1 Introduction

The mined construction of underground infrastructure has made steady progress over recent years. It is now possible to construct underground works with very little impairment of buildings or traffic flow at ground level. Particularly in inner-city areas, with sensitive infrastructure and high population density, there is an enormous demand for underground structures.

The cavities created in this way have until now mostly been for underground transport routes, although there are also other possible uses such as energy extraction, storage and refuge spaces, utility tunnels and, not least, underground urban development. This has led to extensive schemes and projects, particularly in Japan due to the very restricted space availability (Figure 1-1).

Particularly in the field of shield tunnelling, the prominent role of Japan has been unmistakeable. But the development of this construction method is also at a high and internationally respected level in Germany and other parts of Europe. The shield construction process enables the production of elongated underground structures, even at shallow depths, in soil with poor load-bearing capacity or under the groundwater table, without causing any disturbance or significant settlement on the ground surface. Ground conditions with loose spherical material can be mastered, as can soft plastic or flowing soils. But the use of these machines is also practicable in temporarily stable ground, where the shield only acts as head protection. All in all, shield machines have a wide scope of application.

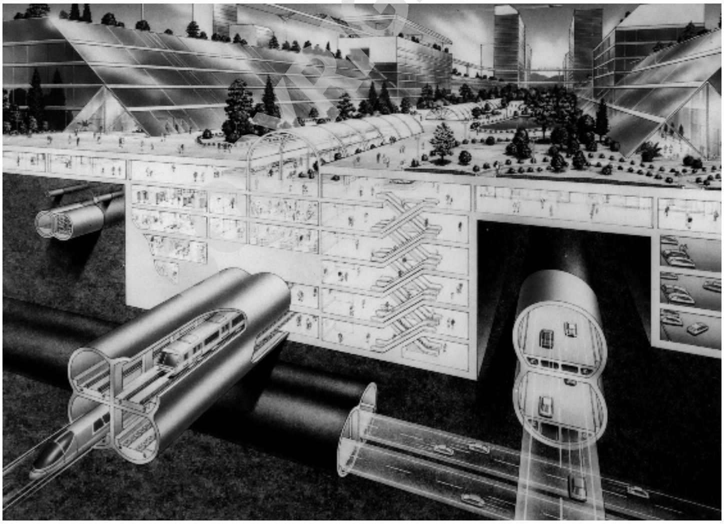


Figure 1-1 Japanese scheme for the exploitation of underground space in an inner-city area [155]

Mechanised Shield Tunnelling, 2nd Edition
B. Maidl, M. Herrenknecht, U. Maidl, G. Wehrmeyer

The shield construction process could but should not generally replace other methods of tunnelling. It can, however, offer a technically feasible and also economic alternative to other methods of tunnelling in unfavourable geological conditions, for long contract sections, high advance rate requirement or where stringent surface settlement limits apply. The essential advantages and disadvantages are summarised below.

Advantages:

- the possibility of mechanisation and high advance rate,
- precision of profile,
- minimisation of the effect on buildings on the surface,
- improved safety for the miners,
- environmentally friendly construction method,
- raising of the groundwater table,
- little noise,
- enables a high-quality and economic lining.

Disadvantages:

- long lead time for the design, production and assembly of the shield machine,
- long familiarisation time,
- elaborate and expensive site facilities (a separating plant may be required); tenders may only be competitive for longer tunnels,
- performance risk in changeable ground,
- the cross-section normally has to be round with little possibility of variation,
- high cost of altering the excavated geometry, e.g. for wider sections,
- the lining normally has to be specially designed to resist the thrust forces.

Application is therefore practicable where the advantages can be sensibly exploited and the disadvantages are taken into account as far as possible in the design and construction planning. Experience shows that a shield in the smaller diameter range can generally compete with other tunnelling methods for tunnel drives up to 2,000 m. For longer tunnels, economic applications of shield machines are possible and even cheaper than using open machines or conventional methods.

The successful use of a shield always requires meticulous design and planning of the machine, the lining and the logistics. Experience and know-how are essential for a practicable and economic scheme. According to [235], too many clients have chosen the wrong machine or construction concept for the ground conditions and have later been faced with unacceptable settlement on the surface, unexpectedly slow advance rates, spalling or failure of the lining, water ingress or other defects. For the client, only a tunnel constructed on schedule, of good quality and at reasonable cost, and with as little impact on the environment as possible is of interest. The designers of shield equipment need to take these natural concerns into consideration. Mechanical engineering issues have to be effectively linked to those of the tunnel itself. Constant exchange of experience between mechanical and civil engineers is essential, with the appropriate evaluation of experience from completed projects.

1.1 Basic principles and terms

The basic principle of a shield is that a generally cylindrical steel construction is driven along the tunnel axis while the ground is excavated. The steel construction supports the excavated cavity until temporary support or the final lining has been installed. The shield therefore has to resist the pressure of the surrounding ground and hold back any groundwater.

While the cavity along the sides of the tunnel is supported by the shield skin itself, additional support measures will be required to support the face, depending on the ground and groundwater conditions encountered. Figure 1-2 shows five different methods of stabilising the face, which are described in detail in Chapter 2. These are:

- natural support,
- mechanical support,
- compressed air support,
- slurry support,
- earth pressure balance support.

These methods of supporting the face represent the great advantage of the shield tunnelling process. In contrast to other methods of tunnelling, it is possible to provide immediate support of the ground as soon as it is disturbed.

In addition to the type of face support, the method of excavation is an important characteristic of shields. The most simple process is manual digging in hand shields, and this is still used today in exceptional cases, for example for short sections and under certain geological conditions. Mechanical excavation is, however, more usual. This can be differentiated into mechanical partial- and full-face excavation. In partial-face excavation, the face is worked in sections using machinery such as hydraulic excavators or roadheaders, which are operated and controlled either by operators or automatically. The full face can be excavated, according to the ground conditions encountered, by open-mode wheels, rim wheels (in some cases with shutters) or closed cutter heads. Further methods are hydraulic excavation using pressurised jets of fluid and extrusion excavation, where the action of the thrust cylinders on highly plastic soil forces it through closable openings in the front wall of the shield. Excavation processes are described in more detail in Chapter 4.

The removal of the excavated material requires special transport systems to move the muck from the face, through the shield and to the surface. The most suitable system depends directly on the nature of the ground encountered and the associated type of face support and excavation, since these factors have a great influence on the consistency and transport properties of the muck. Figure 1-3 gives an initial overview of the possible transport systems through the shield, which will be explained in more detail in Chapter 5. There are numerous transport methods available today, which can be categorised into the three basic groups

- dry transport,
- fluid/slurry transport,
- high-density solid pumping.

Transport along the tunnel can use pumped pipes, conveyor belts, dumpers or rail-based systems (muck trains). The transfer area to the tunnel transport system is integrated into the backup.

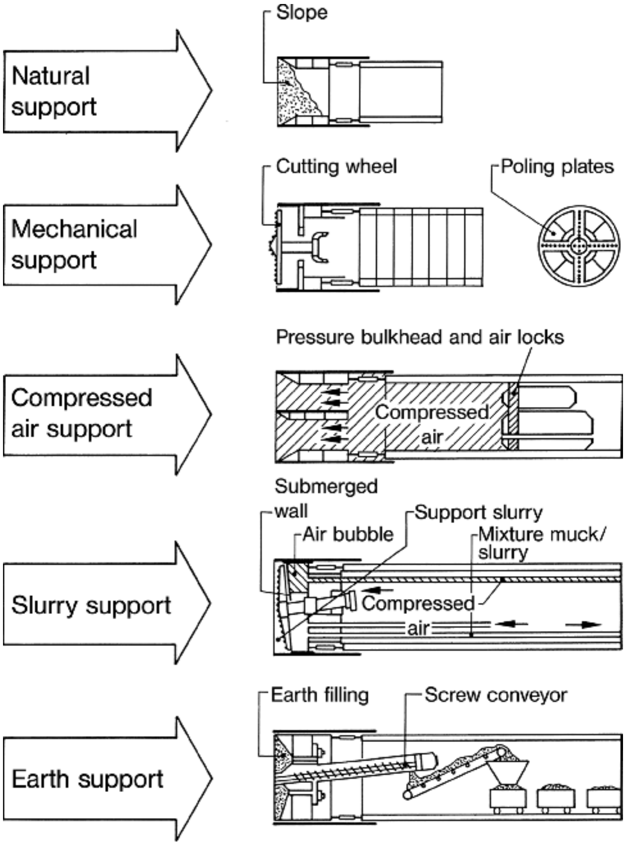
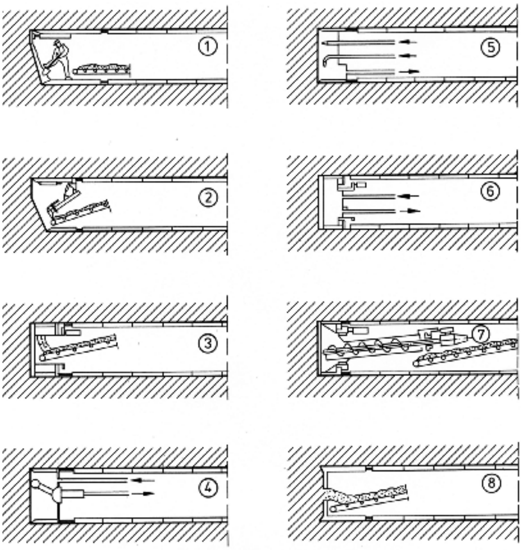


Figure 1-2 Methods of supporting the ground and holding water at the face [266]

The shield is pushed forward in the direction of the tunnel axis with the progress of excavation in order to support the resulting cavity. The required thrust forces are produced by hydraulic cylinders, normally pushing against the already installed lining. This means that the tunnel lining and boring machinery have to be finely matched. The correct function of the shield and the quality of the final tunnel lining both depend on this compatibility, which is dealt with in more detail in Chapter 6.

The cavity produced by excavation is mostly supported with precast elements called segments. There are numerous different forms, materials, possible layouts, sealing systems and installation methods, which require detailed description (Chapter 6). Other lining systems are also possible and are already in use today (Figure 1-4). The pumping of concrete under pressure into formwork (called the extrusion process) is an interesting possibility, but has not been further developed. Even shotcrete can be used in connection with shield tunnelling.

As the support is normally installed inside the protection of the shield skin, a gap remains as the shield progresses further. The gap has to be filled in order to minimise loosening and settlement. This has to be suitably backfilled or grouted and the shield must be provided with the appropriate equipment.



1. Manual excavation and dry removal of the spoil on a conveyor belt,
2. Mechanical partial-face excavation (in this case using a hydraulic excavator arm) and dry transport on a conveyor,
3. Mechanical full-face excavation and dry transport on a conveyor belt (the transfer to the conveyor belt can be either in the central or lower part of the cutting wheel through muck pockets),
4. Mechanical partial-face excavation and slurry transport,
5. Hydraulic excavation and slurry transport,
6. Mechanical full-face excavation and slurry transport,
7. Mechanical full-face excavation, transport with a screw conveyor and transfer to a conveyor belt,
8. Extrusion excavation and transfer of the material onto a conveyor belt.

Figure 1-3 Methods of muck removal in shield tunnelling

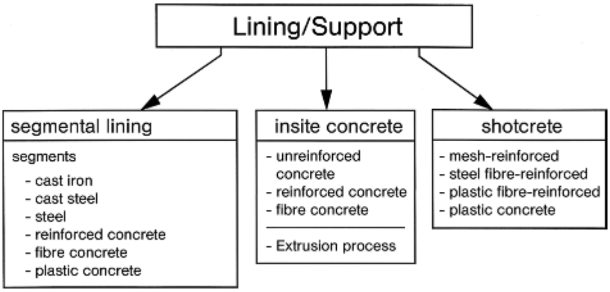


Figure 1-4 Possible types of lining in shield tunnelling

1.2 Types of tunnel boring machine according to DAUB

The recommendations of DAUB (the German Tunnelling Committee) are reproduced in their entirety in Chapter 19 [54].

1.2.1 Categories of tunnelling machines German association for underground construction (TVM)

Tunnelling machines either excavate the full face with a cutter head or cutting wheel or part of the face with suitable excavation equipment.

These can be tunnel boring machines (TBM), double shield machines (DSM), shield machines (SM) or combination machines (KSM). While the acronym “TBM” in English will be used for all types of tunnelling machines, the German DAUB reserves the abbreviation for the hard rock machines.

As the ground is excavated, the machine is pushed forward, either continuously or intermittently.

A systematic categorisation of tunnelling machines is shown in Figure 1-5 (see also Appendix 1 “Overview of tunnelling machines” in Chapter 19).

1.2.2 Tunnel boring machines (TBM)

Tunnel boring machines are used for driving tunnels through stable hard rock. Active support of the face is not required and, in any case, is technically impossible. These machines can normally only drive a circular cross-section.

Tunnel boring machines can be differentiated into those without shields (open gripper TBM), reamer or enlargement tunnel boring machines (ETBM) and shielded tunnel boring machines (TBM-S).

These machines are described in detail in [203].

1.2.2.1 Tunnel boring machines without shield (gripper TBM)

Open tunnel boring machines without shield are used in hard rock that has medium to long stand-up time. They have no complete shield skin. Economic application can be greatly influenced and limited by the high cost of wear of the excavation tools.

In order to be able to apply thrust force to the cutter head, the machine is braced radially by hydraulically driven grippers acting against the sides of the tunnel.

Excavation is carried out with little damage to the surrounding rock mass and to an exact profile by disc cutters mounted on the rotating cutter head. The machine fills a large part of the cross-section. Systematic support of the tunnel walls is normally installed behind the machine (10 to 15 m or more behind the face). In rock with a shorter stand-up time or

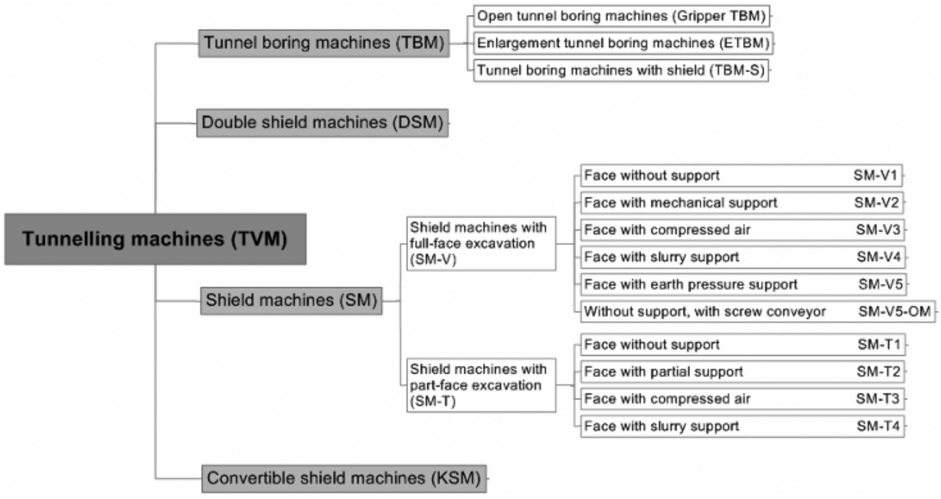


Figure 1-5 Types of tunnel boring machines

liable to rock falls, support measures such as steel arches, poling plates or rock bolts are installed at the closest possible distance behind the cutter head.

Where shotcrete lining of the tunnel is necessary, this should only be applied in the rearward part of the backup area in order to keep the mess off the machinery and control gear in the forward machine area as far as possible. In exceptional cases, however, shotcrete may have to be applied as close behind the face as possible.

If the geological forecast describes poor rock or a heterogeneous condition of the rock mass (high degree of jointing and fault zones), it is recommended to equip the machine to enable advance investigation drilling or advance rock consolidation.

The excavation of the face produces material in small pieces with the associated dust development. Machines therefore require equipment for the reduction of dust development and dedusting. This can be:

- spraying with water at the cutter head,
- a dust shield behind the cutter head,
- dust extraction with dedusting on the backup.

Material handling and disposal from the machine nowadays requires very long backup facilities.

1.2.2.2 Reamer tunnel boring machines (ETBM)

Reamer tunnel boring machines (enlargement machines) are used in hard rock to enlarge a previously bored pilot tunnel to the intended final diameter. The enlargement to the final diameter is performed in one or two working steps using an appropriately constructed cutter head.

The main elements of these machines are the cutter head, the bracing and the drive mechanism. The bracing of the specialised machines is situated in front of the cutter head with grippers in the pilot tunnel, and the cutter head of the machine is drawn towards the grippers as it bores. In faulted rock formations, measures to improve the fault zone can be carried out from the previously bored pilot tunnel in order to minimise the risks during the boring of the main tunnel.

1.2.2.3 Tunnel boring machines with single shield (TBM-S)

In hard rock with a short stand-up time or liable to rock falls, shielded tunnel boring machines are used. For this case, the installation of the lining within the shield is appropriate (segments, pipes etc.). While advancing, the machine can be supported from the lining, so bracing is not normally required. The remaining statements made about tunnel boring machines apply accordingly.

1.2.3 Double shield machines (DSM)

Double shield machines (DSM) consist of two parts arranged one behind the other. The front part is equipped with the cutter head and the main thrust cylinders, and the back part houses the auxiliary thrust cylinders and the grippers. The front part of the machine can be advanced by a complete ring length ahead of the back part using a telescopic section.

In stable hard rock, the gripper shoes resist the drive torque and the thrust forces. The secure fixing of the back part of the machine using the grippers enables the assembly of the segmental lining in the shield tail while boring is in progress. In a stable rock mass, it may also be possible to omit the installation of the lining.

In unstable ground, where the gripper shoes cannot find sufficient resistance, the thrust can be resisted from the last segment ring. The front and back parts of the machine are retracted together and the thrust forces are pushed from the segment ring by the auxiliary thrust cylinders.

It is not normally possible to actively support the face or the sides of the excavation.

Due to the rapid advance of the back part of the machine after a boring stroke has been completed and the grippers are being regripped, the rock mass has to be able to stand up independently until the annular gap has been completely filled with grout or stowed with pea gravel.

1.2.4 Shield machines (SM)

These can be shield machines with full-face excavation (with a cutter head: SM-V) and shield machines with partial-face excavation (using a roadheader boom, excavator: SM-T). Shield machines are used in loose ground above and below the groundwater table. This normally means that the ground around the cavity and at the face has to be supported. Shield machines can be further divided according to the type of face support (Figure 1-5).

1.2.4.1 Shield machines with full-face excavation (SM-V)

1) Face without support (SM-V1)

If the face will stand up, e.g. in clay soil with stiff consistency and sufficient cohesion or in solid rock, open shields can be used. The cutting wheel fitted with tools excavates the soil and the muck is removed on a conveyor belt.

In solid rock liable to rock falls, shield machines with a mostly closed cutter head fitted with disc cutters and fully protected from the unstable ground by a shield skin are normally used. The thrust forces and the cutter head drive torque are transferred through the thrust cylinders to the last ring of segments installed.

2) Face with mechanical support (SM-V2)

With tunnelling machines with mechanical support, the support of the face during excavation is provided by elastically fixed support plates arranged in the openings of the cutting wheel. In practice, however, experience shows that that no appreciable mechanical support of the face can be provided by the rotating cutting wheel. For this reason, this type of cutting wheel did not prove successful in unstable ground and is no longer in use today. The mechanical face support by the cutting wheel or the support plates should only be considered a supplementary safety measure and the supporting effect should not be taken into account in calculations to verify the stability of the face.

3) Face with compressed air support (SM-V3)

Shield machines of type SM-V3 can be used below the groundwater table even if it cannot be lowered or groundwater lowering is not allowed. In this case, the water at the face must be held back with compressed air. A precondition for the displacement of the groundwater is the formation of an air flow to the surface. Impermeable strata above the tunnelling machine can retain the applied air and prevent the effective displacement of the water (and thus the formation of an air flow). The permeability limit of the surrounding ground is therefore significant.

As no pressure difference can be built up at the face, compressed air cannot generally provide support against earth pressure, which applies particularly in permeable soil. The loss of the apparent cohesion in non-saturated soil is also possible.

For the duration of tunnelling work, either the entire tunnel is pressurised or the machine is provided with a pressure bulkhead to maintain the excavation chamber under pressure. In both cases, air locks are required. Particular attention needs to be paid to compressed air bypassing the shield tail seal and the lining. The recommendations and requirements for working under compressed air should complied with.

Any additional support of the face provided by the cutting wheel or support plates should be regarded solely as an additional security. It is not permissible to take the supporting effect into account in calculations to verify the stability of the face.

4) Face with slurry support (SM-V4)

Tunnelling machines with slurry support provide support to the face through a pressurised fluid, which is specified depending on the permeability of the surrounding ground. It must be possible to vary the density and viscosity of the fluid. Bentonite suspensions have proved particularly successful for this purpose. In order to support the face, the working chamber is closed from the tunnel by a pressure bulkhead.

The required support pressure can be regulated very precisely with an air bubble behind a submerged wall and by adjusting the output of the supply and extraction pumps. The required and the maximum support pressures over the entire length to be bored should be calculated before the start of tunnelling – referred to as the slurry support pressure calculation.

The soil is excavated from the full face by a cutting wheel fitted with tools (open-mode or rimmed wheel) and removed hydraulically. Subsequent separation of the removed suspension is essential.

If it is necessary to enter the excavation chamber, for example to change tools, carry out repair work or to remove obstructions, the support slurry has to be replaced by compressed air. The support slurry then forms a low-permeability membrane on the face, which however is of limited durability (risk of drying out). The membrane permits the support of the face by compressed air and may need to be renewed regularly. The support slurry can be completely (empty) or only partially (lowering) replaced by compressed air. The maximum partial lowering is limited particularly by the requirement for sufficient working space. This should be chosen to be large enough for safe working to be possible at all times and so that an adequately large space is available for the workers to retreat.

If an open cutting wheel is used, it should be possible to mechanically close the face with shutter segments in the cutting wheel or with plates, which can be extended from behind, in order to protect the personnel working in the excavation chamber while the machine is stopped, and this is also sensible owing to the limited duration of the membrane effect.

Stones or rock benches can be reduced to a size that can be removed by disc cutters in the cutting wheel and/or crushers in the working chamber.

In stable ground, the slurry shield can also be operated in open mode without pressurisation, with water being used for muck removal.

Any additional mechanical support of the face provided by the cutting wheel or support plates should be regarded solely as additional security, and it is not permissible to take the supporting effect into account in calculations to verify the stability of the face.

5) Face with earth pressure support (SM-V5)

Tunnelling machines with earth pressure support provide support to the face with remoulded excavated soil. The excavation chamber of the shield is closed from the tunnel by a pressure bulkhead. A cutting wheel, fitted with tools and more or less closed, excavates the soil. Mixing arms on the back of the cutting wheel (rotors/back buckets) and on the pressure bulkhead (stators) assist the remoulding of the soil to a workable consistency. The pressure is checked with pressure cells, which are distributed on the front of the pressure bulkhead. A pressure-tight screw conveyor removes the soil from the excavation chamber.

The support pressure is regulated by varying the revolution speed of the screw conveyor or through the pressure-volume-controlled injection of a suitable conditioning agent. The pressure gradient between excavation chamber and tunnel is provided by friction in the screw. Either the soil material in the screw can ensure the sealing of the discharge device or an additional mechanical device has to be installed. Complete support of the face, in particular the upper part of it, is only successful when the soil acting as a support medium can be remoulded to a soft or stiff-plastic mass. This is particularly influenced by the percentage content of fine-grained material smaller than 0.06 mm. The scope of application of earth pressure balance (EPB) shields can be extended through the use of soil conditioners such as bentonite, polymers or foam, but attention should be paid to the environmentally acceptable disposal of the material.

In stable ground, the EPB shield can also be operated in open mode without pressurisation with a partially filled excavation chamber (SM-V5-OM). In stable ground with water ingress, operation is also possible with partially filled excavation chamber and compressed air.

If the groundwater pressure is high and the ground is liable to liquefaction, the critical location of the transfer of material from the screw conveyor to the conveyor belt can be replaced by a closed system (pumped material transport).

Any additional mechanical support of the face provided by the cutting wheel or support plates should be regarded solely as additional security and it is not permissible to take the supporting effect into account in calculations to verify the stability of the face.

1.2.4.2 Shield machines with partial face excavation (SM-T)

1) Face without support (SM-T1)

This type of open mode shield can be used with a vertically or steeply sloping and stable face. The machine consists of a shield skin and the excavation tools (excavator, milling head or ripper tooth), the spoil removal equipment and the thrust cylinders. The excavated material is removed on a conveyor belt or chain scraper.

2) Face with partial mechanical support (SM-T2)

For partial support of the face, working platforms and/or poling plates can be used. In platform shields, the tunnelling machine is divided into one or more platforms at the face. Natural slopes form on these, which support the face. The ground is excavated manually or mechanically. Platform shields have a low degree of mechanisation.

A disadvantage is the danger of large settlements resulting from uncontrolled face support. In shield machines with face support, the face is supported by poling plates supported on hydraulic cylinders. In order to excavate the soil, the poling plates are partially withdrawn. A combination of poling plates and platforms is also possible. If support of the crown alone is sufficient, hinged poling plates can be fixed at the crown.

3) Face with compressed air support (SM-T3)

If there is groundwater, this can be retained by compressed air with machines of type SM-T1 and SM-T2. Either the entire tunnel is filled with compressed air or the machine is fitted with a pressure bulkhead (comparable to SM-V3). The excavated material is removed hydraulically or dry through the air lock.

4) Face with slurry support (SM-T4)

In the past, many trials have been undertaken to achieve active face support through the use of support fluid with partial face machines (e.g. Thixshield). The excavation chamber in this case has to be completely filled with support slurry. The excavation of the soil can be mechanical or using high-pressure jetting.

As the excavation of the ground cannot be sufficiently controlled, this method of tunnelling has not proved successful and is no longer used.

1.2.5 Adaptable shield machines with combined process technology (KSM)

Numerous tunnels pass through highly changeable geological conditions, which can range from rock to loosely compacted soil. This requires the excavation mode to be adapted to the geological conditions and the use of correspondingly adapted shield machines. These can be categorised into:

a) Shield machines that enable the change of excavation mode without rebuilding:
   Earth pressure shield SM-V5 ↔ Compressed air shield SM-V3,

b) Shield machines that have to be rebuilt to change the excavation mode technology. The following combinations have been used:

Slurry shield SM-V4 ↔ Shield without support SM-V1,
Slurry shield SM-V4 ↔ Earth pressure shield SM-V5,
Earth pressure shield SM-V5 ↔ Shield without support SM-V1.

The rebuilding work normally lasts a number of shifts.

1.2.6 Special types

1.2.6.1 Blade shields

In blade shields, the shield skin is split into blades, which can be advanced independently. The ground is excavated by partial face machinery, cutting wheel or excavator. An advantage of blade shields is that they do not have to be circular and can, for example, drive a horseshoe-shaped section, in which case the invert is normally open. This is described as blade tunnelling. Because of various negative experiences in the past, however, blade shields are seldom used today.

1.2.6.2 Shields with multiple circular cross-sections

These shields are characterised by overlapping and non-concentric cutting wheels. This type of machine is currently only offered by Japanese manufacturers and mostly used to drive underground station cross-sections. The machines are difficult to steer and have not yet been used in Europe.

1.2.6.3 Articulated shields

Practically all types of shields can be equipped with an articulated joint to divide their length. This is provided particularly when the length of the shield skin is longer than the shield diameter, in order to make the tunnelling machine easier to steer. The layout can also be necessary to drive very tight radius curves.

The description of the tunnelling machines is then according to one of the categories described above. A separate category of "articulated shields" is no longer usual.

1.2.7 Remarks about the individual types of tunnelling machines with diagrams

1.2.7.1 Tunnel boring machines (TBM)

The most important application of tunnel boring machines (TBM) (Figure 1-6) is competent to loose rock, in which case the ingress of groundwater and joint water can be overcome. The uniaxial compression strength σ_D should be between about 25 and 250 MN/m^2. Higher strengths and toughness of the rock or a high content of abrasive minerals represent limits to the scope of economic application. Problems with the bracing of the machine can also make an application questionable. In order to evaluate the rock, the splitting strength and RQD value can be measured. With a degree of fracturing of the rock mass with RQD of 50 to 100 % and a joint spacing > 0.6 m, the use of a TBM should be safe. If the fracturing is higher, the stability should be investigated. The use of a TBM is ruled out in loose ground or solid rock with properties similar to soil.

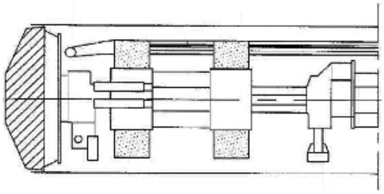


Figure 1-6 Open gripper TBM

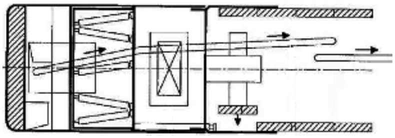


Figure 1-7 Double shield TBM

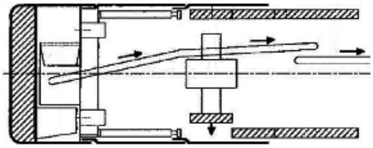


Figure 1-8 Single shield TBM, full-face excavation

1.2.7.2 Double shield machines (DSM)

Double shield machines (Figure 1-7) are mainly used on tunnel projects with shorter sections with loose to brittle rock, in addition to long sections through stable rock. In stable rock (see the requirements for the use of a TBM), the tunnel can be bored in continuous mode using the grippers. In fault zones or sections with low rock strength, in which the grippers can no longer be used, the shield is telescoped in and the tunnelling machine now supports itself off the last ring of segments.

1.2.7.3 Face without support (SM-V1)

This type of machine (Figure 1-8) can only be used in stable, mostly impermeable cohesive soil with high fines content. The stability of the face should be verified with calculations. The excavation sidewalls should be able to stand up until the final installation of the tunnel lining and this should be verified. Loosening of the ground, which could lead to a reduction of the subgrade reaction, should also be ruled out. If there are buildings sensitive to settlement on the surface, the deformation of the ground and loosening should be verified based on the usual damage classification (e.g. gradient of the settlement trough).

In hard rock, this type of machine is used in loose to brittle rock, also with groundwater and joint water. If the rock strength is high in a stable rock mass, the bonding strength can be reduced considerably. This corresponds to a joint spacing of ≈ 0.6 to 0.06 m and an RQD value between about 10 and 50 %. Generally, however, these machines can also be used with lower rock compression strengths below 5 MN/m^2, for example in heavily weathered rock.

The stability of the face and the excavated sides should be verified with calculations. If there is high ingress of formation water, appropriate measures should be provided.

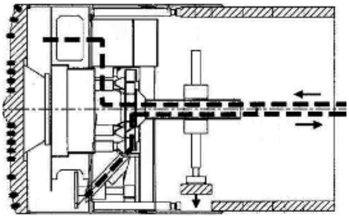


Figure 1-9 Slurry shield with air bubble support

1.2.7.4 Face with mechanical support (SM-V2)

As a result of numerous failed projects, this type of machine is no longer recommended.

1.2.7.5 Face with compressed air (SM-V3)

The application of compressed air enables the machine type SM-V1 to be used in stable ground, even in groundwater. The air permeability of the ground or the air consumption and the verification of the formation of a flow field and of blowout safety are essential criteria for the application of this machine type. The groundwater table should be above the tunnel crown with an adequate safety margin.

1.2.7.6 Face with slurry support (SM-V4)

The main areas of application for slurry shields (Figure 1-9) are in coarse and mixed-grained soil types. The groundwater table should be above the tunnel crown by an adequate margin. During excavation, a pressurised fluid, e.g. bentonite suspension, supports the face. Highly permeable soils impede the formation of a membrane. If the permeability is greater than $5 \cdot 10^{-3}$ m/s, there is a risk that the bentonite suspension can flow uncontrolled into the surrounding ground. The addition of fine material and filler or additives to improve the rheological properties can expand the scope of application. Alternatively, additional measures to reduce the permeability of the soil may be necessary (for example filling of pore cavities). Stones and blocks, which cannot be pumped, are first brought down to size by crushers. High fines content can lead to problems with separation. It should also be borne in mind that the rheological properties of the support medium are worsened by very fine material, because the separation of clay fractions and bentonite is not technologically feasible.

1.2.7.7 Face with earth pressure support (SM-V5)

Machine types with earth pressure support (Figure 1-10) are particularly suitable for soils with a fines content (< 0.06 mm) of over 30 %. In coarse and mixed-grained soils and rock, thrust force and cutting wheel torque increase over-proportionately with increasing

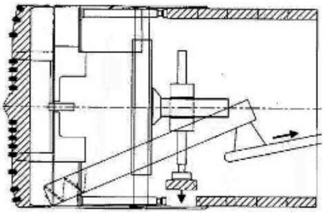


Figure 1-10 Earth pressure balance shield

support pressure. The hydraulic behaviour of the excavated soil can be improved with the addition of a suitable conditioner, e.g. bentonite, polymer or foam. For active control of the support medium and to ensure low-settlement tunnelling, soil conditioning with foam is recommended outside the predefined area of application.

Earth pressure balance shields have the advantage that operation in open mode (SM-V5-OM) with partially filled and non-pressurised excavation chamber, i.e. without active face support, is also possible without alteration of the process technology. It should, however be noted that in this mode, due to the design of the cutting wheel and screw, the excavated soil/rock is grind much more than is the case with removal by conveyor through the centre (SM-V1). If the ground tends to stick, then obstructions and increased wear have to be expected. To improve the material flow and to reduce the tendency to sticking, conditioning measures should be planned. Particularly unfavourable for earth pressure shields, in soil as well as in rock, is a combination of high support pressure, high permeability, high abrasiveness and difficult breaking of the grain structure.

1.2.7.8 Face without support (SM-T1)

This type of machine can be used above the groundwater table, if the face is continuously stable – see also SM-V1.

Partial face machines always offer easy access to the face, so the process can offer great advantages if a lot of obstructions are expected.

1.2.7.9 Face with partial support (SM-T2)

This type of machine (Figure 1-11) can be used when the support of the material spreading on the platforms at its natural angle of repose is adequate for the driving of the tunnel with limited control of deformation. Poling plates can be used to provide additional support at the crown and on the platforms. The main areas of application are in weakly- to non-cohesive gravel-sand soils above the groundwater table with the relevant friction angle.

1.2.7.10 Face with compressed air support (SM-T3)

The use of this type of machine (Figure 1-12) is appropriate when types SM-T1 and SM-T2 are used in groundwater. The entire working area, including the already excavated tunnel, or just the excavation chamber, is pressurised.

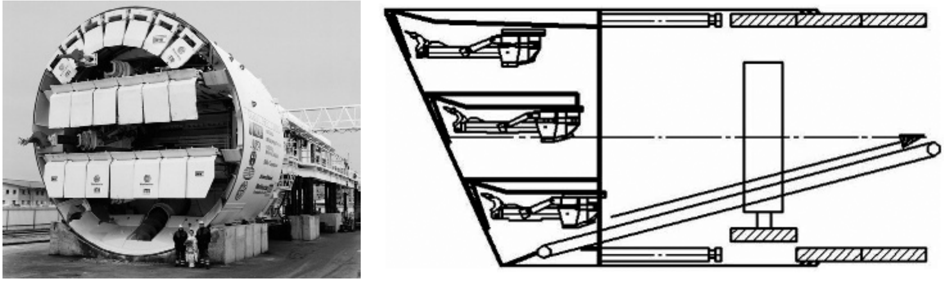


Figure 1-11 Partial-face excavation with mechanical face support

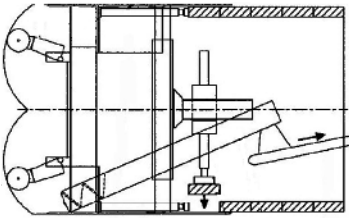


Figure 1-12 Partial-face excavation with compressed air face support

1.2.7.11 Face with slurry support (SM-T4)

Partial-face excavation machines with slurry support are no longer used.

1.2.7.12 Adaptable machines (KSM)

Adaptable machines (Figure 1-13) combine the areas of application of the relevant machine types in changeable ground conditions. Their application spectrum is therefore extended to both criteria.

The number of rebuilding changes from one tunnelling mode to another should be kept as low as possible, because rebuilding is time- and cost-intensive.

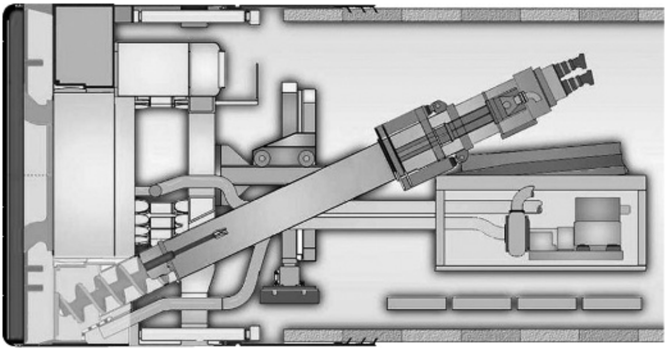


Figure 1-13 Adaptable shield machine

1.3 Origins and historical developments

The human race has been building tunnels for about 5,000 years. Tunnels have been excavated for the protection of goods and people, for secret passages to forbidden locations and for the exploitation of resources or to accelerate transport.

Tunnellers soon learnt to support rock liable to falling and in loose ground with timbering, followed by a brickwork lining. This method could also succeed in ground with percolating or joint water, and this continued into the 19th century, but was not practical below the groundwater table, in loose ground or particularly under open water. The situation altered in 1806, when the ingenious engineer Sir Marc Isambard Brunel invented and later patented the principle of shield tunnelling in London. The purpose was the construction of a crossing of the River Neva in St Petersburg, which could remain open in winter, needed because the piers of the bridge were badly damaged each year by pack ice from Lake Ladoga. Brunel developed a tunnel solution for this project, although a suspension bridge had originally been proposed.

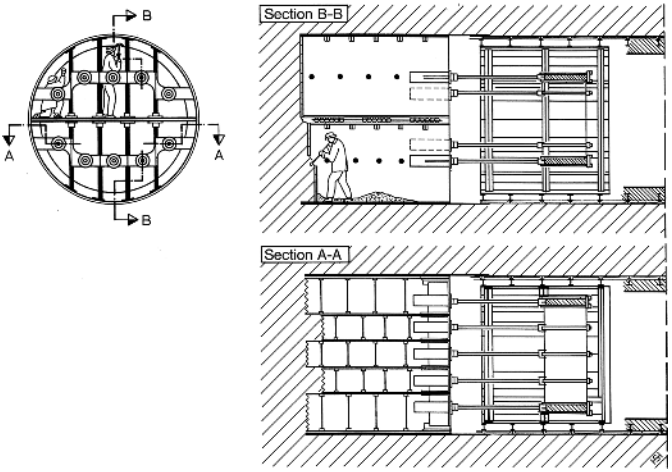


Figure 1-14 Box shield used by M. I. Brunel, 1806 [268]

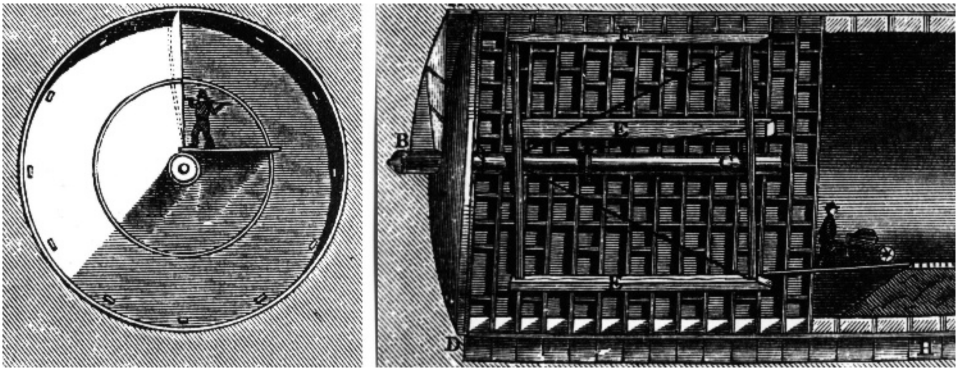


Figure 1-15 Screw shield used by M. I. Brunel, 1818 [251]

The original shield construction of M. I. Brunel featured a division into cells, each with a worker working independently and safely (Figure 1-14). In one method, the cells were fixed in the shield structure and the entire shield was driven forward by hydraulic cylinders after the excavation of a section; in another method, the single cells could be advanced independently. All closed full shields in use today are based on the former method; the latter was never put into practice, unless the blade shield could be considered as a further development of it.

A completely different process with closed shield skin and full-area, screw-shaped excavation with immediate lining is shown in Figure 1-15. This shield can be regarded as the predecessor of the earth pressure shields.

The Thames Tunnel project in London finally gave M. I. Brunel the opportunity to put his ideas into practice (Figure 1-16). The shield was rectangular and consisted of 12 adjacent frames, each divided into three chambers. One miner worked in each of these chambers – 36 miners altogether. The system worked like this: first the top poling boards were driven into the ground with screw jacks. The timbering to the face was then removed starting from the top, and the soil was excavated for about 150 mm, the face was timbered again and supported with screw jacks. The entire frame was supported from the brickwork lining, which had been filled in behind. Work on the Thames Tunnel started in 1825 amid great difficulties, and the tunnel was only completed in 1843 after more than five severe water inflows. It is interesting that after the first serious flood had stopped work (Figure 1-17), Callodan suggested the use of compressed air in 1828, which Brunel however turned down [268].

In 1869, the engineer James Henry Greathead used a circular shield for a further tunnel under the Thames, which also marked the first use of circular cast iron segments for the lining [19]. The construction of the 402 m long tunnel with an external diameter of 2.18 m was completed without great difficulties, as the tunnel passed through impermeable clay along its entire length, and there were no water problems. The circular Greathead shield was the pattern for most subsequent designs. Figure 1-18 shows one of the two Greathead shields used for the construction of the Rotherhithe Tunnel (1904–1908) with 9.35 m diameter. The tunnel under the Thames linked Rotherhithe to Ratcliffe.

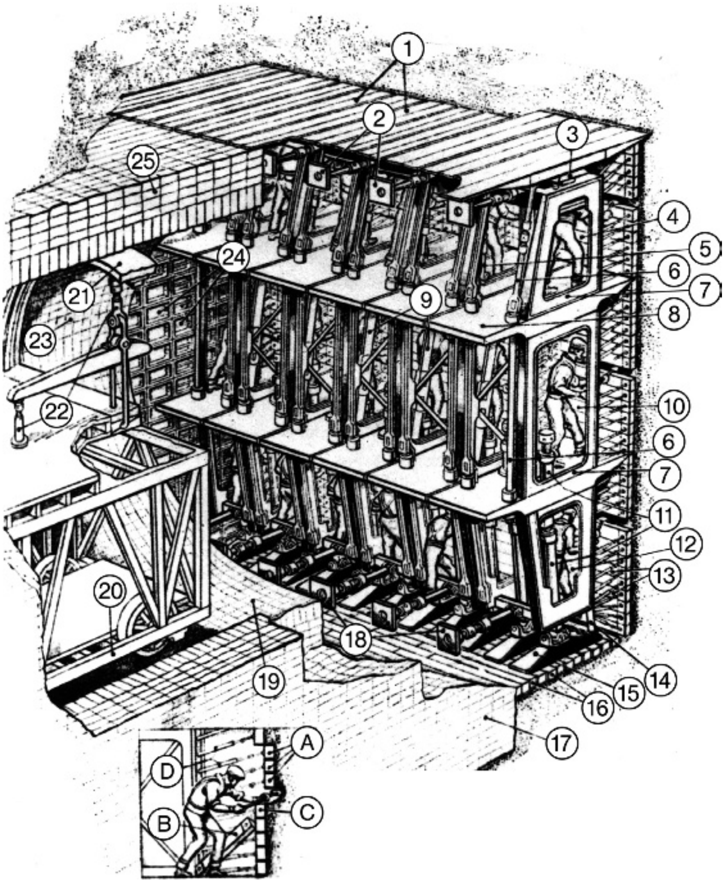


Figure 1-16 Shield used by Sir M. I. Brunel for the Thames Tunnel, 1825/43 [213]

1 top poling boards
2 screw jacks
3 abutment
4 upper chamber
5 jack
6 strengthening
7 side framing
8 floor (upper chamber)
9 bracing
10 middle chamber
11 support
12 lower chamber
13 timbering
14 jack
15 jack base plate
16 floor timbering
17 brickwork
18 thrust jacks
19 invert
20 wheeled working platform
21 vault falsework
22 jack
23 western side wall
24 shield
25 brickwork in the crown

A forward timbering
B timber board
C initial timbering
D jack

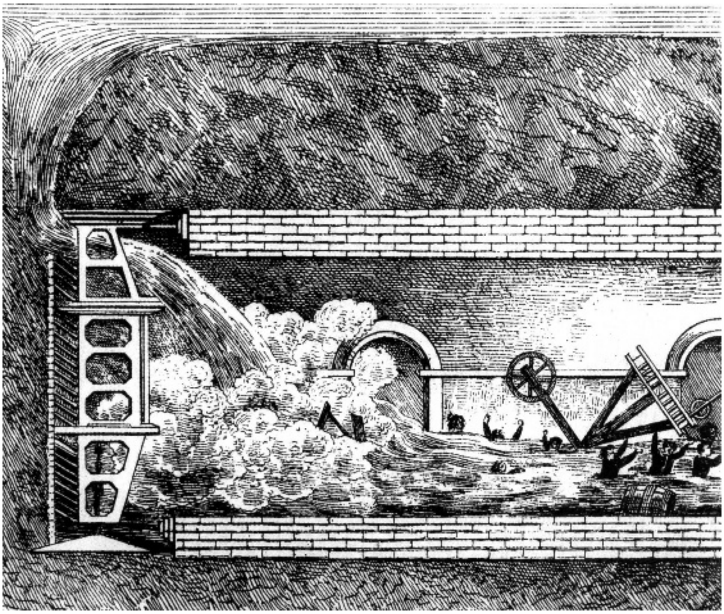


Figure 1-17 Flooding of the tunnel under the River Thames on 12 January 1828 [213]

The problem of controlling water in the construction of underwater tunnels in loose ground was first solved by Admiral Sir Thomas Cochrane through the use of compressed air, following the suggestion from Callodan to Brunel from 1828. In 1830, he invented the compressed air lock, which enabled access to a working space under increased pressure [8], [268]. The first uses of compressed air in a tunnel occurred almost simultaneously in 1879 in Antwerp and 1880 in New York, although these were worked without shields.

In 1886, Greathead achieved the application of a shield in combination with compressed air for the first time for the construction of the London Underground [128]. The use of compressed air considerably simplified tunnelling in water-bearing strata. This was the birth of the compressed air shield, and a critical gap was closed in tunnelling capability, leading to a considerable increase in the number of shield tunnels all over the world. At the start of the 20th century, most tunnels were being excavated using Greathead-type shields.

Brunel's invention naturally soon led to the idea of replacing the manual digging of the ground with mechanical excavation. The first patent for such a mechanised shield was applied for by the Englishmen John Dickinson Brunton and George Brunton (Figure 1-19) and was granted in 1876 [268]. The shield had a hemispherical rotating cutting head built up of single plates. The cut material was intended to fall into mucking buckets mounted radially on the cutting head. The buckets threw the excavated material onto a conveyor belt, which transported it backwards out of the shield. The cutting head itself was turned by six hydraulic cylinders, which worked against a ratchet ring fixed to the cutting head. This idea was later repeated for the construction of the underground railway in Kiev.

A better design was the Price shield, named after its inventor, J. Price, and patented in 1896 (Figures 1-20, 1-21). This machine was used with great success in London clay from

1897. It was the first machine to make use of the performance of a rotating cutting head based on simple principles inside a Greathead shield. The cutting head consisted of four arms arranged like spokes, on which the cutting and raking tools were fitted. The cutting head was also fitted with basin-shaped buckets, which picked up the excavated soil and deposited it down a slide onto waiting trucks for carting way. The cutting head was electrically driven through a long shaft [268].

In soil with higher permeability, it is difficult to support the face with compressed air. Greathead therefore developed a shield in 1874 with fluid-supported face to avoid the disadvantages of compressed air. The soil was intended to be removed hydraulically by a fluid and transported hydraulically as slurry (Figure 1-22).

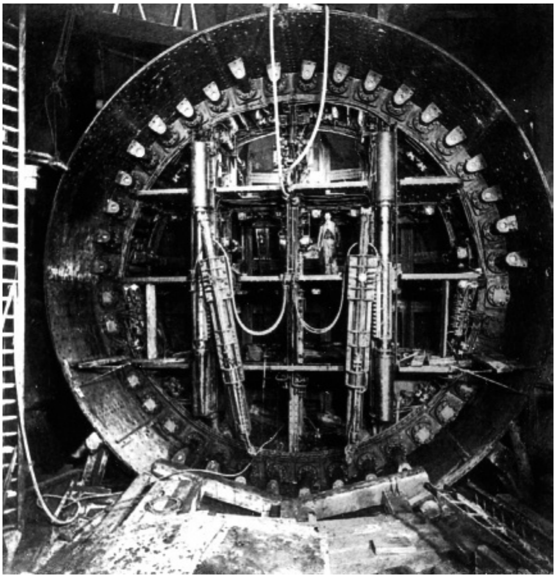


Figure 1-18 Greathead shield, 9.35 m external diameter, Rotherhithe Tunnel, 1904–1908 (Markham)

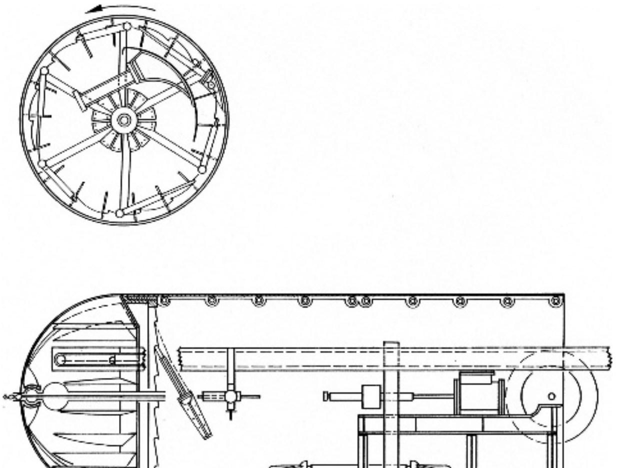


Figure 1-19 Mechanised shield used by J. D. and G. Brunton, U.K. Patent, 1876 [268]

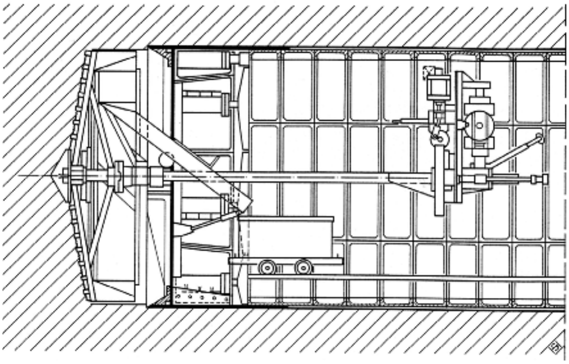


Figure 1-20 Mechanised shield used by J. Price, U. K. Patent, 1896 [268]

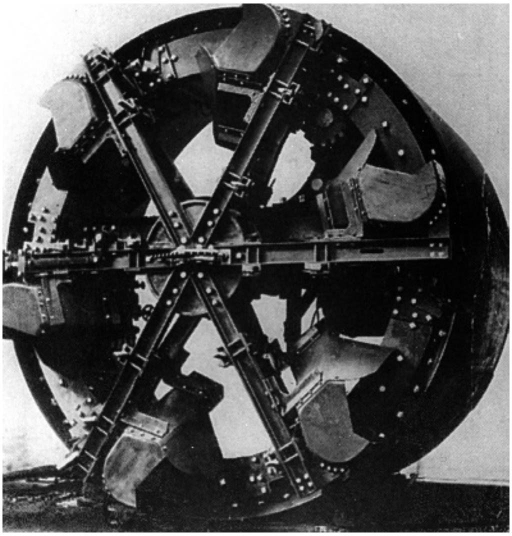


Figure 1-21 Mechanised shield used by Price, 1902 (Markham)

In 1896, Haag applied for a patent in Berlin for the first shield with fluid-supported face in Germany, with the excavation chamber full of fluid being hermetically sealed as a pressure chamber (Figure 1-23).

But the idea of a slurry-supported face was not successfully tested until 1959 with the design of Elmer C. Gardner for a sewage tunnel of 3.35 m diameter. In 1960, Schneidereit introduced the idea of active face support with bentonite suspension. H. Lorenz patented the stabilising effect of bentonite under pressure for face support. The first use of a slurry shield, with the excavation of the face by a cutting wheel and hydraulic removal of the muck, was a 3.1 m diameter machine in 1967 in Japan. In Germany, Wayss & Freytag AG developed and used the first shield with bentonite-supported face in 1974.

The development of earth pressure balance shields started much later, although the screw shield of Brunel (Figure 1-15) can be considered the predecessor of the basic idea. The first design was developed in 1963 by the Japanese Sato Kogyo Company Ltd. (Figure 1-24), who were looking for a method of tunnelling through soft and flowing soil beneath the groundwater table. The development of the EPB shield was surprising, because compressed air and slurry shields were already in use in Japan at the time. The reason for the development lay in the stringent environmental regulations and laws, which already applied in many of the larger cities in Japan. These related to groundwater and air pollution and the tipping of the spoil, but also required precautionary measures to avoid illness and accidents to workers under compressed air.

The journey from the historical origins of shields to the highly mechanised machines of today, as shown for example by multi-face shields, was a long and sometimes arduous or even dangerous path. To describe single developments in still more detail would exceed the space available in this book. Interested readers are recommended to read the handbook by Barbara Stack [268], which gives a detailed description of the individual principles in shield tunnelling and the associated patents.

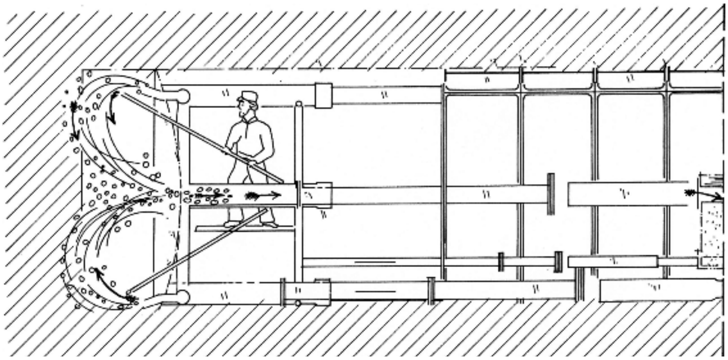


Figure 1-22 Slurry shield used by Greathead, patented 1874 [268]

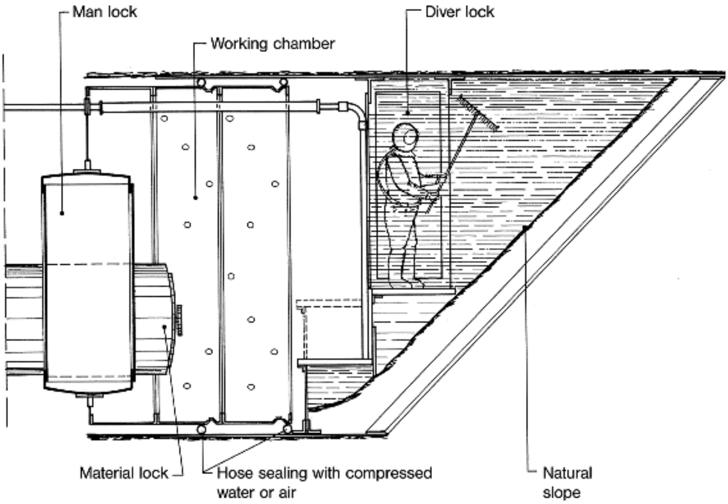


Figure 1-23 Fluid shield used by Haag, patented 1896

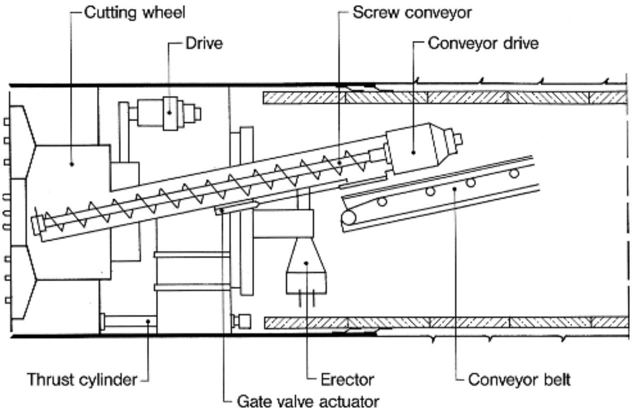


Figure 1-24 Earth pressure balance shield, Sato Kogyo Company, 1963 [268].

Some classic shield tunnels from the years 1826–1914 are summarised in table 1-1.

Table 1-1 Classic shield tunnels 1826–1914, excerpt from [128]

Year	Project	Length [m]	Diameter [m]	Daily advance [m/d]	Remark	Lining
1826–1842	Thames Tunnel (London)	460	11.40 × 7.10	1.50	Brunel shield (rectangular)	brickwork
1869–1870	Broadway (New York)	90	2.85		Beach shield (abandoned)	brickwork
1869–	Tower Subway (London)	403	2.20	2.60	Greathead shield	cast iron segmental lining
1886–1890	City South Subway (London)	10,200 various	3.10–3.45	4.00	first use of compressed air	cast iron segmental lining
1890–1893	Glasgow harbour road tunnel	580	5.20	1.00	compressed air	cast iron segmental lining
1892–1894	Sewage tunnel (Clichy)	465	2.50	2.00–3.00	compressed air to 2.9 bar	cast iron segmental lining
1896–1899	Spree road tunnel (Berlin)	375	4.00	1.40	compressed air	rolled steel profiles with concrete
1898	Orleans railway (Paris)	1,230	9.75		segment shield	Brickwork
1899–1904	Sewage tunnel (Hamburg)	2,150	3.05	1.30	compressed air (0.6–1.5 bar)	
1907–1911	Elbe Tunnel I (Hamburg)	920	5.95	1.70	compressed air (2.0–2.7 bar)	steel profiles with concrete
1911–	Sewer tunnel (Wanne-Eickel)		2.85			Brickwork
1911–	Sewer tunnel (Gelsenkirchen)	670	3.90	5.20	compressed air	Concrete