure pattern does not form a gradient, or only a partial gradient, and instead resembles an omnidirectional pressure distribution.

It must be emphasized that excavation in compressed-air mode remains inherently associated with risks, as illustrated in Chapter 1 of this article. The use of compressed air within EPB machines—regardless of how the operating mode is designated—does not eliminate the hazards linked to supporting the tunnel face by this method. It should further be noted that the shield employed in the construction of the New York Subway (in the year 1916) had a diameter of approximately 5 m. The full tunnel face area of this shield, supported by compressed air, corresponds to roughly one-third of the face height of a machine with a cutter diameter of 10 m.

Table 3: Operating modes of Earth Pressure Balance Shields

Mechanical interpretation		Geotechnical interpretation	
Open mode		No face support (V1)	
Transition mode		Comb. (V1 & V5)	 
Half Open Mode		Comb. (V5 & V3)	 
Closed Mode		Eart Pressure Support (V5)	
Closed Mode with Piston Pumps			
Closed Mode with Slurry Transport			

Paper (Recommendations for the Selection 2022 revised 2025), from which the left column of table 3 "Operating Modes of EPB Shields" is reproduced, further identifies three distinct excavation regimes within closed-mode operations. This once again highlights the differing perspectives of mechanical engineering and geotechnical engineering on the same issue. While from the mechanical standpoint these regimes indeed represent separate operational modes, from the geotechnical perspective they all remain forms of earth-pressure support.

4. MECHANICAL FACE SUPPORT SHIELDS

Shield machines with mechanical face support were defined as follows: *"Supporting of the tunnel face is carried out via an almost closed cutterhead."* (Recommendations and Guidelines 2000) In (Recommendations for Face Pressure 2016), it is stated: *"Shield machines with mechanical face support were historically used in tunnelling. The usage of these machines is no longer recommended."* —thus, they have been consigned to history. Recently, the role of cutterhead in face stability has started to attract researchers' attention again.

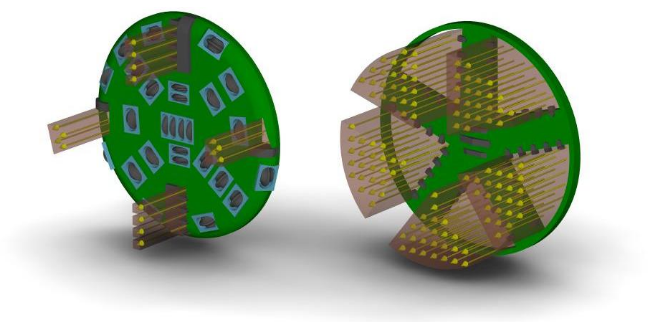


Figure 6: Graphical interpretation of the support pressure media transfer depended on the cutterhead opening ratio

Calculations of face support pressures for EPB (Earth Pressure Balance) and slurry machines are traditionally carried out under the assumption that the supporting medium applies a uniform pressure across the tunnel face, as if the machine had no cutterhead. Since an increasing number of hybrid machines are currently being manufactured—machines capable of tunnelling even in rock environments, with cutterheads characterized by a smaller opening ratio—it is necessary to also consider the mechanical supporting function of the cutterhead itself. This issue is addressed, for example, in (CHEN X.J., FANG P.P., CHEN Q.N., HU J., YAO K., LIU Y., 2024).

Awareness of the contribution of the cutterhead to the overall face support function could lead to more accurate calculations of the required support pressures and to minimizing so-called "performance killers," among which an excessively high support pressure certainly belongs. This domain appears to offer considerable scope for experimental investigation as well as for numerical analysis.

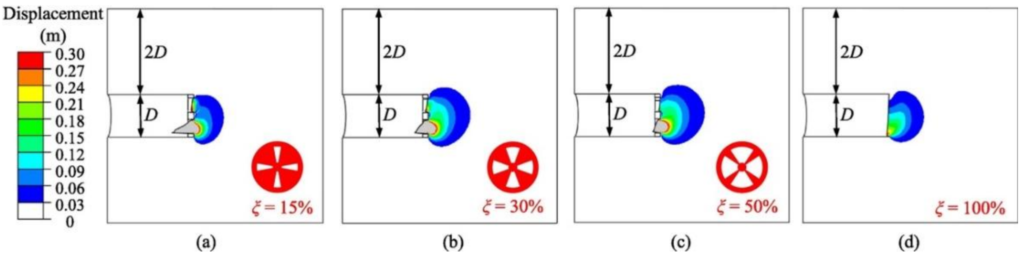


Figure 7: Effect of cutterhead opening ratio on face stability (Recommendations for Face Pressure 2016)

Consequently, every excavation carried out by EPB or slurry machines represents a combination of principles V2 and V5, or alternatively V2 and V4 (see Table 1). The extent of the V2 contribution always depends on the robustness of the cutterhead design, the opening ratio, as well as the distribution of openings within the cutterhead.

5. SLURRY PRESSURE BALANCE SHIELDS

Slurry shields are characterized by the fact that face support is provided by slurry, which is a suspension of water and bentonite. In the tunnelling process, slurry essentially has two functions: the aforementioned support of the tunnel face and serving as a transport medium for the removal of excavated material. As noted, this principle is inspired by the construction of underground diaphragm walls in non-cohesive soils.

In the mid-1980s, the company Herrenknecht developed the mixshield, a shield that uses bentonite slurry for face support, with the support pressure being precisely regulated by an automatically controlled air cushion. For exact and precise support pressure control at the tunnel face, a bulkhead separates the slurry-filled chamber into a front excavation chamber and a rear intermediate chamber, the working chamber. In the intermediate chamber, the support pressure is generated by a pressurized air bubble and transferred to the bentonite suspension. Communication between the two chambers takes place via a bulkhead opening in the invert area. First mixshield project was the DESY particle accelerator HERA in Hamburg 1985 (HERRENKNECHT M., 2019).

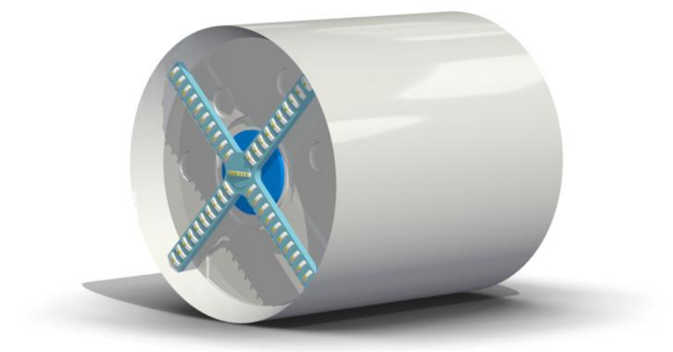


Figure 8: Visualization of the first mixshield, that was used for the excavation of particle accelerator in Hamburg

In their original conception, EPB and slurry shields represented complementary technologies designed to cover the full spectrum of ground conditions, ranging from clays and fine-grained silts to coarse gravels. EPB machines are generally considered suitable for fine-grained soils, whereas slurry shields are more appropriate for coarse-grained materials. Over time, however, EPB machines have become increasingly versatile, extending their applicability across a broader range of geological environments. This development has occurred largely because EPB technology has, in part, adopted principles of slurry shields; even in coarse-gravel formations, a slurry is formed within the excavation chamber, serving as a support medium. This is corroborated, for example, by (Recommendations and Guidelines 2000), which states: *"In order to extend the range of application of shield machines with earth pressure balance support, suitable agents for conditioning the soil material can be applied: bentonite, polymer, foam from polymers."*

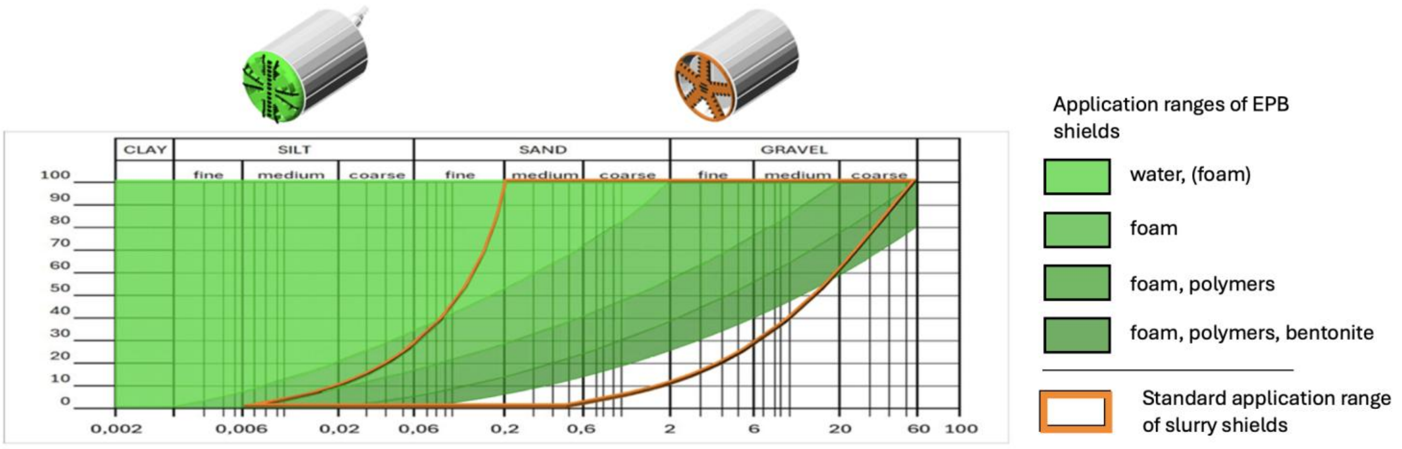


Figure 9: Application ranges of EPB vs slurry shields [Thewes 2007]]

It is evident that from the early days of the invention of the earth-pressure and bentonite shields, tunnelling engineers and machine designers began to consider how both construction principles could be combined into a single concept, thereby creating a universal machine capable of operating in virtually all ground conditions.

The first such machine, designated as a multi-mode TBM, was designed in the 1980s. (BÄPPLER K., BATTISTONI F., BURGER W., 2018) In 2000, a multi-mode TBM was successfully deployed on the Socatop road tunnel project in Paris. In 2013, Herrenknecht supplied a TBM for the Miami Port Tunnel project that was capable of operating both in Earth Pressure Balance (EPB) mode and in Water-Controlled Process (WCP) mode. The WCP allows hydraulic muck removal: the discharge gate is bypassed, and the excavated material is transferred directly from the screw conveyor through a crusher into a slurry pipeline, which then pumps the material to a surface separation plant.

Over time, the generation of multi-mode TBMs evolved into a new class of shielded machines – the Variable Density TBMs.

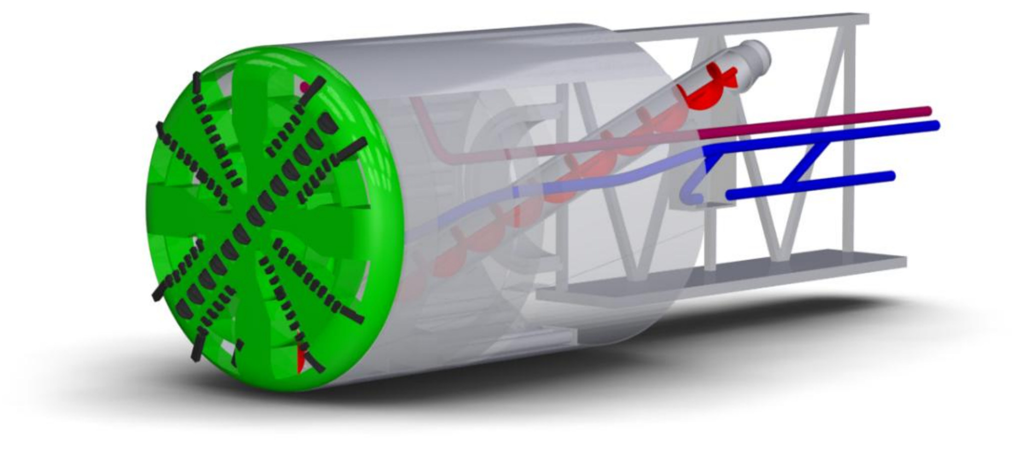
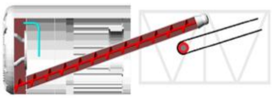
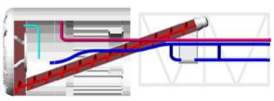
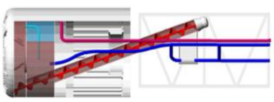
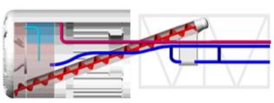


Figure 10: Visualization of the Variable Density Shield

6. VARIABLE DENSITY TBMS

If we were to look for an answer to the question of how far the technological development of tunnelling shields has progressed over the past two hundred years, the most fitting answer would be the Variable Density TBM. This is a tunnelling machine that, without any major structural modifications, is capable of excavating in four different modes and can therefore combine the principles of both EPB and mixshields as needed. This machine can also be operated using a high density in the excavation chamber that would be too dense for classic slurry operation but that would be too fluid for a classic EPB operation. The shield derives its name from the fact that, depending on the encountered geological conditions, it is able to excavate using different types and different densities of support media, as shown in Table 4.

Table 4: Four different excavation modes of the Variable Density TBM

TBM set-up	Work mode	Support Medium	Muck-out principle
	EPB mode	Pasty earth cake	Conveyor belt
	EPB mode with additional bentonite support	Pasty-liquid earth cake	Slurry pipes
	slurry-supported mode with High Density Support Medium (HDSM)	Thick suspension (bentonite suspension with filler)	Slurry pipes
	slurry-supported mode with normal bentonite suspension (Low Density Support Medium – LDSM)	Thin suspension (bentonite suspension)	Slurry pipes

The first Variable Density TBM was used for the 9.5-km long underground section of the first line of the Klang Valley MRT Project in Greater Kuala Lumpur. The soil structure of the Kuala Lumpur Limestone is demanding due to its characterization of highly erratic karst features with eroded limestone rock beneath a layer of topsoil. For a total of 8.6 km, six Variable Density TBMs (Ø 6.62m) were deployed.

The machines proved themselves to be up to the task over a two-year construction period, paving the way for current projects involving tunnelling in extremely challenging unconsolidated rock.

In 2016, a Variable Density TBM was used in the Shatin to Central Link (SCL) extension of Hong Kong's metro network. Other projects in which Variable Density TBMs have been deployed include, for example, Metro Line B in Lyon, the High Speed Two railway in London, the Hampton Roads Bridge–Tunnel Expansion in the United States, and Metro Line 4 in Rio de Janeiro. It can be expected that the list of such projects will grow dynamically in the coming years.

7. CONCLUSION

The tunnelling shield, originally invented as an emergency solution for conditions in which the tunnelling methods of the time were failing, has over the past two centuries developed into one of the most widely used tunnelling techniques in the world. Various methods of face support were developed, and hand in hand with them, the designs of tunnelling machines evolved as well. The development to date has culminated in the Variable Density TBM, through which tunnel builders gain a powerful tool that essentially uses—or to some extent combines—all previously known methods of face support. Thanks to this, it is capable of excavating in a wide range of soils and rock conditions, including mixed-face environments. It is then up to the tunnellers themselves to know how to use this tool: to understand which type of support medium is suitable for the given geological conditions, and to be aware of all the limitations associated with each specific type of face support. Only in this way can tunnelling machines be used with maximum efficiency and with minimal impact on the surrounding environment and structures located within the zone affected by excavation.

LITERATURE

MCCRAY J., The 1880 Tunnel Tragedy That Claimed 20 Lives Beneath the Hudson, Hudpost, 21.7.2025.

Tells How It Feels to Go Up In A Geyser, New York Times, 21.2.1916

EDWARDS C., MERRILL K., Baltimore Metro Northeast Extension, Rapid Excavation and Tunnelling Conference, Society for Minning, Metallurgy, and Exploration, 1995

Recognizing the bentonite machine, Tunnels & Tunnelling, BTS, 1/2019

BRIERLEY G.S., Pressurized Face Tunnelling: A Historical Perspective, Tunnel Business Magazine, 8/2015

HERRENKNECHT M., Innovations in Mechanized Tunnelling since 1970, Muir Wood Lecture 2019, International tunnelling and underground space association 4/2019

Recommendations and Guidelines for Tunnel Boring Machines, ITA-AITES, p. 1-118, 2000

Recommendations for the Selection of Tunnel Boring Machines, German Tunnelling Committee (ITA-AITES), 1/2022 (revised version 8/2025)

HERRENKNECHT M., THEWES M., BUDACH CH., The development of earth pressure shields: from the beginning to the present, Geomechanics and Tunnelling, 4/2011

BABENDERERDE S., HOEK E., MARINOS P.G., CARDOSO A.S., EPB-TBM Face Support Control in the Metro do Porto Project, Portugal, Proceedings 2005 Rapid Excavation & Tunnelling Conference, Seattle

Recommendations for Face Pressure Calculations for Shield Tunnelling in Soft Ground, German Tunnelling Committee (ITA-AITES), 2016

CHEN X.J., FANG P.P., CHEN Q.N., HU J., YAO K., LIU Y., Influence of cutterhead opening ratio on soil arching effect and face stability during tunnelling through non-uniform soils, Underground Space vol. 17, pages 45 – 59, 8/2024

BÄPPLER K., BATTISTONI F., BURGER W., Variable Density TBM – Combining Two Soft Ground Technologies, Tunnel Business Magazine, 3/2018

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