CHAPTER II

TBM AND TUNNELING METHOD

In order to succeed with high benefits from tunneling work in a known geological condition, it is important for tunnel engineers to gain enough knowledge about the TBM and the method of construction related to each machine. This chapter describes the different kinds of TBMs, which are commercially available, and then the criteria for selecting some soft ground TBMs are also given. A more detail about the EPB tunneling method, which is used in the current tunneling project, is described in the last section of this chapter.

2.1 History of Shield Tunneling Methods

In tunneling work, a shield is used as a temporary structure to protect the workmen during excavation through soft soil or unstable rock. Based on Sutcliffe (1996), TBMs were first developed and used with soft grounds by Marc Isambard Brunel and James Henry Greathead in England. These shields progressed by breaking the excavation into small compartments excavated by hand. The first Brunel shield, patented in 1818, excavated these comportments and advanced the shield in a spiral pattern, with lining segments following in the same spiral. The shield did not rotate, but the spiral arrangement of the head meant that the inner excavated along a spiral path at right angles to the direction of the tunnel.

Subsequently, a rectangular cross-section of tunneling shield, which was also developed by Marc Isambard Brunel, was used to excavate a tunnel beneath the River Thames between Wapping on the north bank and Rotherhithe on the south one in London. The shield consisted of 12 connected iron frames which allowed a total of 36 workers to excavate the soil at its face safely. When the workers of all the cells had excavated about 4.5 inches of soil, the shield was then pushed forward by screw jacks and successively the brick tunnel lining was assembled behind it (Figure 2.1). This tunneling was began in 1825 and finally completed in 1841 due to some difficulties during this period (Channel4). However the tunnel was officially opened in 1843.

The initial idea of tunneling shield construction was hitting Sir Brunel up when he saw the shell of the shipworm *Teredo navalis*, a mollusk whose efficiency at boring through submerged timber he observed while working in a shipyard (WIKIPEDIA, The Free Encyclopedia).

1 Cast iron frame
2 Poling boards
3 Screw jacks holding poling boards in place
4 Iron plates
5 Brick tunnel lining
6 Pivoted feet to frames
7 Main jacks

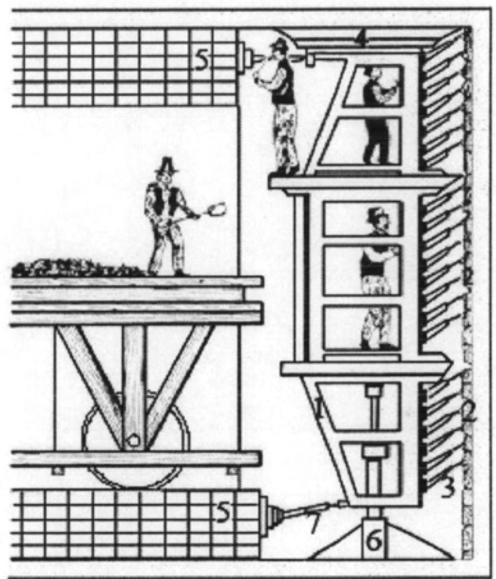


Figure 2.1 Marc Isambard Brunel's rectangular tunneling shield (Gardner, 1996)

Using a circular shield, which was in charged by James Henry Greathead, the second tunnel under the Thames was excavated in 1869. This shield offered greater protection to the miners against face collapse and it moved forward by screw jacks thrusting on the cast iron liners erected behind the shield. In addition, a lime slurry was used to grout the tail void behind the liner segments. It is the first time that the cast iron liners and lime slurry grout were used in tunnel construction. These circular shields gradually became more mechanized and exchanged features with the developing Rock TBMs (Sutcliffe, 1996).

2.2 Different Kinds of TBMs

During its service life, a TBM is heavily used day and night under the different underground environments and sometime it is subjected to very a high stress. According to Sutcliffe (1996), a TBM has five simple functions:

- To excavate the ground,
- To remove the material excavated,
- To maintain line and grade of the excavation,
- To support the excavated tunnel temporarily until permanent support can be provided,
- To handle adverse ground conditions.

Moreover, these functions must be performed:

- Safely,
- Reliably,
- Continuously for many months,
- Through any and all ground conditions,
- Quickly,
- Economically.

An overview of different kinds of TBMs, which are used for rock and/or soft ground tunneling, are given in the following sections.

2.2.1 Rock TBMs

The rock TBMs described here refer to Gripper TBMs or Open TBMs and Shielded TBMs, which are manufactured by Herrenknecht and Wirth Company. The gripper TBM (Figure 2.1) is suitable for driving in stable rock. The main elements in the construction of this open TMB are the cutter head with its associated drive housing, the support construction (the so-called gripper) and the advance mechanism. The cutter head is equipped with cutters (disks). The rotating cutter head presses the disks against the tunnel face applying high pressure. The disks perform rolling movements on the tunnel face causing the loosening of the rock. The excavated rocks, usually described as chips, are picked up by buckets (openings in the cutter head) and transported via hoppers onto the conveying system. The TBM conveyor transports the material for the complete length of the TBM to the transfer band between TBM and backup system. From there, the excavated material is transported via conveyors either to the outside or to the loading dock of the muck cars.

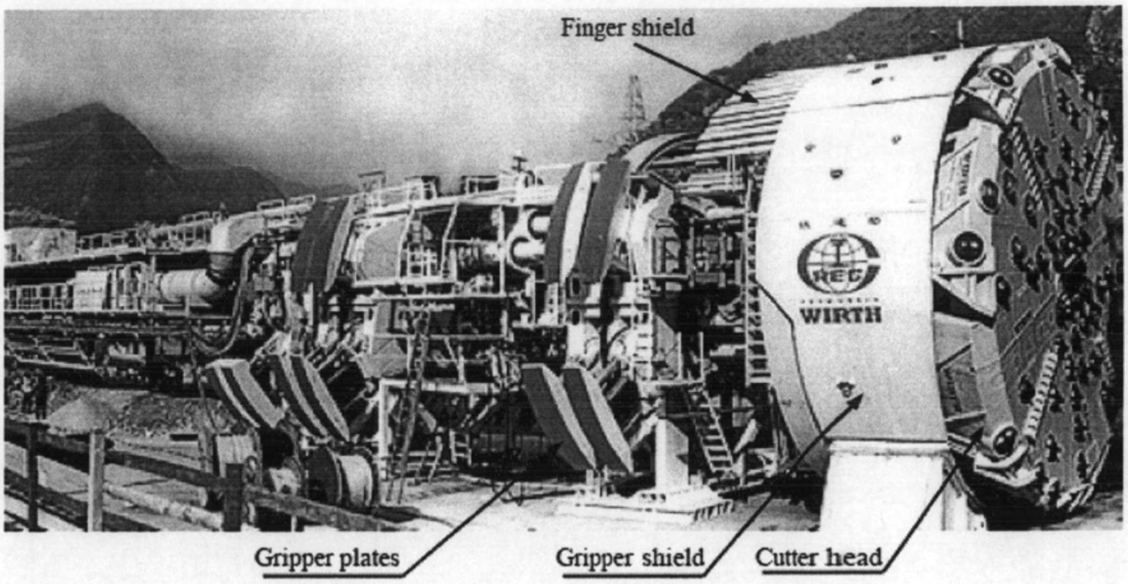


Figure 2.2 Open TBM or gripper TBM (Wirth Company)

When the boring machine is driven through unstable (or even stable) rock, the shielded TBM is necessary. The main elements in the construction of the shielded TMB, according to information issued by Wirth company on its website, consist of the shield which gives the machine its name, a construction-like steel tube in which all other components of the machine are embedded, the cutter head and its drive housing, the advance mechanism and the robot-like device for installation of the tunnel lining or the so-called erector. The tunnel lining, usually consisting of prefabricated concrete sections, is installed with the erector, protected by the rear shield mantle, the so-called tail shield. Shielded TBM, which can be used for tunneling in either stable or unstable rock is shown in Figure 2.2 (LOVAT Company).

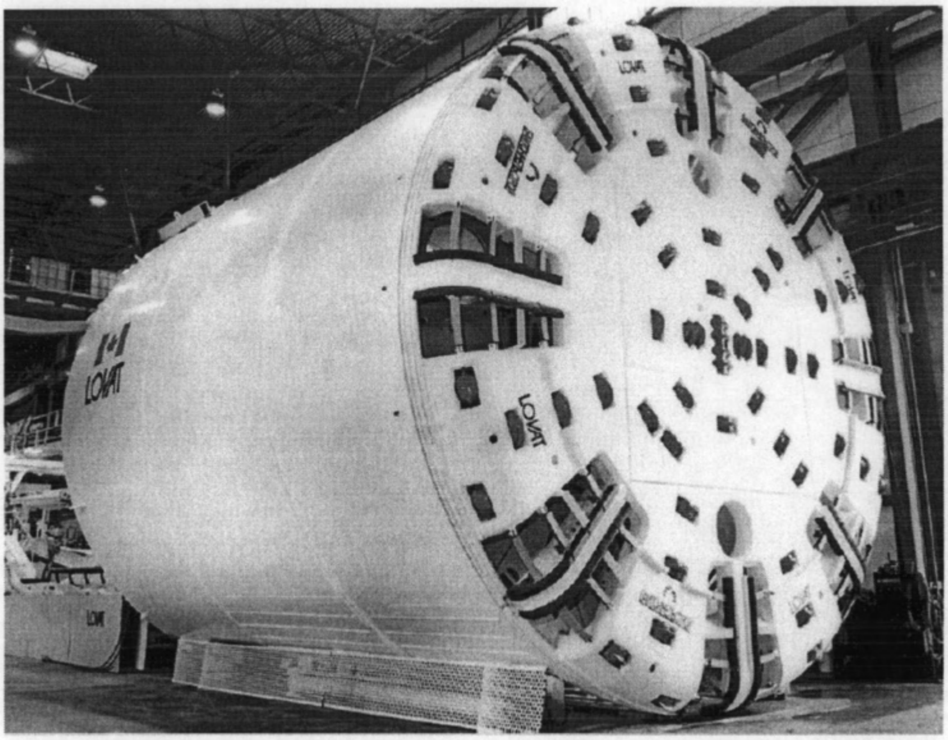


Figure 2.3 Shielded TMB (LOVAT Company)

2.2.2 Soft Ground TBMs

Nearly all soft-ground tunneling machines are circular. Based on Monsees, (1996), these machines, including shields, have five basic components as follows:

- The *cutting edge* trims the outside perimeter of the tunnel. In a digger shield, a rotating "cheese grater" mounted on the face of a drum, the cutting edge cuts only those portions of the perimeters not excavated by the digger mechanism. With a fully mechanized tunneling machine the front edge occasionally may not cut the ground depending upon the configuration of the cutter head, specifically when gauge or perimeter cutters are used.
- The *body* of the machine is usually a steel cylinder, stiffened by generally vertical and horizontal bracing members, by the housing and attachments for the face support and propulsion jacking systems in a simple shield, and by the equipment in a tunneling machine. In a shield the bracing members also divide the face into the number of working pockets or zones that are necessary to provide safe and stable working cells for mining and mucking.

- The *tail* of the machine extends rearward from the body and provides protective cover for the workers and the out line for the erection of the tunnel support system. To assure the support system is always within the tail (or, conversely, that unsupported ground is never exposed) the tail length must be such that at least one-half of the length of the last fully erected supporting element stays within the tail shield when the shove jacks are fully extended.
- The *shove jack system* provides the forward propulsions for the machine. These jacks are located around the perimeter of the shield and are housed within the body. They usually obtain reaction for their thrust from the tunnel support system to the rear.
- The *hood* projects ahead of the body thereby providing protection for workers at the face, this portion located at the front of a classical shield. Working with this protection, the breasting or face support system is advanced stepwise to complete the excavation required for each shove of the shied. With a full-face or closed machine, there often is no hood, and face stability is provided by control of the openings in the machine face or cutting head.

(Monsees, 1996, pp. 97-121)

Since the tunnel face stabilization based on compressed air was found to be hard for human body, only two types of shields are commonly used for tunneling in water bearing soil: one is slurry shield machine and the other is EPB shield machine. The basic principle of these two machines is briefly described in the next sections, sections 2.2.3 and 2.2.4.

2.2.3 Slurry Shield Machine

Basic principle of this TBM is to maintain the tunnel's cutting face during the excavation phase by filling the working chamber, located behind the cutter head, with bentonite slurry (Wirth Company). In addition, the slurry acts as a means to transport the excavated soil, after mixing, from working chamber to the surface by pumping. The Figure 2.4 shows a schematic representation of the slurry shield machine, in which the slurry feed conduit and return pipe for suspension removal are mentioned.

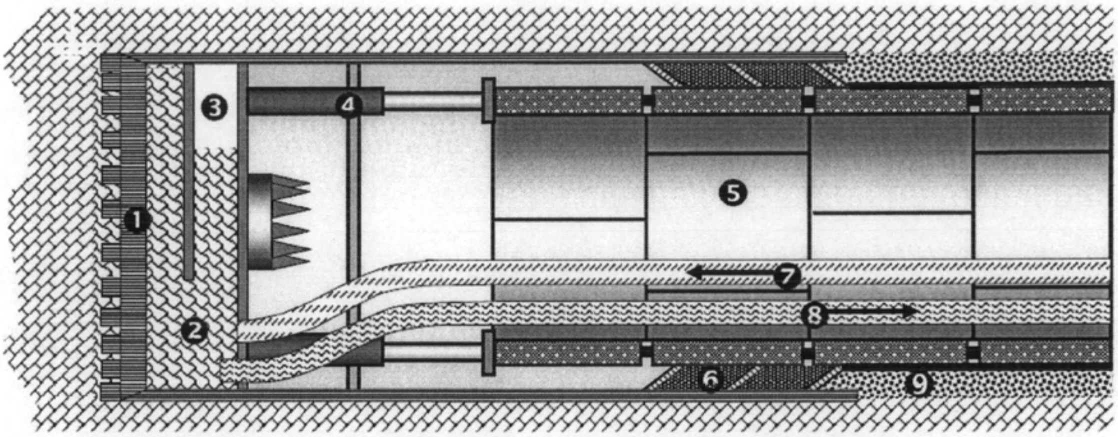


Figure 2.4 Principle of slurry shield machine (EFNARC, 2005)

2.2.4. EPB Shield Machine

In contrast to the other shields, the stability at the working face of EPB depends on a secondary support medium. In other words, the soil is loosened by the cutting wheel served to support the working face.

The shield area in which the cutting wheel rotates is designated as the extraction chamber and is separated from the shield section, which is under atmospheric pressure, by the pressure wall (Herrenknecht Company). In brief, the excavated material exits the extraction chamber by means of screw conveyor and then it is loaded in the train cars, which circulate in the tunnel, via a long reversing belt conveyor. The material is then discharged at the inlet shaft.

The EPB system is schematically shown in Figure 2.5, in which the extraction chamber, screw conveyor and erector arm are also mentioned. Since the EPB shield is selected for the current project, a relatively detailed description about the EPB tunneling method is given in section 2.4 of this chapter.

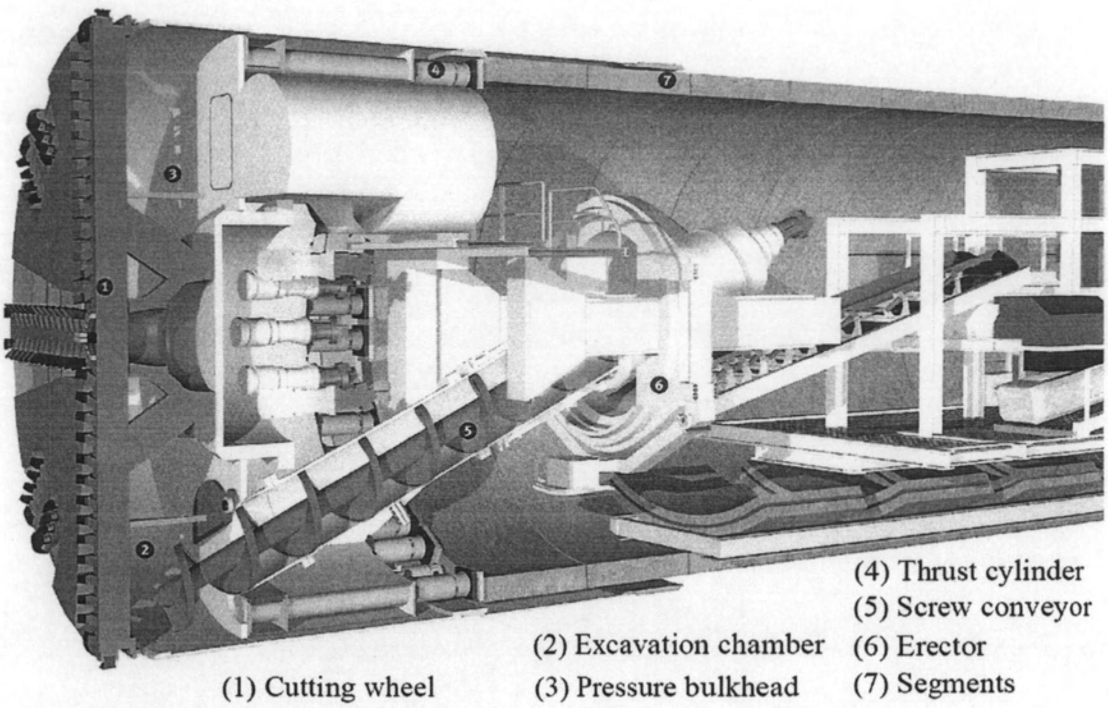
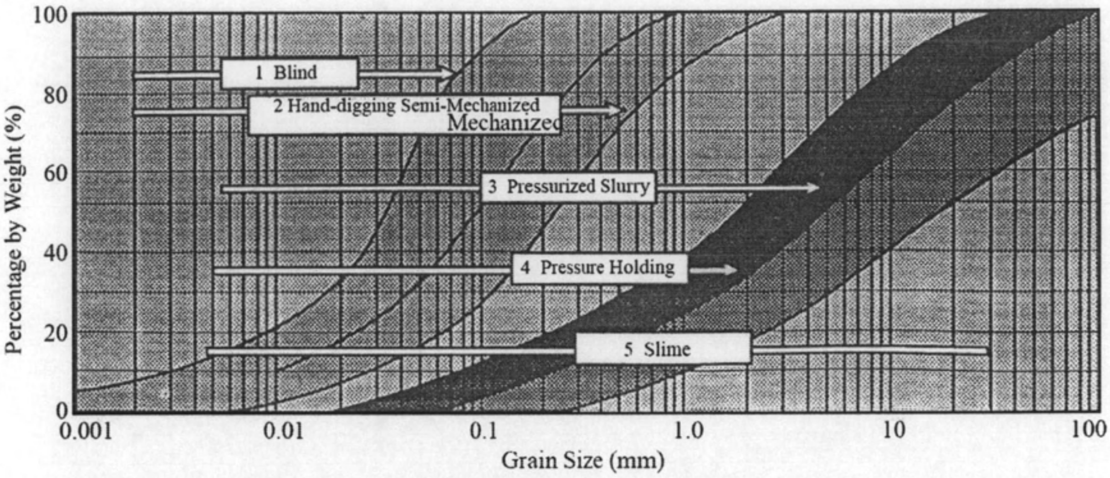


Figure 2.5 Principle of EPB shield machine (Herrenknecht Company)

2.3 Criteria for Selection of Soft Ground TBMs

In response to the development of underground space used for most urban areas, the soft ground tunneling deserves attention. However, the selection of a suitable TBM is a critical point for the success of construction. Monsees (1996) described some variables to be considered in selecting a soft-ground tunneling machine including water conditions, tunnel size, support system, excavation conditions, and the excavation environment.

Figure 2.6 shows the applicability of various soft ground machines in relation to the grain size distribution curve. Tables 2.1 and 2.2 contain a summary of the types of machines and their application to various ground conditions.



Clay	Silt	Fine	Coarse	Fine	Medium	Coarse	Cobble
		Sand		Gravel			

Figure 2.6 Applicability of soft ground machines versus grain size (Monsees, 1996)

An appropriate selection of TBM for a given subsoil condition leads to a high performance of tunneling work in terms of excavation speed, and problem minimization including safety. Although some tunneling machines can be used in various types of soil with different physical conditions, the selection of these machines depends also on the experience of machine operators.

Table 2.1 Conventional Machines (Monsees, 1996)

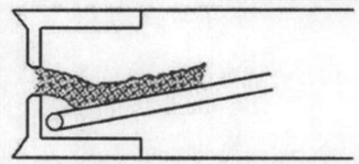
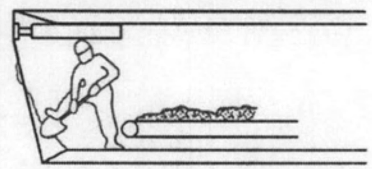
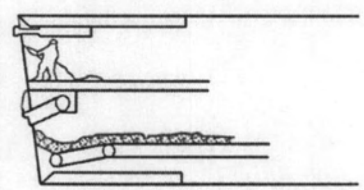
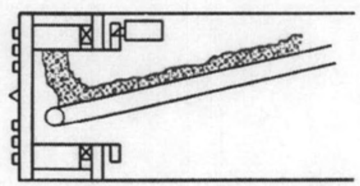
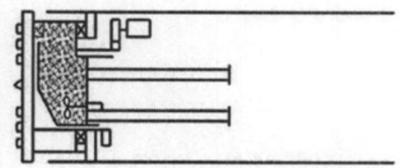
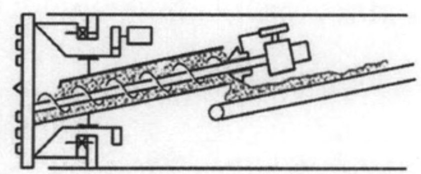
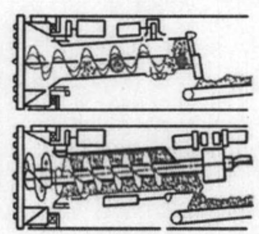
Type	Description	Notes	Sketch
Blind Shield	A closed face (or blind) simple shield used in very soft clays and silts. Muck discharge is controlled by adjusting the aperture opening and the advance rate.	Used in harbor and river crossings in very soft soils. Often results in a wave or mound of soil over the machine.	
Open face, hand-dug shield	Good for short, small tunnels in hard, non-collapsing soils. Usually equipped with face jacks to hold breasting at the face. If soft conditions require it, this machine may have movable hood and/or deck.	A direct descendent of the Brunel shield. Now largely replaced by more mechanized equipment. Sometimes used at the head of large cross-section, jacked tunnels.	
Semi-mechanized	Similar to the open face, but with a back hoe, boom cutter (roadheader) or the like.	Until very recently, the most common shield. Often equipped with "pie plate" breasting and one or more Tables. Can have trouble in soft, loose, or running ground. Compressed air may be used for face stability in poor ground.	
Mechanized	A fully mechanized machine. Excavates with a full face cutter wheel and pick or disc cutters.	Manufactured with a wide variety of cutting tools for various soils. Face openings (door, guillotine, and the like) can be adjusted to control the muck taken in versus the advance of the machine. May also be used with compressed air for face stability in poor ground.	

Table 2.2 Special Machines (Monsees, 1996)

Type	Description	Notes	Sketch
Slurry face machine	This machine uses pressurized slurry to balance the groundwater and soil pressure at the face. It has a bulkhead (closed face) to maintain the slurry pressure on the face; that slurry must be piped down and recycled from the surface. It may also be equipped with a stone crusher for occasional cobbles. This machine is good for water bearing silts and sands with the gravels.	Best for sandy soils; tends to gum up in clay soils; with coarse soils, face may collapse into the slurry. Coarse soils are defined as • Gravel content > 60% • Clay and silt content < 10% • Water content < 18% • Coefficient of permeability ≥ 10^{-2} cm/s • Cobbles greater than 8 in.	
Earth Pressure Balance (EPB) machine	This machine has a closed chamber (bulkhead) face that uses trapped water and soil material to balance the groundwater and/or collapsing soil pressure at the face. It uses a screw discharger with a cone valve or other means to form a sand plug to control "balance" the earth pressure. It is good for clay and clayey and silty sand soils, generally below the water table	Also best for sandy soils, with acceptable conditions defined as • Clay and silt content >7% • Gravel content < 70% • Cohesive soils (not less than 40% clay and silt) have N-value <15. • Water content >18% in sandy soils and >25% in cohesive soils	
EPB high-density slurry machine	A hybrid machine that injects a denser slurry (sometimes called slime) into the cutting chamber. Developed for use where soil is complex, lacks fines or water for an EPS machine, or is too coarse for a slurry machine.	Has worked in soil with 85% gravel content and cobbles and boulders up to 20 in.x10in.x7in. Has worked in sandy gravel soil with N=30 to 50 and sandy or silty soil with N=5 to 35.	

2.4 EPB Tunneling Method

The EPB shield machines are proffered machines for tunneling in clay, clayey or silty sand soils, generally below the ground water table. Moreover, in comparison with the slurry shield machines, the EPB shield makes the on site muck handling easier and eliminates the need for a sophisticated separation plant on the surface (EFNARC, 2005). The EPB shield machines are very well known in Thailand since they were used in all the previous important tunnel excavations in this country.

2.4.1 History of EPB Shield Machine: its development and implementation

Since the compressed air and slurry shield tunneling methods were found with some disadvantages and limitations, the Sato Kogyo Company Ltd. developed the first concept of EPB shield in 1963 as shown in Figure 2.7. After many experiments in the laboratory and in the field, this machine was successfully built in 1966 by Ishikawajima Harima Heavy Industries Company Ltd. The first EPB shield tunneling method was first used in 1974 on a 1900-meter collector drive in Tokyo (Suwansawat, 2002). The invention of this machine eliminated the need of slurry and compress air technique.

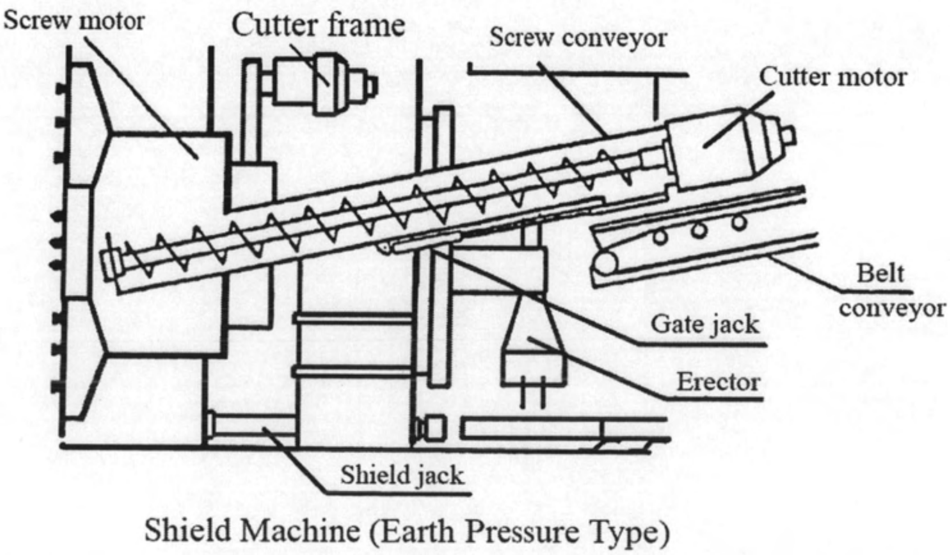


Figure 2.7 Typical EPB shield introduced by Sato Kogyo Company, 1963 (cited by Suwansawat, 2002)

Later , the EPB method had been extensively used in Japan. By 1980, around 16% of all the shield tunneling methods used for tunnel construction in this country were based on the EPB techniques (Naito, 1984 cited by Greenwood, 2003). Later on, the EPB shields were adopted and produced by the various manufacturers in order to respond to the demands of underground transportation system as well as other uses in the populated city.

Table 2.3 shows some examples of major tunneling projects where the EPB tunneling method was used. In some projects more than one EPB shield with different dimension, outer diameter (OD) and length, were used to complete the whole project. However, all the data given in the table are based on the available information provided by the related sources.

Table 2.3 Tunnels constructed with EPB tunneling method

Country, city/location	Tunnel/Project name	Length (km)	OD of tunnel (m)	OD of EPB shield (m)	Work period	Date open	Source of information
Japan, Tokyo	Tunnel excavation project of SJ51 to SJ53 (Clockwise Route)	2.0181	11.80	12.02	March 14, 2002 to February 15, 2005	-	Dobashi et al. (2006)
Thailand, Bangkok	Chaloem Ratchamongkhon Line Project of the Bangkok Mass Rapid	20	6.30	6.43	August 11, 1977 to August 4, 2002	2004	Tokuda et al. (2006)
Netherlands, Rotterdam	Botlek Rail Tunnel	3	9.45	9.775	1999 to 2002	2002	Maidl (1999)
Spain, Madrid	Line 10 of the Madrid Underground	2.15	7.20	7.38	1995 to 1996	1996	Arnaiz et al. (1998)
Canada, Sarina	St. Clair River Tunnel	1.80	9.2	9.52	March 1993 to May 1995	-	Wayss & Freytag Ingenieurbau AG
Singapore	Changi Airport line	7	5.90	6.15	1999 to -	2001	TAC (2000)
Italy, Milan	Milan Urban Link Line	3	7.5	8	-	-	Lunardi et al. (1993)

2.4.2 Tunnel Excavation

According to the information issued by Herrenknecht Company, the tunnel excavation based on EPB technique can be performed in the following procedures:

- The soil is loosened by the tools of the cutting wheel, drops through the openings in the cutting wheel into the extraction chamber (Figure 2.5) and mixes together with the plastic pulpy soil which is already there. Uncontrolled penetration of the soil from the working face into the extraction chamber is prevented by transferring the power of the tunneling jacks from the pressure wall to the pulpy soil. At the point when the pulpy soil mixture in the extraction chamber is no longer compressed by the pressure of the earth and water which lies ahead, a state of equilibrium is reached.
- The material which has been extracted is removed from the extraction chamber with a screw conveyor (Figure 2.5 and 2.7). The amount of material conveyed is regulated by the revolutions of the screw and the diameter of the opening of the upper screw valve.
- The screw conveyor transfers the extracted material to the first conveyor belt of the conveyor belt cascade (Figure 2.5). Via this belt, the extracted material reaches the so-called reversing belt. The transport cars for the extracted material in the backup system in the reversing operation are loaded via this belt.
- If the TBM is operated open (open mode), the screw for transporting the extracted material is bypassed and the extracted material is transported to the machine belts by the cutting wheel. To enable the extracted material to be offloaded to the machine belt the muck ring, located in the pressure wall, has to be retracted.

At the same time as the cutting face is rotating, screw and belt conveyor are moving the excavated soil (mud), the hydraulic jacks behind the shield are also extending in order to keep the face pressure in equilibrium as well as to advance the machine its self. For the EPB shield machine used in BMA flood diversion, Saensaep-Latphrao Phrakhanong project, each hydraulic jack has a maximum force of 1500 kPa and can extend up to 165 cm. Figures 2.8 and 2.9 show the transportation of excavated soil by belt conveyor and train cars respectively while Figure 2.10 shows the hydraulic jacks in full extension.

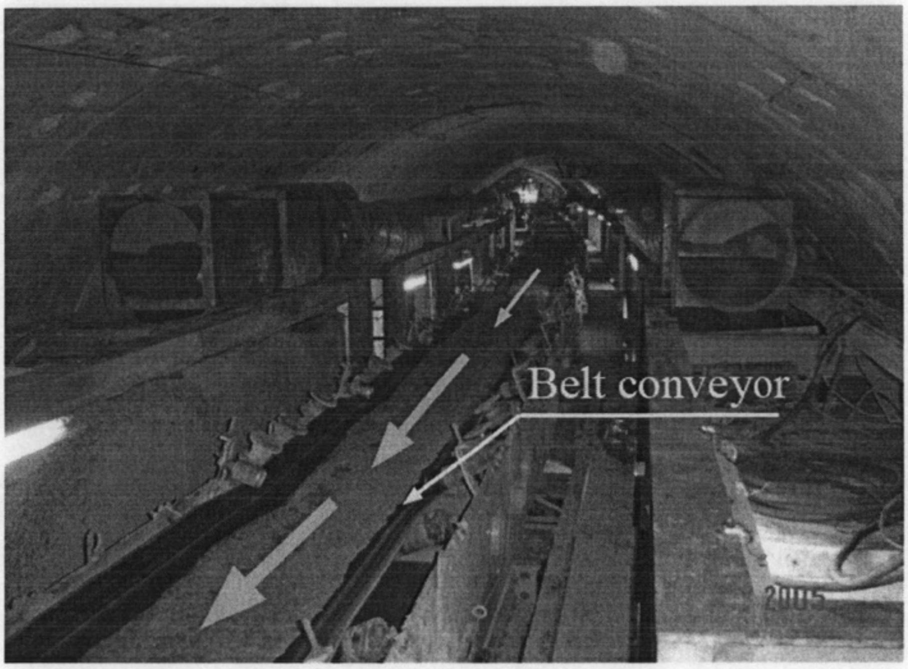


Figure 2.8 Reversing belt conveyor transporting excavated soil (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

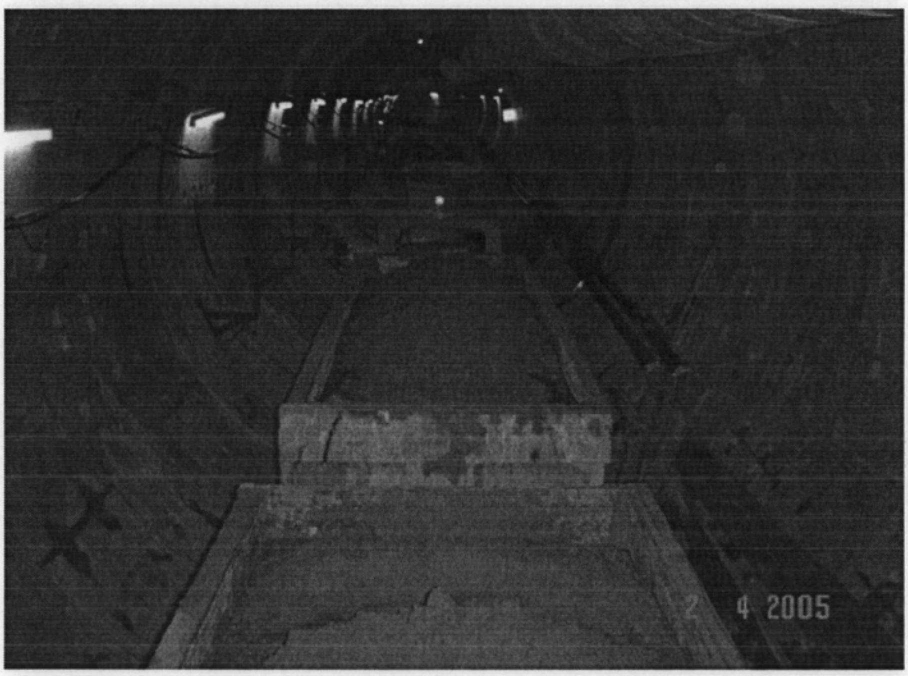


Figure 2.9 Train cars transporting excavated soil (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

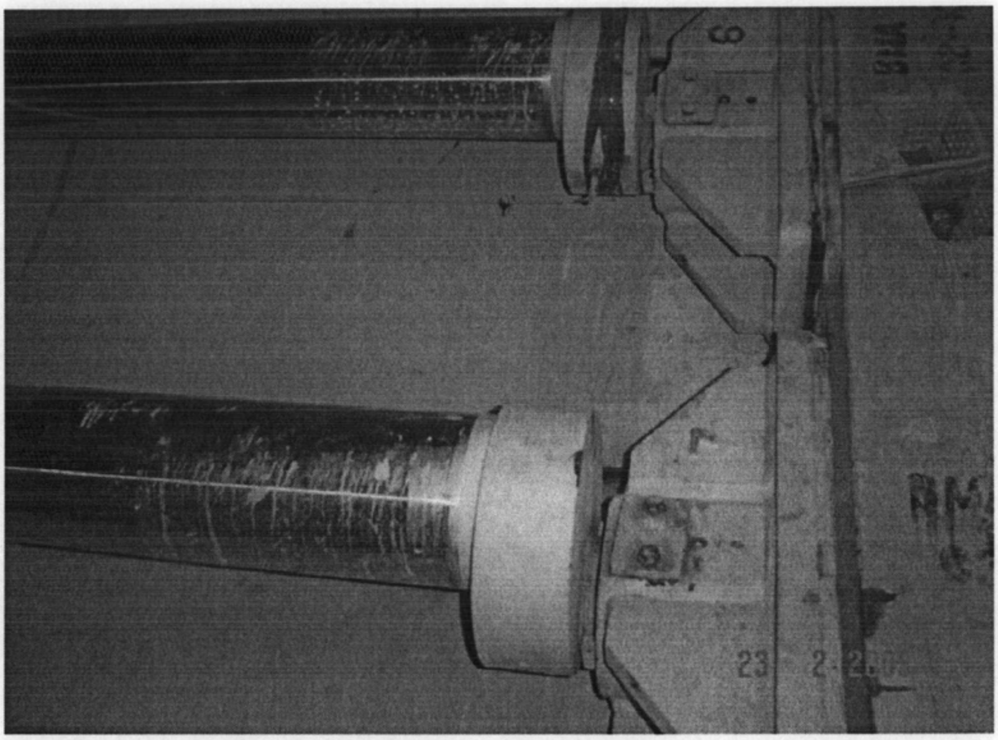


Figure 2.10 Hydraulic jacks pushing on the segmental lining behind the shield (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

2.4.3 Erection of Segmental Lining

The segmental linings are commonly used with shield tunneling method, i.e. EPB method. In most purposes such as tunnel for subway transportation and sewage, the assembly of these segmental linings already provides a sufficient stability and serves as the final structure without secondary lining. For MBA flood diversion tunnel project (Saensaep-Latphrao Phrakhanong), one ring of the lining consists of five standard segments and one key segment, which is made from reinforced concrete, as shown in Figure 2.11. The installation of these segments was done within a space designated at the tail of the shield using the erector arm (Figure 2.12). A perfect look of the flood diversion tunnel after about two and half months of construction is shown in Figure 2.13.

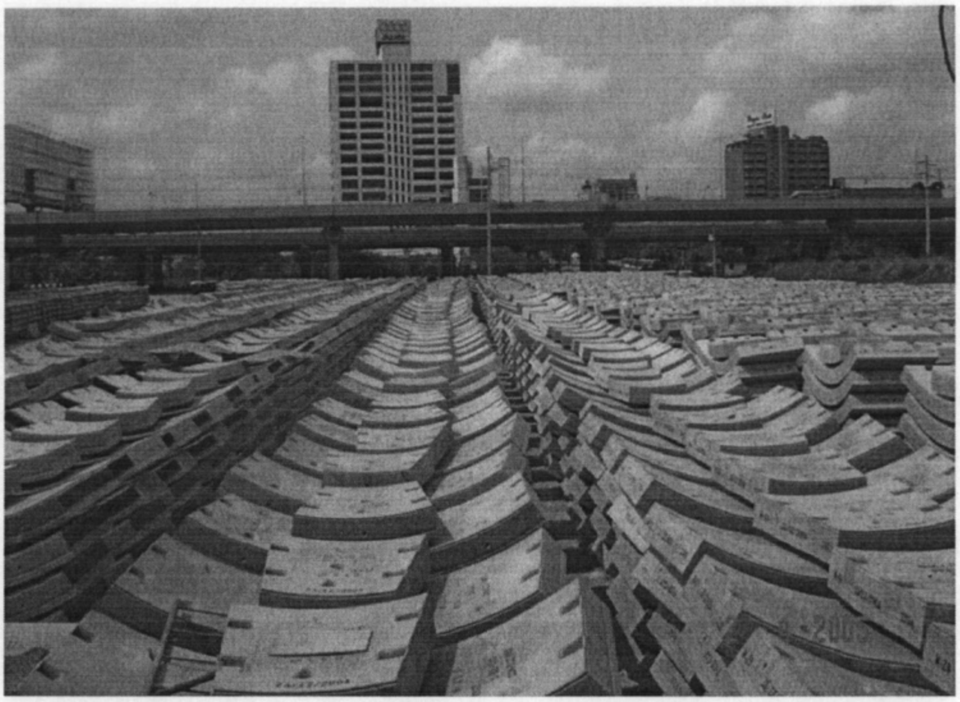


Figure 2.11 Reinforced segmental linings of BMA flood diversion project (Saensaep-Latphrao Phrakhanong)

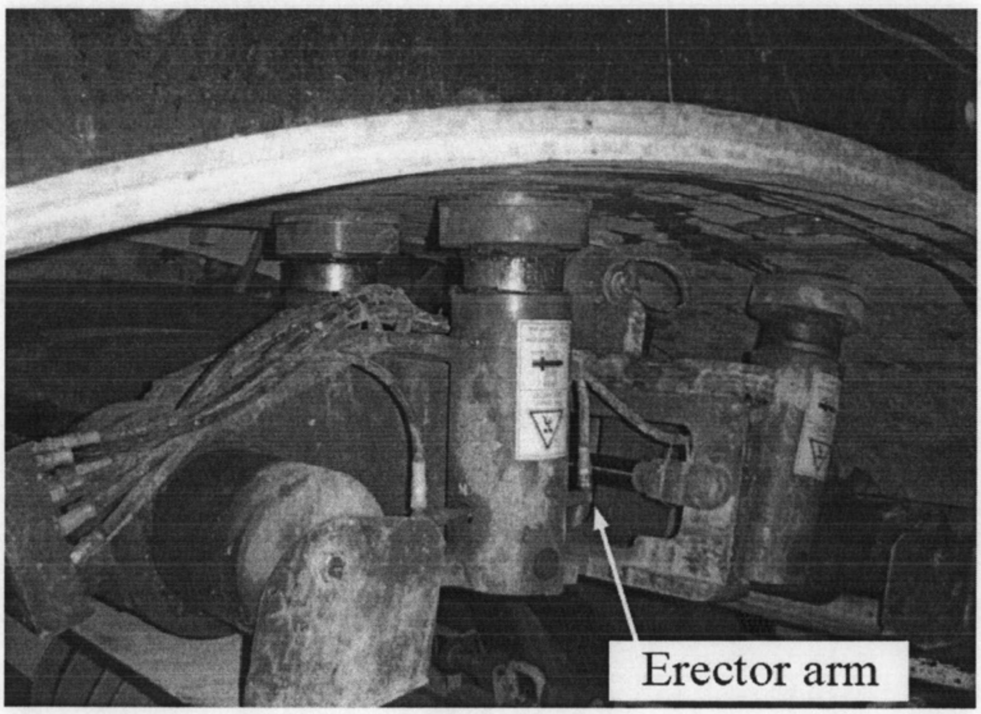


Figure 2.12 Erector arm installing a segmental lining at the crown of the tunnel (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

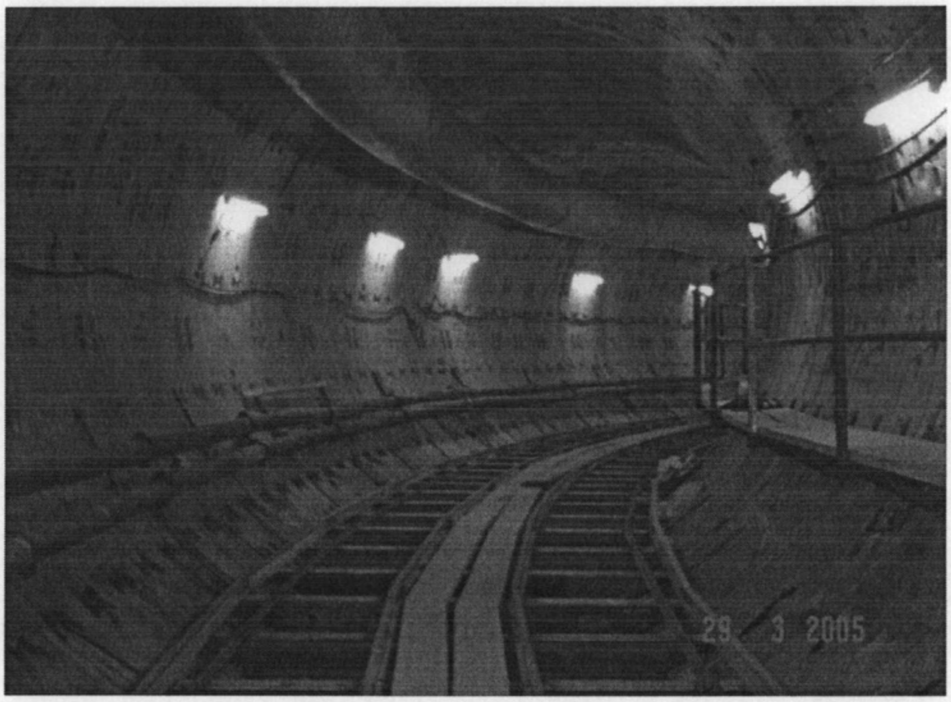


Figure 2.13 Tunnel lining after erection (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

2.4.4 Grouting of Tail Void

As the outer diameter of the tunnel lining is smaller than that of the excavation, the void always happens after the shield moves forward. This remaining void must be continuously injected with the grout material through the grout hole, which is located in the middle of each segment. For the BMA flood diversion project (Saensaep-Latphrao Phrakhanong), the injected grout is a mixture of material A and B of which a ratio is 92:8. The components of material A consist of cement, bentonite, water and stabilizer. However, material B consists of a special sodium silicate which serves as an accelerator. Figure 2.14 shows the grouting pipe attaching to a grout hole during the injection. The pipes corresponding to each material A and B are also mentioned.

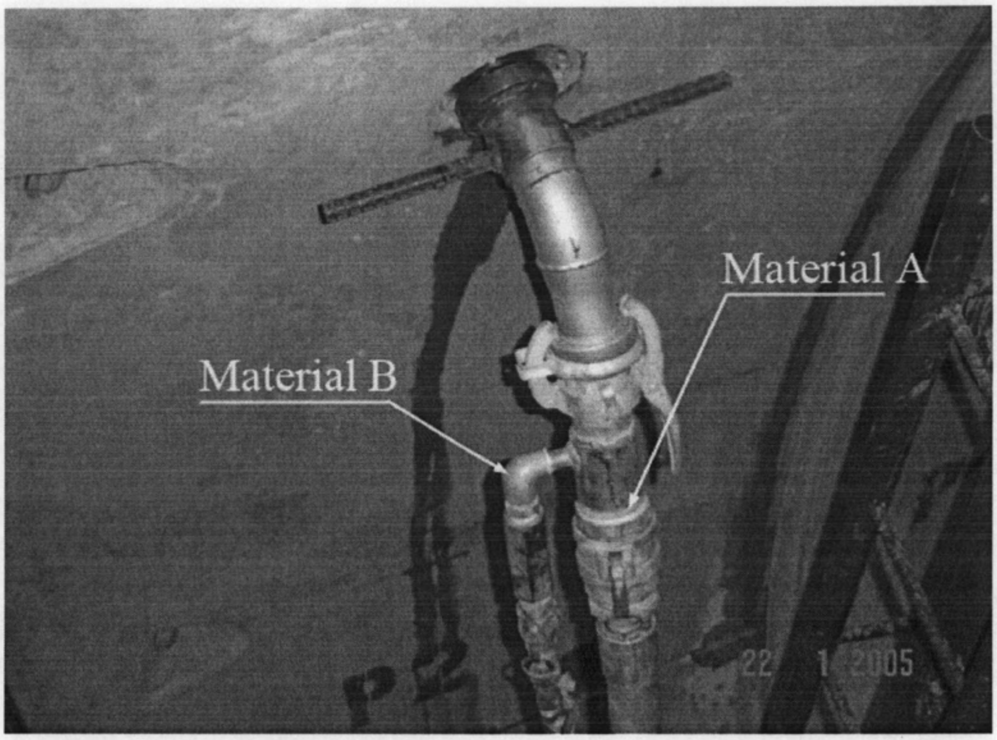


Figure 2.14 Grouting pipe attaching to grout hole (BMA flood diversion project, Saensaep-Latphrao Phrakhanong)

According to the subsoil conditions indicated in section 5.2 of Chapter V and the criteria for selecting a soft ground TBM described in section 2.3, the EPB shield machine is the most appropriate tool for this project. Moreover, the construction company already has experience with this machine during the MRTA subway project. The main components of selected EPB are also clearly mentioned in Chapter V.