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## Topic
**MECHANIZED TUNNELLING**

## Title
**Recommendations and Guidelines for Tunnel Boring Machines (TBMs)**

## Author
**ITA WG Mechanized Tunnelling**

## published
**in "Recommendations and Guidelines for Tunnel Boring Machines (TBMs)",**
**pp. 1 - 118, Year 2000**
**by ITA - AITES, www.ita-aites.org**

***Working Group:*** **WG 14 - "Mechanized Tunnelling"**

***Open Session, Seminar, Workshop:*** **-**

***Others:*** **Recommendations**

***Abstract:*** -

***Résumé:*** -

***Remarks:*** This report contains four individual reports prepared by ITA Working Group No. 14 ("Mechanized Tunnelling"). The purpose of the reports is to provide comprehensive guidelines and recommendations for evaluating and selecting Tunnel Boring Machines (TBMs) for both soft ground and hard rock. The reports are contributed by representatives from seven countries as follows:

I. "Guide lines for Selecting TBMs for Soft Ground", Japan and Norway
II. "Recommendations of Selecting and Evaluating Tunnel Boring Machines", Germany, Switzerland and Austria
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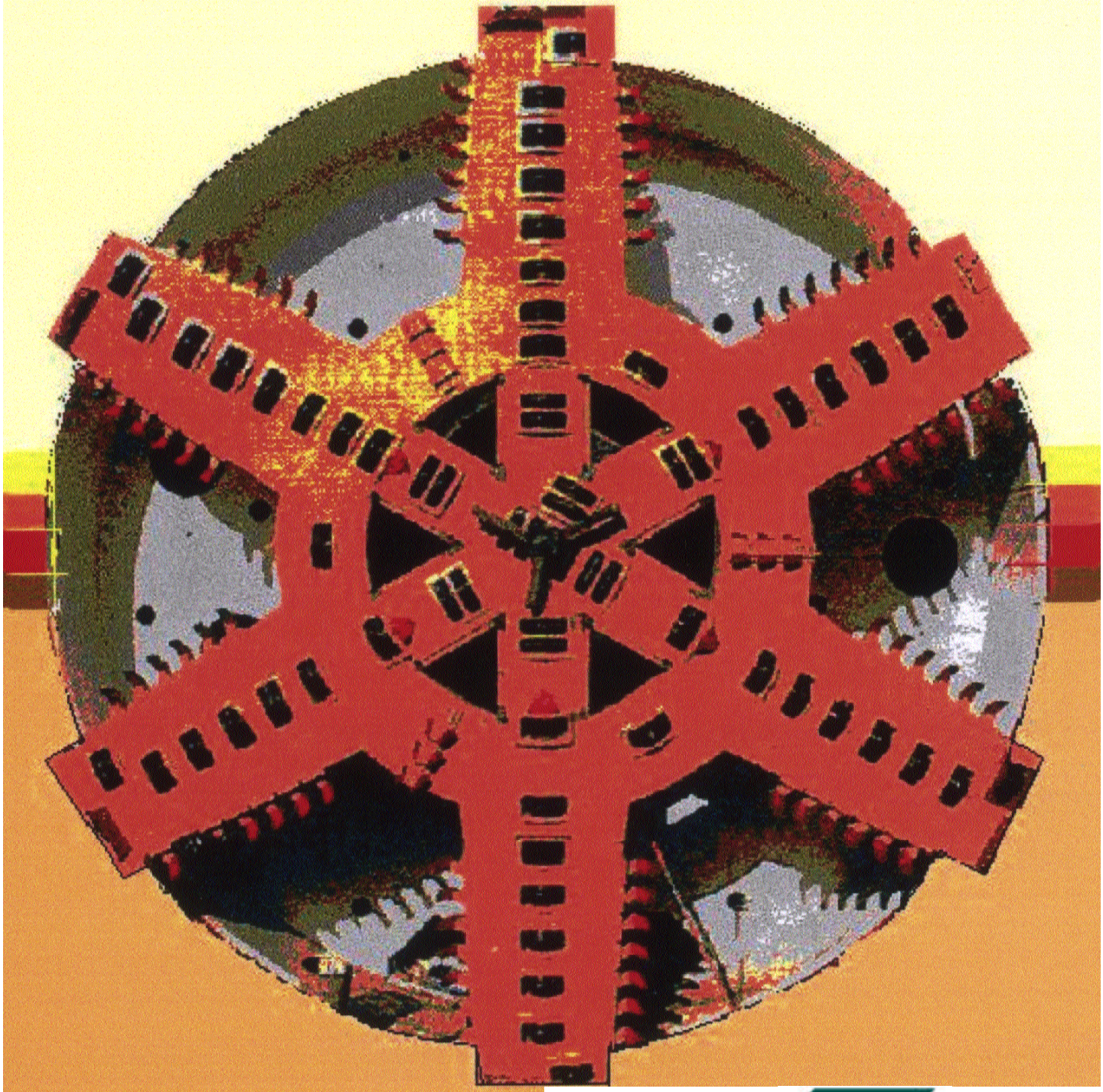
Each report offers up to date technologies of mechanized tunneling for both hard and soft ground and includes, among others, classifications of TBMs, their application criteria, construction methods, ground supporting system and other equipment necessary for driving tunnels by TBMs.

Since a cylindrical steel shield was first used for the construction of the Themes River Tunnel Crossing in England in 1823, tunnel works have been steadily mechanized. Especially, as urban tunneling was developed in the latter half of the 20th century, technological progress seen in this area was remarkable. Meanwhile, the circumstances surrounding tunnel construction have become increasingly complex and difficult. Tunneling technologies in recent years are developed by sophisticated and multi-disciplinary engineering principles to cope with the diverse physical, environmental and social circumstances. This report is intended to provide fundamental and useful knowledge of mechanical tunneling that can be used by designers, manufacturers and the end users of tunnel boring machines.

It is hoped that this report provides common ground for understanding tunneling technologies among international tunneling communities and eventually helps establish a standard set of criteria for designing and utilizing tunnel boring machines.

# RECOMMENDATIONS AND GUIDELINES FOR TUNNEL BORING MACHINES (TBMs)

**WORKING GROUP N°14 - MECHANIZED TUNNELLING - INTERNATIONAL TUNNELLING ASSOCIATION**



TRIBUNE HORS SÉRIE
MAI 2001 - ISSN 1267-8422

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# Preface

This report contains four individual reports prepared by ITA Working Group No. 14 ("Mechanized Tunneling"). The purpose of the reports is to provide comprehensive guidelines and recommendations for evaluating and selecting Tunnel Boring Machines (TBMs) for both soft ground and hard rock. The reports are contributed by representatives from seven countries as follows:

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### I. GUIDELINES FOR SELECTING TBMS FOR SOFT GROUND
**by Japan and Norway**



### II. RECOMMENDATIONS OF SELECTING AND EVALUATING TUNNEL BORING MACHINES
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**by France**

**Japan and Norway**

# Guidelines for Selecting TBMs for Soft Ground

**ITA Working Group No. 14**
**Mechanized Tunneling**

**PREFACE**

Tunnels are playing an important role in the development of urban infrastructures. Several construction methods for tunneling have been developed to cope with various geological conditions. Those methods can be categorized in two types; drill and blast method and by the use of Tunnel Boring Machine (TBM). This report focuses on tunneling by TBM and is prepared to offer guidelines and recommendations for selecting types of TBMs for urban tunnel construction. Its main purpose is to help project owners, contractors and manufacturers evaluate the applicability and capability of TBMs and other factors that should be taken into consideration for selecting of TBMs.

ITA has been collecting data and information from its member countries, in hope of providing a comprehensive international "manual" for TBM tunneling methods. As the contents of this report represent Japanese and Norwegian versions of the subject, they may be revised or supplemented as necessary to meet particular conditions of the respective countries.

This report consists of two parts; one is for the TBMs in soft ground prepared by Japanese Working Group and the other is for the TBMs in hard rock prepared by Norwegian Working Group. The Norwegian version is an excerpt from the "Project Report 1-94, Hard Rock Tunnel Boring" published by University of Trondheim, Norway, and is included in Appendix. Small diameter tunneling is not included in this report (e.g. micro-tunneling with pipe jacking etc.).

Technologies surrounding TBMs have been receiving great deal of attention. They have been primarily aimed at mechanization and automation of tunnel boring under various geological conditions, with the combined technologies of soil, mechanic and electronic engineering. The technological progress will continue to come from innovative commitments of tunnel builders, teaming with tunnel designers and manufacturers.

It is hoped that this report will assist the members of ITA publish the comprehensive international manual for TBMs and will further contribute to the development of tunneling technologies.

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## 1 CLASSIFICATION OF TUNNEL EXCAVATION MACHINE

Tunnels are constructed under many types of geological conditions varying from hard rock to very soft sedimentary layers. Procedures commonly taken for tunneling are excavation, ground support, mucking and lining. Variety of construction methods have been developed for tunneling such as cut and cover, drill and blast, submerged tube, push or pulling box, and by the use of tunnel boring machine (TBM).

TBM was first put into practical use for mining of hard rock, where the face of the tunnel is basically self-standing. For tunneling through earth, open type machine was used, in which a metal shield was primarily used for protective device for excavation works.

For tunneling through sedimentary soil, tunnel face is stabilized by breasting, pneumatic pressure or other supporting means. Closed type- tunneling machine was developed, which utilizes compressed air to stabilize tunnel face. The closed type-machine started to dominate for soft ground tunneling, especially in the countries where many tunnels are driven through sedimentary soil layers.

Tunnel excavation machines can be classified by the methods for excavation (full face or partial face), the types of cutter head (rotation or non-rotation), and by the methods of securing reaction force (from gripper or segment). Several types of tunnel excavation machines are illustrated in Fig. 1.1 and Fig. 1.2,

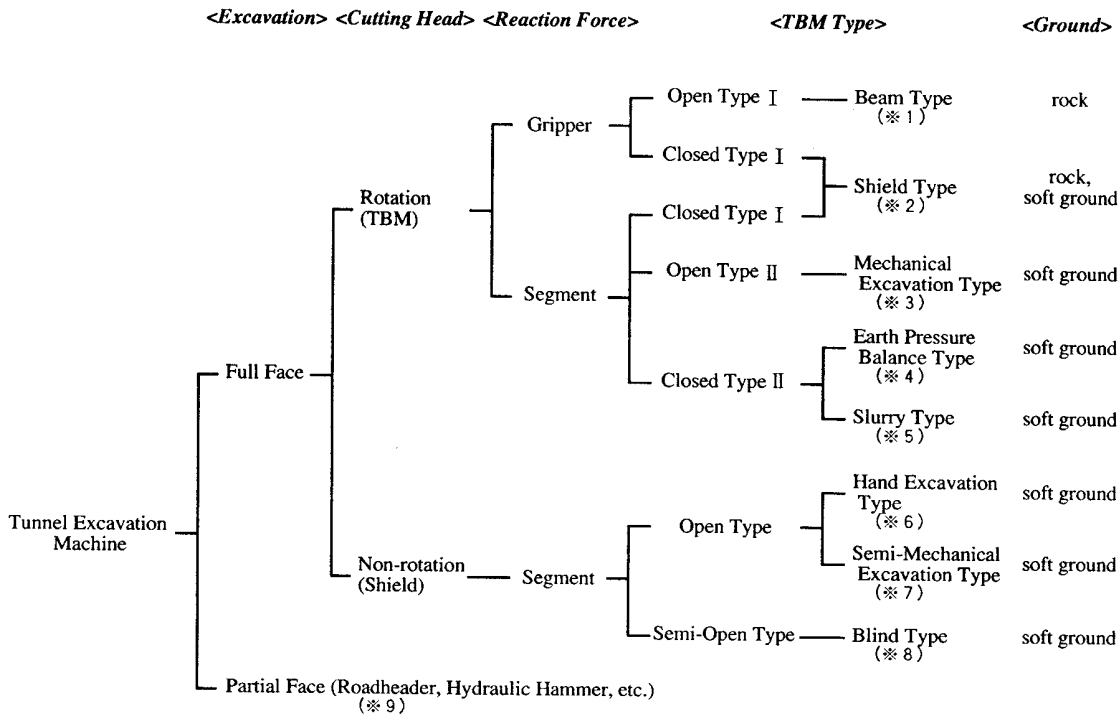
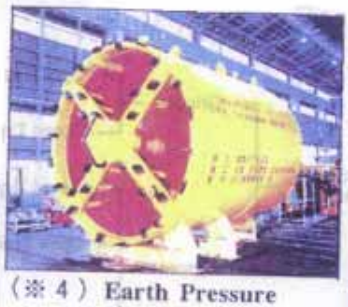



**Fig. 1.1 Classification of Tunnel Excavation Machines**

(※1) Beam Type

(※2) Shield Type

(※9) Roadheader



(※4) Earth Pressure Balance Type

(※3) Mechanical Excavation Type

(※5) Slurry Type

(※7) Semi-Mechanical Excavation Type

(※6) Hand Excavation Type

(※8) Blind Type

**Fig. 1.2 Tunnel Excavation Machines**

### 1.1 Mechanical Excavation Type (Fig. 1.3)

The mechanical excavation type-tunneling machine is equipped with a rotary cutter head for continuous excavation of tunnel face. There are two types of cutter heads; one is the disk type and the other is the spoke type (rod style radiating from the center). The disk type is suitable for large cross section tunnels where tunnel face is stabilized by the disk cutter head. This type of machine is capable of excavating soils containing gravel and boulders with the openings in the disk, which are adjustable according to the size of gravel and boulders. The spoke type is frequently used for small cross section tunnels where the tunneling face is relatively stable. Gravel and boulders are removed by the rotating spoke cutter.

The mechanical excavation type-tunneling machine is suitable for the diluvial deposit that has a self-standing face. Application of this type of machine to the alluvial deposits, which usually do not form a self-standing face, requires one or more supplementary methods such as pneumatic pressure, additional de-watering, and chemical grouting.

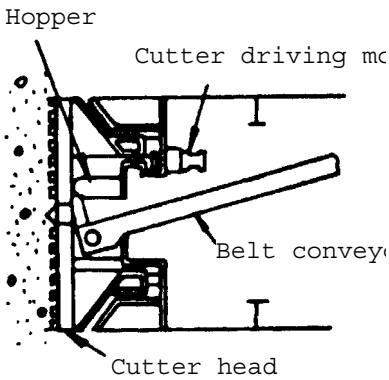



**Fig. 1.3 Mechanical Excavation Type Tunneling Machine**

### 1.2 Earth Pressure Balance (E.P.B.) Type (Fig. 1.4)

Earth pressure balance type tunneling machine converts excavated soil into high-density slurry mix. The face of the tunnel is supported by the pressurized slurry mix injected into a space between its cutter head and a watertight steel bulkhead. It consists of the following four components:

i) A cutter head for excavating the ground
ii) A slurry mixer for mixing the excavated muck with high-density slurry
iii) Soil-discharging devise for removal of the muck
iv) Pressure controlling devise for keeping the pressure of slurry-soil mix steady

The earth pressure balance type is classified into two types by the additives injected to convert the excavated muck into high-density slurry. One is earth pressure type and the other is high-density slurry type.

(1) Earth pressure type
Earth pressure type machine cut the ground with a rotary cutter head. Clay-water slurry is injected into the cutter chamber and is mixed with excavated muck. The slurry mix is pressurized to stabilize the tunnel face and create the driving force of the machine. The excavated muck is later separated from the slurry and discharged by a screw conveyor. This type is suitable for clayey soil layers.

(2) High-density slurry type
High-density slurry type machine cut the ground with a rotary cutter head. The excavated muck is mixed with clay-water slurry. by the rotating cutter. Highly plastic and dense additive is added to the slurry mix in the cutter chamber. The additives are used to increase the fluidity and to reduce the permeability of the soil. The high-density slurry mix stabilizes the tunnel face. The excavated muck is discharged by a screw conveyor. This type is suitable for sand or gravel layers.

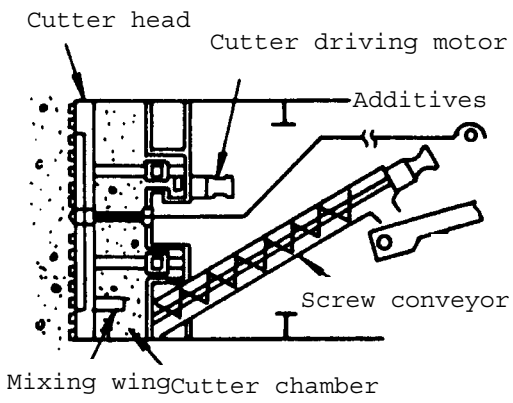



**Fig. 1.4 Earth Pressure Balance Type Tunneling Machine**

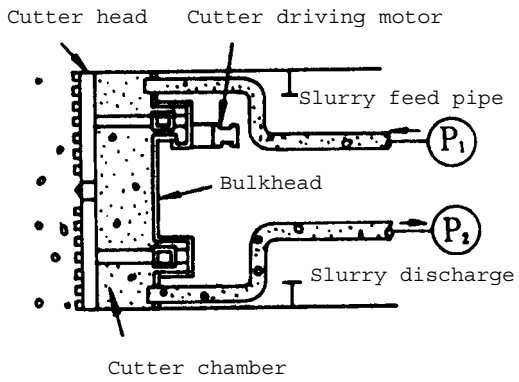



**Fig. 1.5 Slurry Type Tunneling Machine**

### 1.3 Slurry Type (Fig.1.5)

Slurry type tunneling machine cut the ground with a rotary cutter head. The cutter chamber is filled with pressurized slurry mix to stabilize the face of the tunnel. The slurry mix is circulated through pipes to transport it to a slurry treatment plant where the excavated muck is separated from slurry mix. The excavated muck is discharged through pipes and the slurry is circulated back to the cutter head for re-use. The slurry type machine consists of the following three components:

i ) A rotating cutter head for excavating ground
ii) A slurry mixer for the production of slurry mix with desired density and plasticity
iii) Slurry pumps to feed/discharge, circulate and to pressurize slurry mix
iv) Slurry treatment plant to separate excavated muck from slurry

# 2 INVESTIGATIONS OF EXISTING CONDITIONS AND APPLICABILITY OF TBM

## 2.1 Site Investigations

Site investigations are conducted to obtain basic data necessary for determining the project scale, selection of a tunnel route and its alignment, applicability of TBMs, and its environmental impact, and for planning, designing and construction of TBM tunnels. Results of the investigations are also used for operation and maintenance of TBM. The major items of investigation are indicated in the following subsections.

### 2.1.1. Existing site conditions

Existing site conditions along the proposed tunnel route are investigated to survey the following site conditions

i) Land use and related property rights
ii) Future land use plan
iii) Availability of land necessary for construction
iv) Traffic and the type of the roads
v) Existing rivers, lakes and ocean
vi) Availability of power, water and sewage connections

Results of the investigation are mainly used for determining the tunnel route, its alignment, locations and areas of access tunnels and temporary facilities.

### 2.1.2. Existing structures and utilities

Existing structures and utility lines near the tunnel are investigated for their future preservation and for securing the safety of TBM tunneling.

i) Existing surface and underground structures
ii) Existing utilities
iii) Wells in use and abandoned
iv) Remains of removed structures and temporary structures

### 2.1.3. Topography and geology

Topographical and geological conditions are the most important factors affecting the TBM design and construction. In particular, the following items should be investigated by field survey, boring, etc.

i) Topography
ii) Geological structure
iii) Ground conditions
iv) Groundwater

### 2.1.4. Environmental impact

Environmental impact analysis of the tunnel construction should be carried out to select and design construction methods that minimize the environmental impacts to the existing ecosystem.

i) Noise and vibration
ii) Ground movement
iii) Groundwater
iv) Oxygen deficient air and hazardous gas such as methane gas
v) Chemical grouting
vi) Discharge of excavated muck

## 2.2 Applicability of TBMs

Three types of excavation methods, drilling and blasting, TBM for hard rock, and TBM for soft ground, are compared in terms of tunnel dimensions, geological conditions and environmental impacts, and are shown in Table 2.1. The shaded portions of this table indicate the application of TBMs for soft ground.

Among the soft ground TBMs, the mechanical excavation type, earth pressure balance type and slurry type is compared in **Table 2.2** in terms of their applicability to various types of soft ground. This table also indicates the items that should be taken into consideration when applying TBM to soft ground. .

As indicated in **Table 2.2**, earth pressure balance and slurry types are suitable for alluvial deposits that generally are not self-standing. Slurry type is effective for driving through grounds with high groundwater pressure, such as those under river or seabed because the stability of tunnel face can be maintained by properly mixed and pressurized slurry mix. On the other hand, earth pressure balance type is not suitable for grounds with high groundwater pressure because it is difficult to maintain the pressure balanced against ground water pressure due to the opening for the soil discharging screw conveyor.

**Table 2.1 Comparison of Excavation Methods**

| Conditions \ Excavation Method | | Drilling and Blasting | TBM | |
|---|---|---|---|---|
| | | | For Hard Rock | For Soft Ground |
| Tunnel Features | tunnel length | Equipment cost is relatively low. Excavation cost is not greatly influenced by the tunnel length. | The cost of tunnel boring machines is generally high. It is suitable in longer tunnel excavations. | The cost of tunnel boring machines is generally high. It is suitable in longer tunnel excavations. |
| | shape of the cross section | Basically, the shape of excavation has an arched shape at the crown. The shape of the section can be changed during the construction. | Basically, the shape of the excavation is a circle. After boring, other shapes are possible using drilling and blasting as the result of enlargement. | Basically, the shape of the excavation is a circle. Semicircle, multi-circle, oval etc. are also possible using special tunneling machines for excavation. |
| | size of the cross section | Generally, it is possible up to 150m$^2$. The largest record is bigger than 200m$^2$. | The largest record is approximately 12m for the maximum diameter of the tunnel. | The largest record is approximately 14m for the maximum diameter of the tunnel. |
| Geological Conditions | hard rock | Suitable | Suitable except for the extra-hard rock (s>200MPa) | Not applicable |
| | semi-hard rock | Suitable | Suitable | Not applicable |
| | Weak layers such as fractured zones and aquifer zones | Various countermeasures become necessary. | It is not suitable in area where weak ground or water inflow will be frequently encountered. | Applicable<br>See Table.2.2 |
| | Soil | Not applicable | Not applicable | Most suitable<br>See Table 2.2 |
| Environmental Conditions | Noise and Vibration | Due to noise and vibration, it is not suitable in the vicinity of houses and important structures. A supplementary method is necessary to reduce the effects of noise and vibration. | Compared to the drilling and blasting there is less effect of noise and vibration to the houses and important structures. | There is less effect of noise and vibration to the houses and important structures than other excavation methods. |

**Table2.2 Applicability of TBMs to SoftGround Conditions**

| TBM type / Ground condition | N-value | water content or permeability | Open type | | Closed type | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mechanical excavation type | | Earth pressure balance type | | | | Slurry type | |
| | | | | | Earth pressure type | | High-density slurry type | | | |
| Alluvium clay | 0 – 5 | 300% – 50% | s | -Face stability<br>-Ground settlement | l | -Difficulty in extremely weak clay<br>-Volume control of discharged soil | – | -Earth pressure is more suitable. | s | -Difficulty In extremely weak clay<br>-Slurry spouting on surface<br>-Increase of secondary slurry treatment plant |
| Diluvium clay | 7 – 20 | W < 50% | l | -Existence of water bearing sand<br>-Blockage in slit chamber | l | -Liquidity of soil<br>-Volume control of discharged soil | – | -Earth pressure is more suitable. | l | -Increase of secondary slurry treatment plant |
| Soft rock (mudstone) | > 50 | W < 20% | l | -Existence of water bearing sand<br>-Wear of cutter bits | – | -Earth pressure with slurry is more suitable when there is water bearing sand. | – | -Suitable when there is water bearing sand | – | -Suitable when there is water bearing sand |
| Loose sand | 5 – 30 | $10^{-2}$ – $10^{-3}$ (cm/s) | x | -Unstable face | s | - Contents of fine particles | l | -Highly-advanced excavation control | l | -Highly-advanced excavation control<br>-Quality control of slurry solution |
| Dense sand | > 30 | $10^{-3}$ – $10^{-4}$ (cm/s) | s | -Face stability<br>-Groundwater level, permeability | s | - Contents of fine particles | l | -Wear of cutter bits<br>-Dosage of additives | l | -Quality control of slurry solution |
| Sand gravel | > 30 | $10^{0}$ – $10^{-2}$ (cm/s) | s | -Face stability<br>-Groundwater level, permeability | s | - Contents of fine particles | l | -Wear of cutter bits<br>-Dosage of additives | l | -Running away of slurry<br>-Gravel crusher<br>-Fluid transportation system |
| Sand and gravel With boulders | > 50 | $10^{0}$ – $10^{-1}$ (cm/s) | x | -Face stability<br>-Boulder crusher<br>-Wear of cutter bits and face | s | - Contents of fine particles<br>-Wear of cutter bits and face<br>-Boulder crusher<br>-Boulder diameter for screw-conveyer | l | -Wear of cutter bits<br>-Boulder crusher<br>-Boulder diameter for screw-conveyer | s | -Running away of slurry<br>-Boulder crusher<br>-Fluid transportation system |
| Applicability for ground Condition changes | | | It is impossible to change excavation system. | | Applicable<br>Additive injection equipment becomes necessary | | Applicable<br>In general, it is widely applicable for various soil conditions. | | Applicable<br>In general, It is widely applicable for various soil conditions. | |

Note: l Applicable, s Consideration required x Not applicable
Items to consider when applying
In case of x, reasons for not applicable

## 3 TUNNEL BORING MACHINE (TBM)

### 3.1 Machine Specifications

#### 3.1.1. Essential parts of TBM

TBMs are normally manufactured in drum-shaped steel shield equipped inside with excavation and segment erection facilities. The essential parts of the machine include the following items:

i) Rotary cutter head for cutting the ground
ii) Hydraulic jacks to maintain a forward pressure on the cutting head
iii) Muck discharging equipment to remove the excavated muck
iv) Segment election equipment at the rear of the machine
v) Grouting equipment to fill the voids behind the segments, which is created by the over excavation.

#### 3.1.2. Structure of TBM

TBM is composed of the steel shell (so called the shield) for protection against the outer forces, equipment for excavation of soil and for the installation of the lining at the rear. The power and control devices are mounted partly or totally on the trailing car behind the machine, depending on the size and structure of the machine. Steel shell, made of the skin plate and stiffeners, is composed of three portions; hood, girder and tail portion (see Fig. 3.1).

In case of the closed type machine, hood and girder portions are separated by a bulkhead. The soil excavated by the cutter head is taken into the mucking device through the hood portion. In some cases, man-lock is installed at the bulkhead in order to change the cutter bits or to remove obstacles under the pneumatic pressure.

For manual type, breasting is provided at the hood portion. The reaction force is supported by the girder portion where the thrusting devices are installed.
The tail portion of the machine is equipped with erector of the segments. Tail seal for water stop is inserted between the skin plate and the segment ring.
In case of the articulating system, the girder portion is made flexible by dividing the portion into two or more bodies with pins and jacks. Such flexible separation of the body is adopted to allow a smooth turn along the curved alignment of the tunnel with different diameters of the machines, degrees of allowance of over cutting and under various soil conditions,.
When two tunneling machines are connected underground, the alignments and the relative positions of the two machines have to be carefully monitored and adjusted. The final connection normally requires some soil improvement work such as ground freezing, or else with extendable cutter head or hood equipped on either one of the machines.

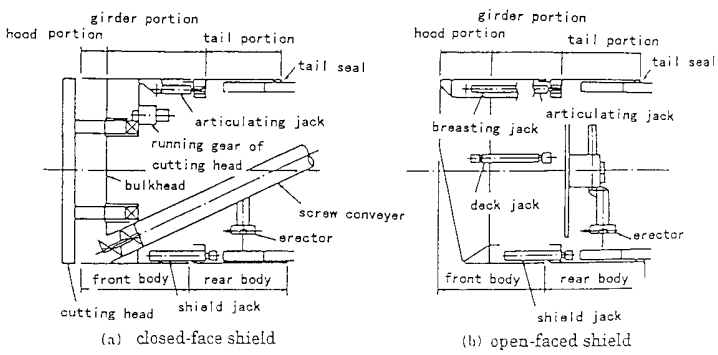



**Fig. 3.1 Components of Tunneling Machine**

### 3.1.3. Types of TBMs for soft ground

As described in the previous section, TBMs for soft ground are classified into three types; earth pressure type, slurry type and mechanical type. These three types of TBMs are summarized in Fig 3.2. Before those three types were developed, other types of TBMs such as the open type, blind type, manual type, and half-mechanical type were used for soft ground. The open type TBM is now mostly replaced by closed type for soft ground tunneling.

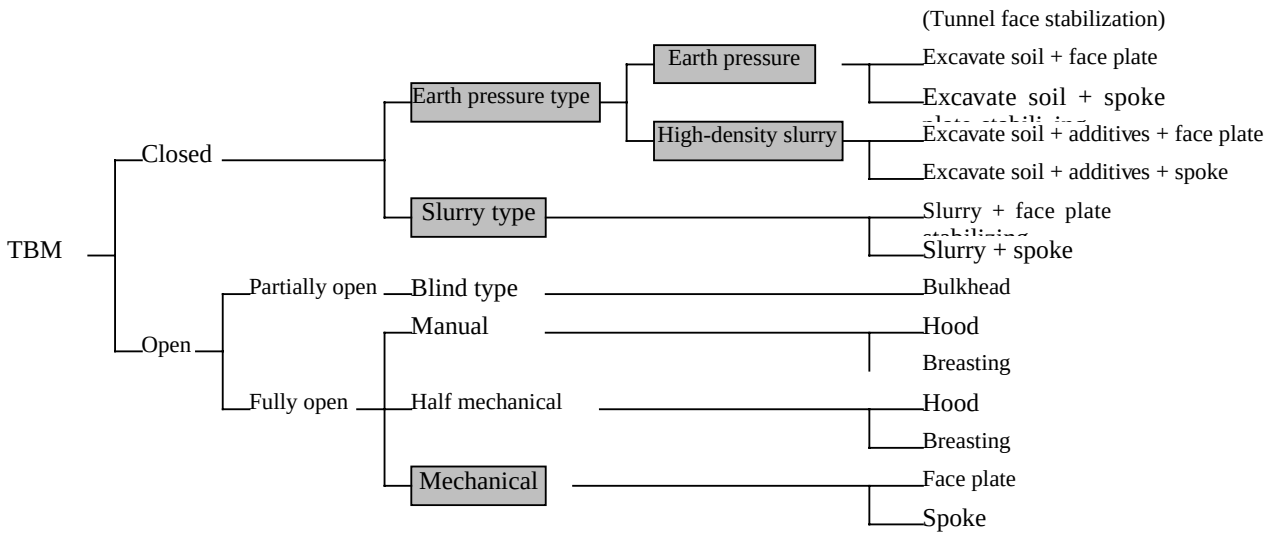



**Fig. 3.2 Type of TBM for Soft Ground**

### 3.1.4. Selection of TBM

Careful and comprehensive analysis should be made to select proper machine for soft ground tunneling taking into considerations its reliability, safety, cost efficiency and the working conditions. In particular, the following factors should be analyzed:

i) Suitability to the anticipated geological conditions
ii) Applicability of supplementary supporting methods, if necessary
iii) Tunnel alignment and length
iv) Availability of spaces necessary for auxiliary facilities behind the machine and around the access tunnels
v) Safety of tunneling and other related works.

Fig. 3.3 indicates a flow chart for selecting TBM for soft ground. In selecting the type of TBM, it is important to consider geological and groundwater conditions that affect the stability of the tunnel face.

Geological condition along the tunnel route is a primary factor to be considered for selecting the type of machine. Particularly, the degree of consolidation of the ground and the size of gravel and boulders in the soil should be thoroughly investigated. Table 3.1 shows the general relationship between the closed type of tunneling machine and soil conditions. In a case where a tunnel is very long or is under complex geological conditions, uniform layers could not be expected throughout the entire length of the tunnel. In such case, a tunneling method is selected based on the geological condition prevailing throughout the tunnel. Special attention should be paid to the following local geological conditions:

i) Soft clayey soil that is sensitive and easy to collapse
ii) Sand and gravel layers with high water contents
iii) Layers which contain boulders
iv) Layers which may contain driftwood or ruins
v) Strata which are composed of both soft and hard layers

Slurry type is easy to be automatically controlled and is the most advanced excavation

method for soft ground tunneling because of its reliability, safety and the minimum disturbance to surrounding ground.
Both earth pressure balance type and slurry type generally does not require supplementary supporting methods under ordinary conditions. The supplementary methods should be considered, however, for tunneling at starting and arrival area where the face of the tunnel is difficult to be stabilized. Also, some supplementary methods such as chemical grouting, ground freezing, pneumatic pressure and boulder crushing are required to drive through grounds with boulders or gravel, under thin overburden or any other special conditions.

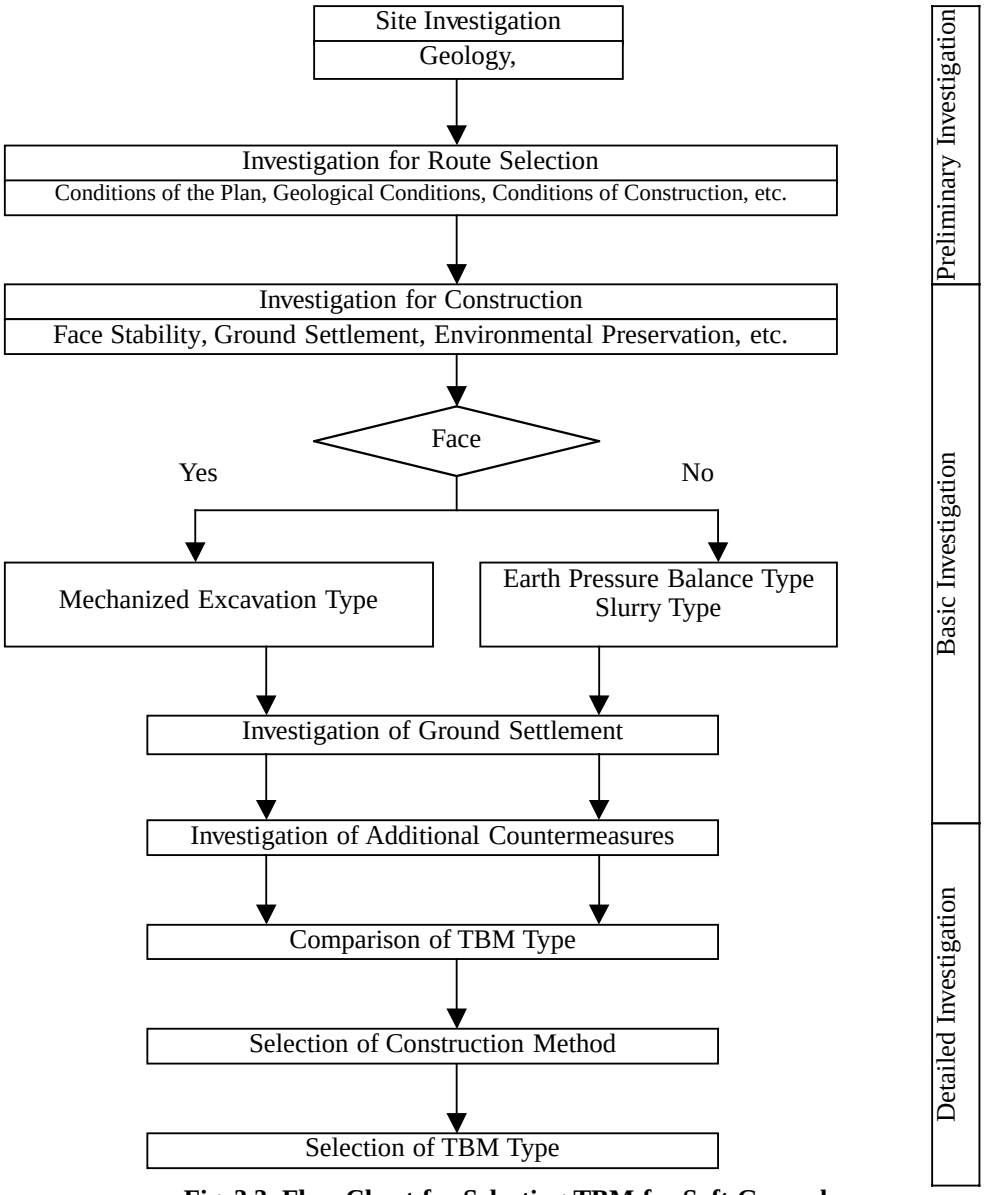



**Fig. 3.3 Flow Chart for Selecting TBM for Soft Ground**

**Table 3.1 Relationship between Closed Type Tunneling Machine and Soil Conditions**

| Soil conditions \ Type of machine | | N-value | Earth pressure balance type | | | | Slurry type | |
|---|---|---|---|---|---|---|---|---|
| | | | Earth pressure type | | High-density slurry type | | | |
| | | | Suitability | Check point | Suitability | Check point | Suitability | Check point |
| Alluvial clay | Mold | 0 | x | _ | s | settlement | s | Settlement |
| | Silt, Clay | 0 – 2 | l | _ | l | _ | l | _ |
| | Sandy silt | 0 – 5 | l | _ | l | _ | l | _ |
| | Sandy clay | 5 – 10 | l | _ | l | _ | l | _ |
| Diluvial clay | Loam, Clay | 10 – 20 | s | Jamming by excavated soil | l | _ | l | _ |
| | Sandy loam | 15 – 20 | s | ditto | l | _ | l | _ |
| | Sandy clay | Over 25 | s | ditto | l | _ | l | _ |
| Solid clay | Solid clay ( muddy pan) | Over 50 | s | ditto | s | Wear of bit | s | Wear of bit |
| Sand | Sand with silty clay | 10 – 15 | l | _ | l | _ | l | _ |
| | Loose sand | 10 - 30 | s | Content of clayey soil | l | _ | l | _ |
| | Compact sand | Over 30 | s | ditto | l | _ | l | _ |
| Gravel Cobble stone | Loose gravel | 10 – 40 | s | ditto | l | _ | l | _ |
| | Compact gravel | Over 40 | s | High water pressure | l | _ | l | _ |
| | Gravel with cobble stone | – | s | Jamming of screw conveyor | l | _ | s | Wear of bit |
| | Large gravel Cobble stone | – | s | Wear of bit | s | Wear of bit | s | Crushing device |

l :normally applicable s:applicable with supplementary means x :not suitable

### 3.2 Orientation and operation of machine

#### 3.2.1. Excavation Control System

Since the closed type machine was developed, tunnel excavation has been mostly controlled by computerized system rather than manually. In addition, various supporting systems necessary for tunneling operation require sophisticated controlling system. A real time computerized system equipped with various sensors is developed for tunneling, in which orientation and operation of machine, excavation, backfill grouting and operation of auxiliary facilities are controlled by a centralized computer system. The system realized accurate alignment, excavation control that maintains the stability of the face of the tunnel, and minimized the disturbance of the surrounding ground. For slurry type tunneling machine, operation of pumps and valves for slurry transportation is computerized based on the data fed by pressure gauges, flow meters and other measuring devices for fluid transportation. Thus, steady pressure of slurry is maintained throughout the tunneling operation.

In the near future, all operation of the machine will be entirely controlled by computerized system from above ground.

#### 3.2.2. Direction Control and Measurement System

Automatic direction control system has been put to practical use that utilizes survey data obtained by real time measurement device instead of the conventional transit-level survey. The system consists of measurement and direction control systems, and comprises of four functions; survey, monitor, analysis and control. The measurement system utilizes laser beam (laser, infrared or diode) or gyrocompass, and measures the location of the machine in three-dimensional coordinates and its attitude (pitching, rolling and yawing).

Direction of the machine is normally controlled by jacks that introduce proper thrust force and rotation moment. Each jack on a cutter disk is controlled by a computerized system based on the target amount of thrust and the direction of machine. In the process of determining the amount of thrust required for each individual jack, a mathematical theory of “fuzzy control theory” has been applied based on the date accumulated through the past performance of the machine. Recent automatic direction control system realizes accuracy of plus or minus 30 mm both horizontally and vertically.

### 3.3 Cutter Consumption

#### 3.3.1. Bit types and Arrangement

There are several types of bits for TBM, such as teeth bit, peripheral bit, center bits, gouging bit, wearing detection bit, etc. Bits are generally made by steel or hard chip alloy that is highly wear resistant. Selection of material and types of bits is made based on the ground conditions, excavation speed and length of the tunnel. Arrangement of bits on the cutter head is decided based on construction conditions, past experience in similar geology, cutting depth and the number of passes of rotating bits.

#### 3.3.2. Wear of Bit

Generally, the amount of wear of bits is proportional to the product of number of passes of rotating bits and length per pass, and is influenced by ground conditions and other factors such as type of machine, geology, material and arrangement of the bits on a cutter head. The amount of wear can be estimated by the following formula;

$$d = (K.\pi.D.N.L)$$

here, d: amount of wear (mm)

K: wear coefficient (mm / km)

D: distance between the center of cutter disk and bit (m)

N: number of revolution of cutter disk per minute (rpm)

L: excavation distance (m)

V: rate of excavation (mm / min)

The wear coefficient, K, above is given by manufacturers based on the pressure applied to bits, the rotating speed, geological conditions, number of passes and material of bits to be used.

#### 3.3.3. Long Distance Excavation

Sometimes, a tunneling machine is required to drive through entire length of tunnel when access tunnels for installation of two or more

machines cannot be constructed due to the lack of land available. In that case, the tunneling machine, especially the cutting bit and tail seal, is required to be highly durable.
For higher durability of the bits, new chipping material such as hard chip alloy has been developed, which are two or three times durable than those of conventional material. Bits can be changed from inside the TBM. Durability of tail seals and the method of changing them are being improved as well.

## 3.4 Ground Support and Lining

### 3.4.1. Design of Lining

The linings of the tunnel must withstand the soil and water pressure acting on the tunnel. Primary tunnel lining is usually constructed by prefabricated concrete segments erected around the periphery of the tunnel. Those segments are connected each other to form circular rings which are installed side by side continuously to form a cylinder. The second lining, when required, is normally constructed by in-situ concrete.

Usually primary lining is designed as a main structural member against the final load, because the secondary lining is installed long after the erection of segments. Therefore, the role of the secondary lining is mostly not for the main structural member, but for the supplementary member for water proofing, anticorrosion, etc. Secondary lining is omitted to save costs when the primary lining is watertight enough or the ground conditions are favorable.

For the design of the segment, several loads and their combination should be considered (see Table 3.2). Temporary loads that vary during the construction such as thrust force by jacks and grouting pressure should be also taken into consideration.

The effects of joints between segments and rings should be carefully assessed when designing segment lining. As several segments are pieced together to produce a ring, the ring may not deform uniformly against the surrounding loads due to weakness at segment joints. The same can be said to the joints between rings. Staggered arrangement is made to reduce these effects of the joints.

Under present design method, segment ring assumes to be a uniform flexural ring, a multi-hinged ring or a ring with rotational springs.

**Table 3.2 Loads on Segments**

| | |
|---|---|
| Main load | vertical and horizontal earth pressure<br>water pressure<br>dead load<br>surcharge load<br>ground reaction |
| Secondary load | internal load<br>temporary load during execution<br>seismic load |
| special load | Influences of adjacent tunnel<br>of adjacent structures<br>of ground settlement others |

### 3.4.2. Types of Segment

As the cost of segments shares significant portion of total tunneling cost, type of segment should be carefully selected from both engineering and economical points of view. Segments are classified into several types; reinforced concrete (RC), steel, cast iron (ductile), composite, and others.

Reinforced concrete prefabricated segments are most commonly used for tunnels driven by TBMs. Reinforced concrete segment is an excellent lining member with high compressive strength against both radial and longitudinal forces. It also has high rigidity and water tightness. On the other hand, it is heavy and has less tensile strength and more fragile than steel ones. Therefore, extreme care should be taken to the removal of forms

during fabrication and to the erection during construction in order to avoid possible damages to segments, especially to their corners. Rectangular shaped segments are commonly used, but hexagonal or other shapes are also produced. They can be either solid or box type.

Steel segment is flexible and is relatively light and easy in handling. Because of the flexibility of steel segment, they should not be subjected to high thrusting force of jacks or grouting pressure to avoid buckling or unnecessary deformation. When the second lining is omitted, proper anticorrosion measures should be taken.

Cast iron (ductile) segment is produced with precise dimensions and therefore can be erected with good water tightness. Because of its strength and durability, it is commonly used at locations under heavy loads or for reinforcing tunnel openings.

In addition to above three types of segments, various types have been used or proposed, such as composite segments (steel and RC, steel and plain concrete), flexible segment that allows certain degree of deformation caused by earthquake or uneven ground settlement. Also, there are several types of radial and longitudinal segment joints such as bolt, cotter, pin and pivot, knuckle and other joint types.

### 3.4.3. Fabrication of Segment

Fabrication of segments has to be carried out under strict quality control to ensure compliance with specified dimensions and strength. Automated fabrication of segments is desired that provide adequate quality control to ensure structural integrity and precise dimensions of segments.
Table 3.3 provides allowable stresses of concrete for pre-fabricated reinforced concrete segment.

Table 3.4 provides typical dimensions of steel and concrete segments.

**Table 3.3 Allowable stresses of concrete for pre-fabricated concrete segments**

| | Allowable stress (N/mm) | | | | |
|---|---|---|---|---|---|
| Design compressive strength | 42 | 45 | 48 | 51 | 54 |
| Bending compressive stress | 16 | 17 | 18 | 19 | 20 |
| Shearing stress | 0.71 | 0.73 | 0.74 | 0.76 | 0.77 |
| Bonding stress to deformed re-bar | 2.0 | 2.1 | 2.1 | 2.2 | 2.2 |
| Bearing stress (overall load) | 15 | 16 | 17 | 18 | 19 |

**Table 3.4 Typical Dimensions of Segments (mm)**

| | Steel Segment | | | Concrete Segment | | |
|---|---|---|---|---|---|---|
| Outer Diameter | Width | Thickness | NO/Ring | Width | Thickness | NO/Ring |
| 1,800 _ 2,000 | 750 | 75<br>100 | 6 | 900 | 100<br>125 | 5 |
| 2,150 _ 2,550 | 900<br>1,000 | 100<br>125 | 6 | 900<br>1,000 | 100<br>125<br>150 | 5 |
| 2,750 _ 3,350 | 900<br>1,000 | 125<br>150<br>175 | 6 | | | |
| 3,550 _ 4,050 | 900<br>1,000 | 125<br>200<br>225 | 7 | 900<br>1,000 | 125<br>150<br>175<br>200 | 6 |
| 4,300 _ 4,800 | 900<br>1,000 | 150<br>175 | 7 | | | |
| 5,100 _ 5,700 | 900<br>1,000 | 175<br>200<br>225 | 7 | 900<br>1,000 | 175<br>200<br>225<br>250<br>275<br>300 | 6 |
| 6,000 | 900<br>1,000 | 200<br>225 | 7 | | | |
| 6,300 _ 6,900 | 900<br>1,000 | 250<br>275 | 7 | 900<br>1,000 | 250<br>275<br>300 | 7 |
| 7,250 _ 8,300 | 900<br>1,000 | 300<br>325<br>350 | 8 | 900<br>1,000 | 275<br>300<br>325<br>350 | 8 |

### 3.4.4. Erection of Segments

The process of primary lining consists of transportation and erection of segments. Segments are usually transported through the tunnel by cars on rails. Automatic transportation system of segments is used to recent projects that transport segments from a depot above ground to the rear end of the machine through access shaft and tunnel.

The erection of segments is done by an erector at the rear room of the machine. The segment erector is equipped with gripping, shifting, rotating and setting devices. Longitudinal joints of segment rings are normally made manually.

## 3.5 Auxiliary Facilities

Generally, tunneling operation by TBM consists of cutting ground by cutter head, jacking to push machine forward, muck transportation, segment erection and grouting of voids behind segments. Auxiliary facilities that are typically required throughout this operation are shown in Table 3.5.
Common facilities are gravel treatment plant, grouting facilities, segment depot and treatment facilities. For the discharge of excavated muck, different types of facilities are required depending on the type of tunneling machines as follows.

### 3.5.1. Earth pressure balance type machine

The excavated muck is removed from the cutter chamber by a screw conveyor and sent out by mucking car or belt conveyor. For small diameter tunnels where working space is quite limited, the excavated muck is mixed with plasticizer and pumped out through the pipe. For these operations, additive mixing plant, a screw conveyor and belt conveyor or mucking cars are required.

### 3.5.2. Slurry type tunneling machine

Sequence of discharging the excavated muck for this type of machine consists of; (i) pouring slurry to the cutter chamber while the soil is excavated and the machine is pushed forward, (ii) mixing excavated soil with slurry and pumping the slurry mix from the cutter chamber to a treatment plant where the slurry mix is separated into soil and slurry, (iii) discharging the separated soil out to the disposal area and circulating the slurry back to the tunnel face for reuse. Auxiliary facilities required for these operations are slurry mixer, feed and discharge pumps and pipes, and slurry treatment plant.

**Table 3.5 Auxiliary Facilities**

| Earth pressure balance type | Slurry type |
|---|---|
| - Segment pool and transportation facilities for segments and materials<br>- Central control room<br>- Gravel treatment facilities, such as crushing device<br>- Grouting facilities for back fill | |
| - Belt conveyor, mucking cars or pumps<br>- Additive mixing plants | - Slurry transport facilities, such as slurry pumps and pipes.<br>- Slurry treatment facilities, such as centrifugal classifier and filter plant |

## 4 TUNNELS CONSTRUCTED BY TBM IN JAPAN

### 4.1 Soft ground tunneling in Japan

Soft ground tunnels driven by TBMs in Japan since 1994 are shown in Table 4.1 below.

**Table 4.1 TBMs in soft ground performed in Japan**

Tunneling Annual Report (JTA 1994)

| | Mechanical | | | | Total | Ratio(%) | Length/ Project |
|---|---|---|---|---|---|---|---|
| | Mechanical | Slurry | EPB | EPB with Slurry | | | |
| Railway | 1 | 23 | 13 | 38 | 75 | 13.8 | |
| | 2600 | 26864.9 | 14703.7 | 43957 | 88125.6 | 14.4 | 1175.0 |
| Road | | 7 | | | 7 | 1.3 | |
| | | 7961 | | | 7961 | 1.3 | 1137.3 |
| Water supply | | 11 | 5 | 16 | 32 | 6.0 | |
| | | 12975.3 | 6586.6 | 23293.4 | 42855.3 | 7.0 | 1339.2 |
| Sewer | 1 | 87 | 43 | 209 | 340 | 62.7 | |
| | 421 | 101393.2 | 41653.3 | 217278.4 | 360745.9 | 59.1 | 1061.0 |
| Utility | | 35 | 3 | 39 | 77 | 14.2 | |
| | | 48473.5 | 2215.5 | 36112.2 | 86801.2 | 14.2 | 1127.3 |
| Other | | 2 | 3 | 6 | 11 | 2.0 | |
| | | 12432 | 5316 | 6633.8 | 24381.8 | 4.0 | 2216.5 |
| Total | 2 | 165 | 67 | 308 | 542 | 100.0 | |
| | 3021 | 210099.9 | 70475.1 | 327274.8 | 610870.8 | 100.0 | 1127.1 |
| Ratio(%) | 0.4 | 30.4 | 12.4 | 56.8 | 100.0 | | |
| | 0.5 | 34.4 | 11.5 | 53.6 | 100.0 | | |
| Length/Project | 1510.5 | 1273.3 | 1051.9 | 1062.6 | 1127.1 | | |

Upper: No. of projects Lower: Tunneling length (m)

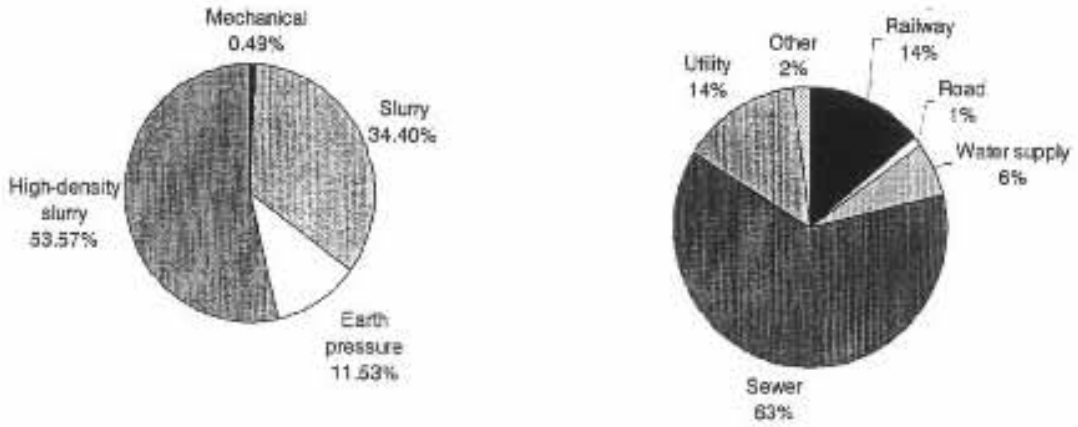
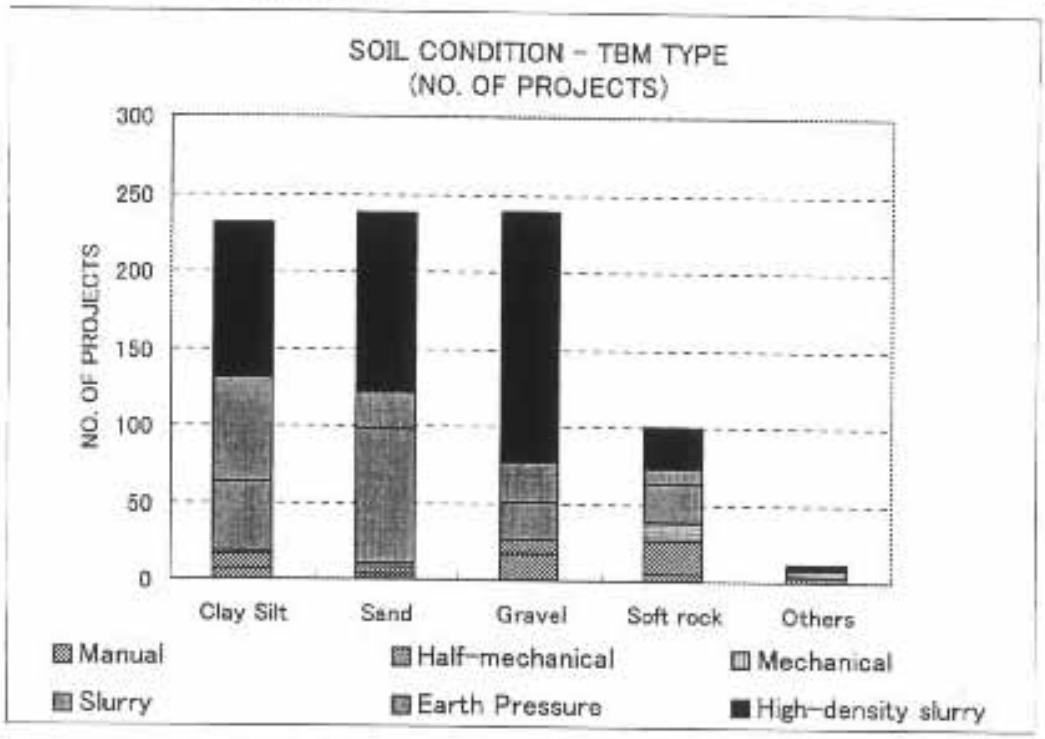



**Fig. 4.1 Tunnels driven by TBMs in Japan**

## 4.2 Types of TBMs and ground conditions

### 4.2.1. Soil Conditions and Types of TBMs



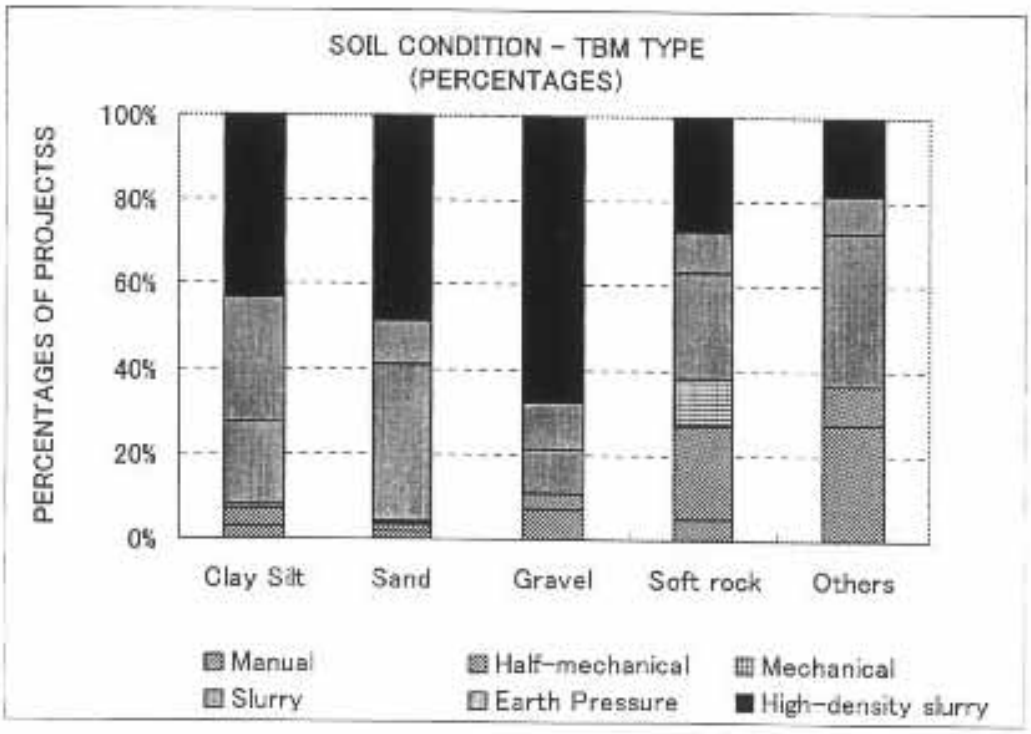
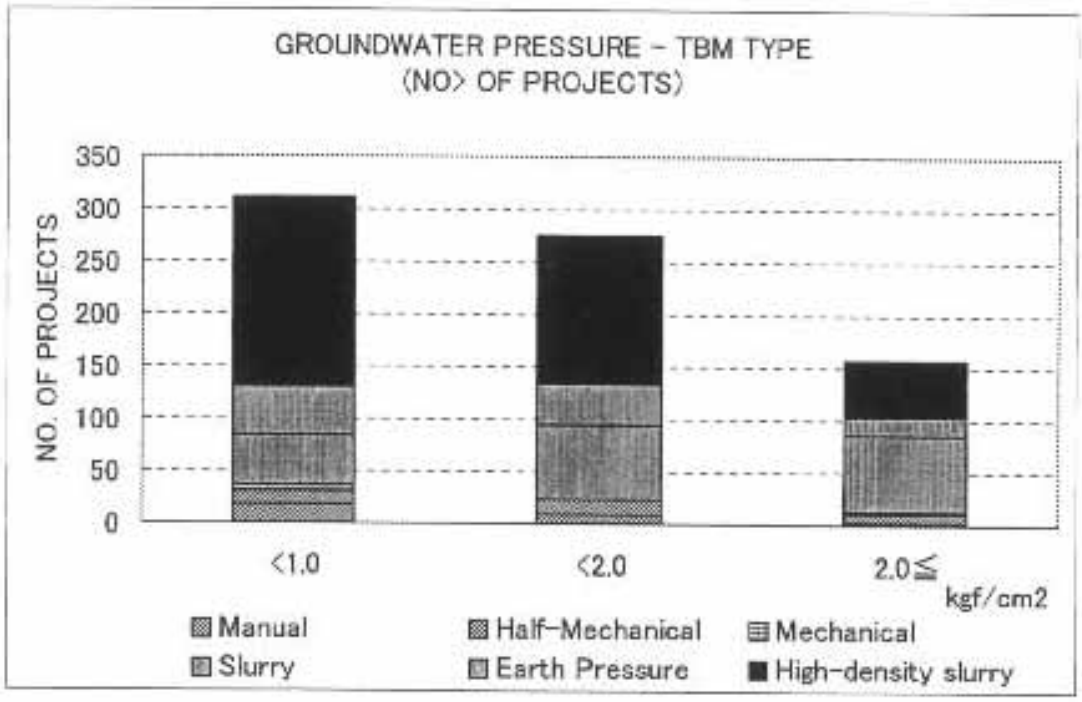




**Fig. 4.2 Soil conditions and TBM methods**

### 4.2.2. Groundwater pressure and Type of TBMs



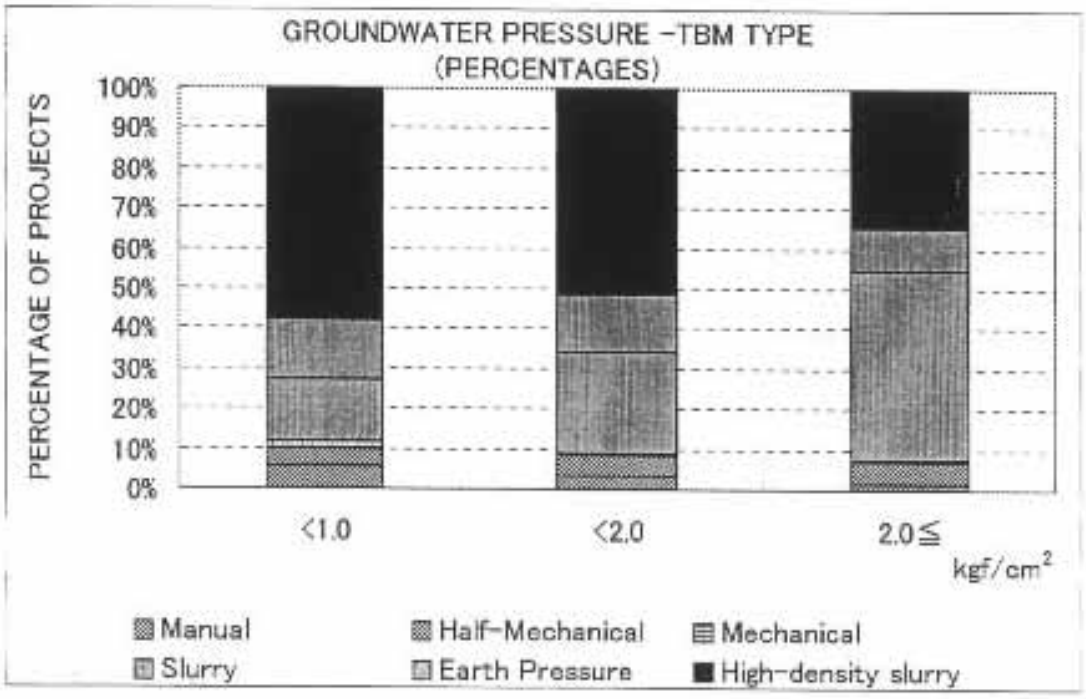
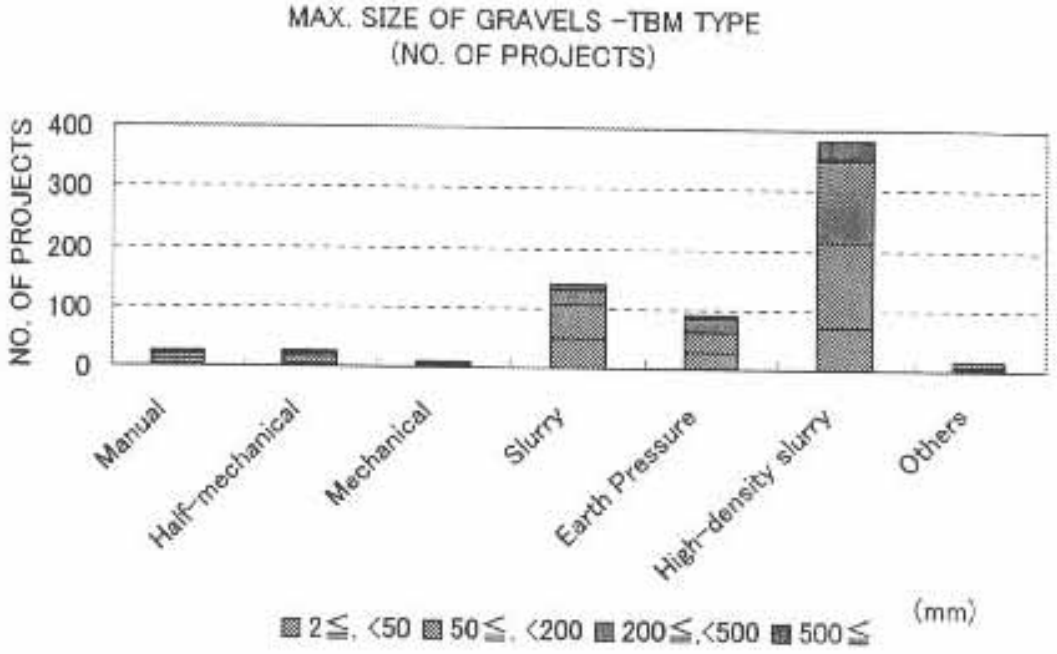




**Fig. 4.3 Groundwater Pressure and Type of TBMs**

### 4.2.3. Max. Size of Gravel and TBM Type



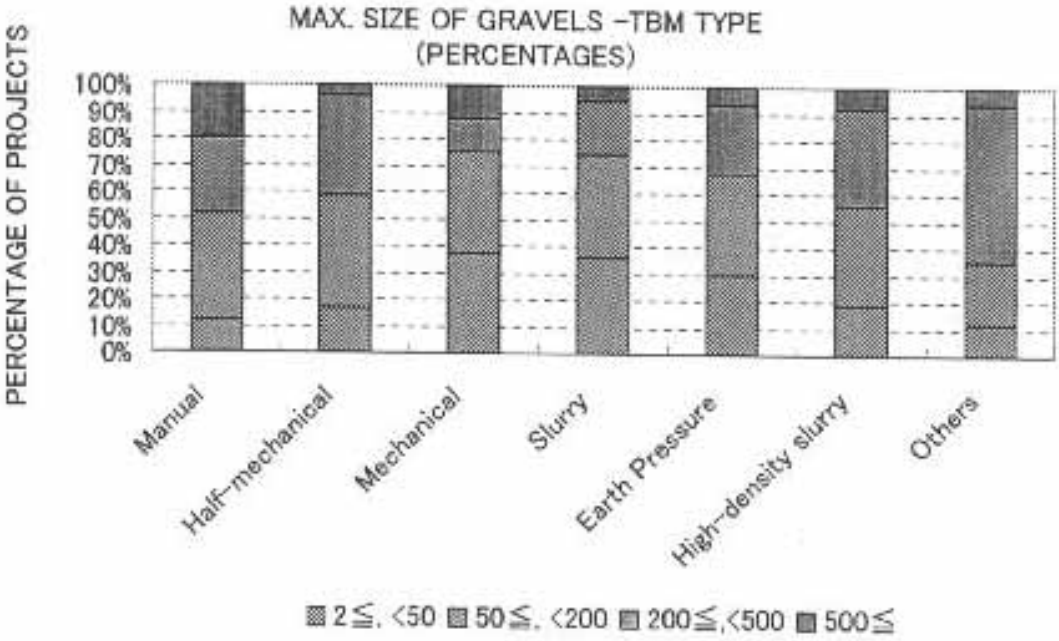




**Fig. 4.4 Gravel Size and Type of TBMs**

## 4.3 Size of TBM

### 4.3.1. Weight

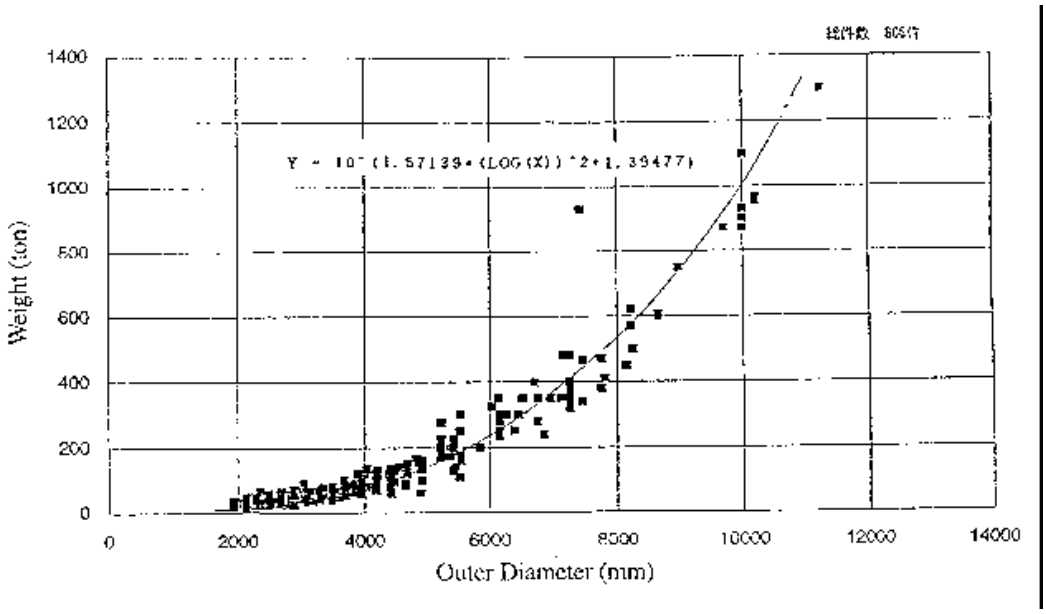



**Fig. 4.5 Diameter and weight of TBM (EPB, Slurry)**

### 4.3.2. Length/Diameter (L/D)

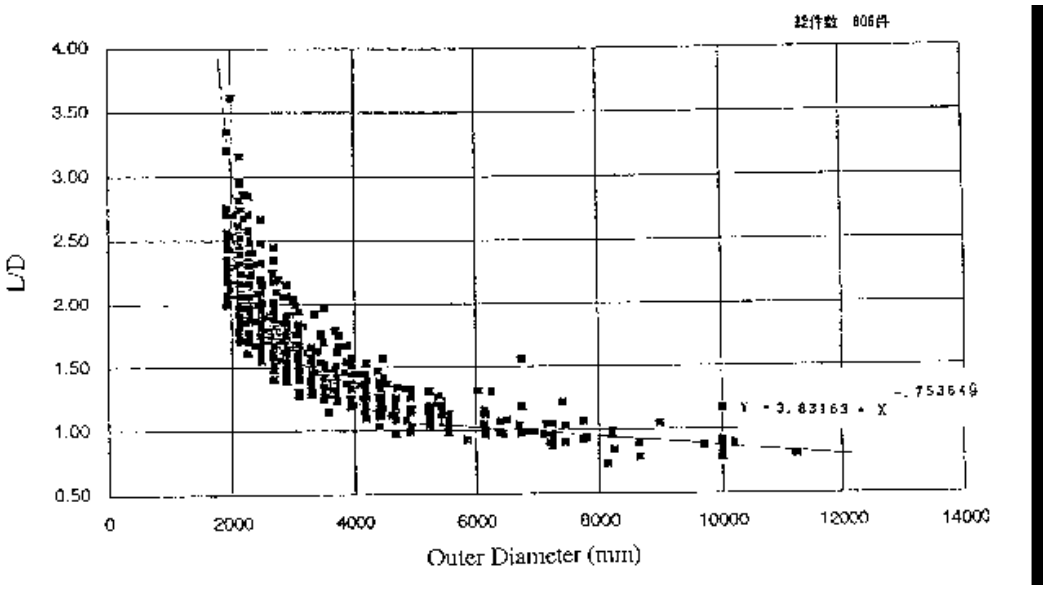



**Fig. 4.6 Diameter and length/diameter (L/D) of TBM**

## APPENDIX: TBM PERFORMANCE IN HARD ROCK

### A-1 General

The following prognosis model is a summary of "Project Report 1-94, Hard Rock Tunnel Boring", published by University of Trondheim, The Norwegian University of Science and Technology, NTH Anleggsdrift.

The prognosis model is based on job site studies and statistics from 33 job sites with 230 km of bored tunnels in Norway and other countries. Data have been carefully mapped, systematized and normalized and the presented results are regarded as representative for well organized tunneling. It should be noted that the prognosis model is valid for parameter values in the normal range. Extreme values may, even if they are correct, not fit the model and give incorrect estimates.

The prognosis model has been developed continuously since 1975 and has in the period up till now been through several phases and adjustments in accordance with increased knowledge and improvements of TBMs, auxiliaries and methods. The model is today considered as a practical and useful tool for pre-calculation of time consumption and costs for TBM bored tunnels in hard rock. The model is based on the use of TBM, Open type.

### A-2 Advance

#### A-2.1 Rock Mass Properties

1. DRILLING RATE INDEX, DRI: Index related to the properties of the rock mass. Together with Fracturing, DRI is the rock mass factor that has the major influence on Penetration Rate.
DRI is calculated from two laboratory tests,

- the Brittlenes Value S20
- Sievers J-Value SJ

The two tests give measures for the rock's ability to resist crushing from repeated impacts and for the surface hardness of the rock. Recorded Drilling Rate Indexes for some rock types are shown in Fig. A.1.

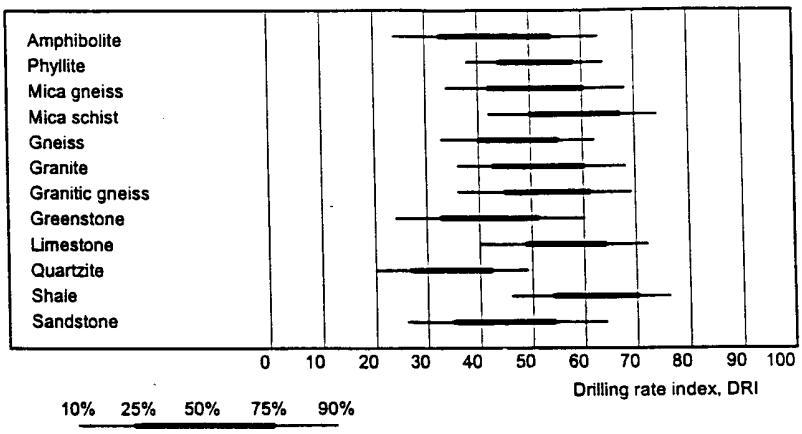



**Fig. A.1 Recorded Drilling Rate Index for various rock types**

2. CUTTER LIFE INDEX, CLI: Cutter Life Index is calculated on the basis of Sievers J-Value and the Abrassion Value steel. ( AVS.) CLI expresses the lifetime in boring hours for cutter rings of steel on TBM. Recorded CLI for some rock types are shown in Fig.A.2

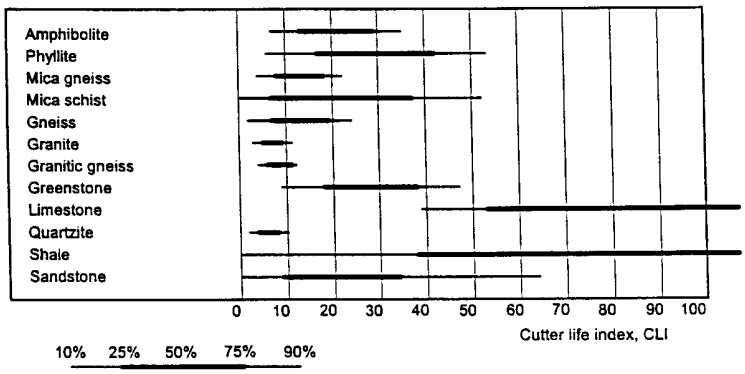



**Fig.A.2 Recorded Cutter Life Index for various rock types**

3. FRACTURING: The most important penetration parameter for tunnel boring. In this context, fracturing means fissures and joints with little or no shear strength along the planes of weakness. The less the distance between the fractures is, the greater the influence on the penetration rate. Rock mass fracturing is characterized by degree of fracturing (type and spacing) and the angle between the tunnel axis and the planes of weakness.

a) JOINTS in this respect are fractures that can be followed all around the tunnel profile.
b) FISSURES are non-continuous fractures which can be followed only partly around the tunnel profile.
c) FRACTURING is recorded in CLASSES with reference to the distance between the planes of weakness. The classes are shown in Fig. A.3. Recorded fracturing for some rock types are shown in.

| Fracture Class (joints Sp/fissures St) | Distance between Planes of Weakness [cm] |
|---|---|
| 0 | - |
| 0-I | 160 |
| I- | 80 |
| I | 40 |
| II | 20 |
| III | 10 |
| IV | 5 |

**Fig. A.3 Fracture classes with corresponding distance between planes of weakness**

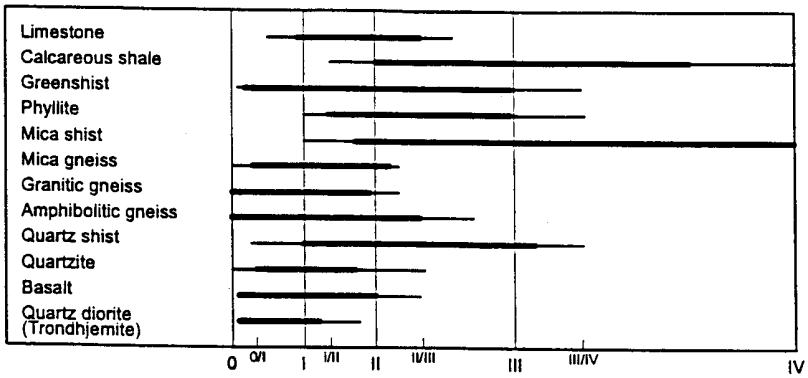



**Fig. A.4 Recorded degree of fracturing for various rock types**

d) FRACTURING FACTOR, Ks combines the effect of the fracturing class and the angle between tunnel axis and planes of weakness. See Fig.A.5. The factor Ks is used in a formula for calculation of penetration rate.

e) EQUIVALENT FRACTURING FACTOR expresses the rock mass properties as the Fracturing Factor Ks adjusted for DRI-value. See Fig.A.5. $K_{EQV} = Ks \times K_{DRI}$

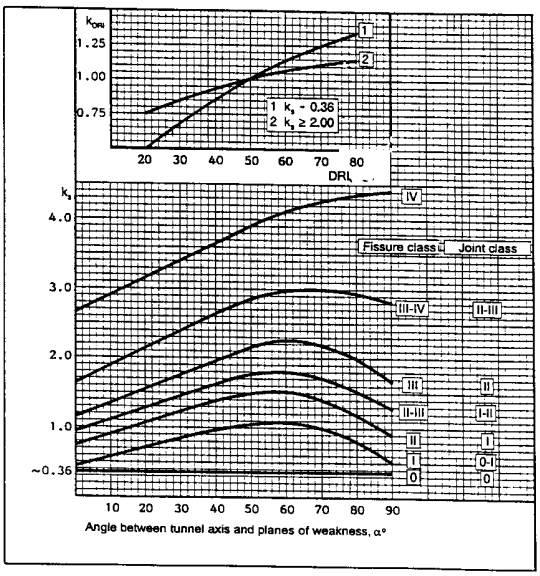



**Fig. A.5 Fracturing factor, Correction factor for DRI≠49**

**A-2.2 Machine Parameters**

1. BASIC CUTTER THRUST: ($M_B$) The gross thrust of the TBM divided by number of cutters, N. Thus, for practical calculating purpose the CUTTER THRUST in this model means the average thrust of all the cutters on the cutter head (kN/cutter). The friction between TBM and rock mass is disregarded. Recommended max. gross average thrust for TBMs with different diameters and cutter diameters are shown in Fig. A.6. For calculation of penetration the cutter diameter and cutter spacing must be taken into account.

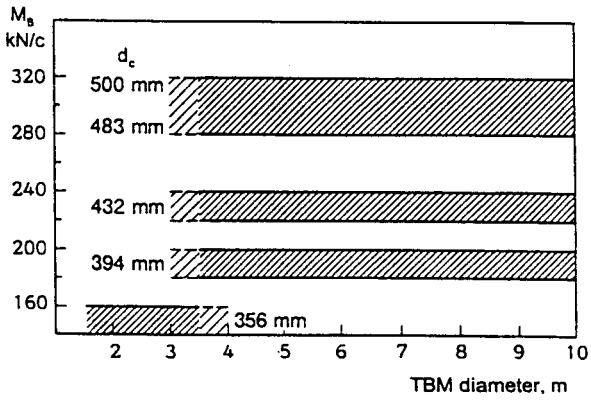



**Fig. A.6 Recommended max. gross average per disc**

2. CUTTER SPACING: The average distance between the cutter tracks on the face = Diameter of TBM /2N (N= number of cutters)._CUTTER SPACING is normally about 70 mm.

3. CUTTER HEAD R.P.M.: Revolutions per. Minute. Cutter head r.p.m. is inverse proportional to the cutter head diameter. This is in order to limit the rolling velocity of the peripheral cutters. Cutter head r.p.m. as function of TBM diameter is shown in Fig. A.7.

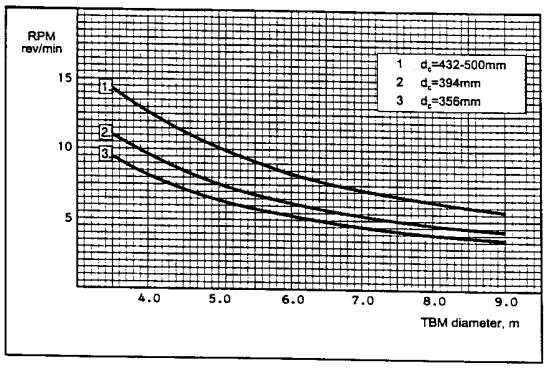



**Fig. A.7 Cutterhead r.p.m. as function of TBM-diameter**

4. INSTALLED POWER ON CUTTER HEAD: (kW) The rated output of the motors that are installed to give the cutter head its torque. The rolling resistance and thus the torque demand increases with increasing net penetration. The available torque may therefore be the limiting factor when the penetration is high and/or the TBM is boring in very fractured rock. See 3) (3) TORQUE - DEMAND below.

**A-2.3 Other Definitions**

1. BASIC PENETRATION RATE: Basic Penetration Rate (i) in mm/rev as a function of equivalent thrust and equivalent fracturing factor is shown in Fig. A.8. For cutter diameters and average cutter-spacing different from _=483 mm and 70 mm respectively the equivalent thrust is given by the formula: $M_{EQV} = M_x \times K_{DX} \times K_A$ (kN/cutter)

Fig. A.9 and Fig. A.10 give correction factor Kd for cutter diameters different from 483 mm and factor $K_A$ for cutter spacing.

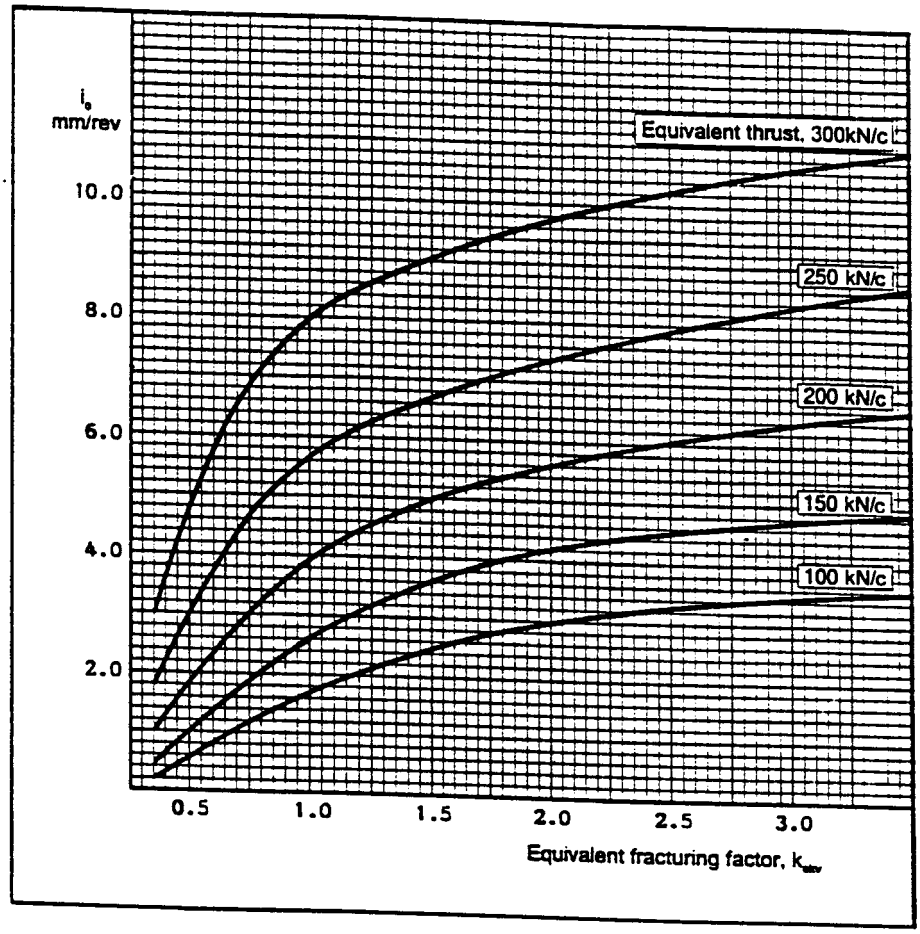



**Fig. A.8 Basic penetration for cutter diameter = 48.3 mm and cutter spacing = 70 mm**

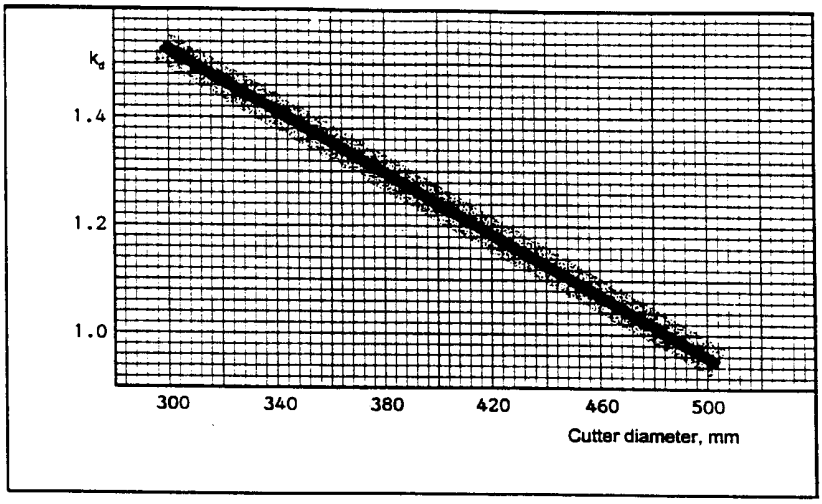



**Fig. A.9 Correction factor for cutter diameter≠483 mm**

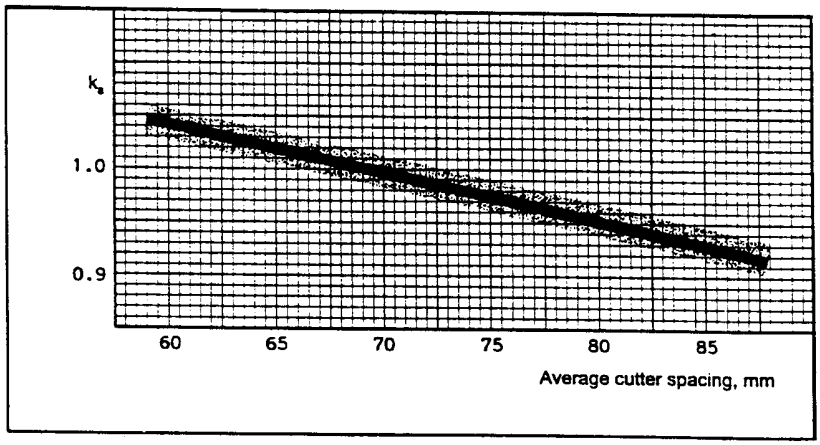



**Fig. A.10 Correction factor for average cutter spacing≠70 mm**

2. NET PENETRATION RATE: Net penetration rate (I) is a function of basic_penetration and cutter head r.p.m.

I = i x r.p.m. x (60/1000) (m/hr)

3. TORQUE DEMAND: For calculated high net penetration or when the rock is_very_fractured, one must check that the installed power on the cutterhead gives sufficient torque to rotate the cutterhead. If not the thrust must be reduced until the required torque is less than the installed capacity. Necessary torque is given by the following formula:

$T_{REQ}$. =0.59 x $r_{TBM}$ x $N_{TBM}$ x M x kc (kNm)
0.59 = Relative position of the average cutter on the cutterhead.
$R_{TBM}$ = cutterhead radius.
$N_{TBM}$ = number of cutters on the cutterhead.
M = Average thrust pr, cutter.
Kc = cutting coefficient (for rolling resistance) kc = Cc x $i^{0.5}$
Cc is a function of cutter diameter and is found from Fig. A.11.

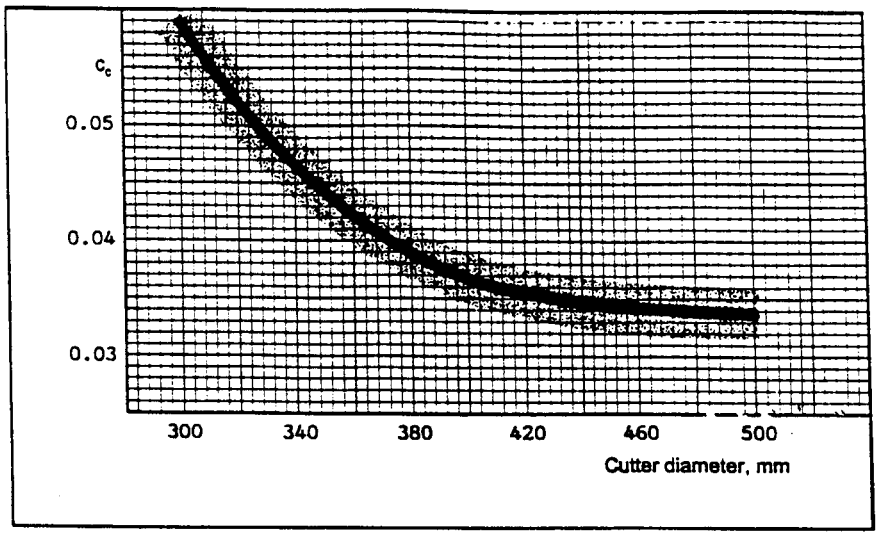



**Fig. A.11 Cutting constant Cc as a function of cutter diameter**

4. Other Limitations to Advance Rate
Besides limitations due to available torque, the system's muck removal capacity may be a limiting factor, particularly for large diameter machines. When boring through marked single joints or heavy fractured rock, it may be necessary to reduce the thrust due to too high machine vibrations and very high momentary cutter loads.

**A-2.4 Gross advance rate**
THE GROSS ADVANCE RATE is given in meters per week as an average for a longer period. Gross advance rate depends on net penetration rate, machine utilization and the number of working hours during the week. Machine utilization is net boring time in percent of the total tunneling time. Total tunneling time includes: Boring $T_B$ (Depends on net penetration rate)

- Regripping $T_T$ (Depends on stroke length, normally 1.5-2.0 m. As an average 4-5 minutes.)
- Cutter change and inspection Tc (Depends on cutter ring life and net penetration rate. Time needed for cutter change may vary from 30 to 60 minutes per cutter.)
- Maintenance and service of TBM, $T_{TBM}$, and back-up equipment $T_{BACK}$ (Time consumption for maintenance and repair depends on net penetration rate as indicated in Fig. A.12.)
- Miscellaneous $T_A$ (Miscellaneous include normal rock support in good rock conditions, waiting for transport, tracks or roadway, surveying or moving of laser, water, ventilation electric cable, cleaning, other things like travel, change of shift etc.) $T_A$ as hours per km is indicated in Fig. A.12.

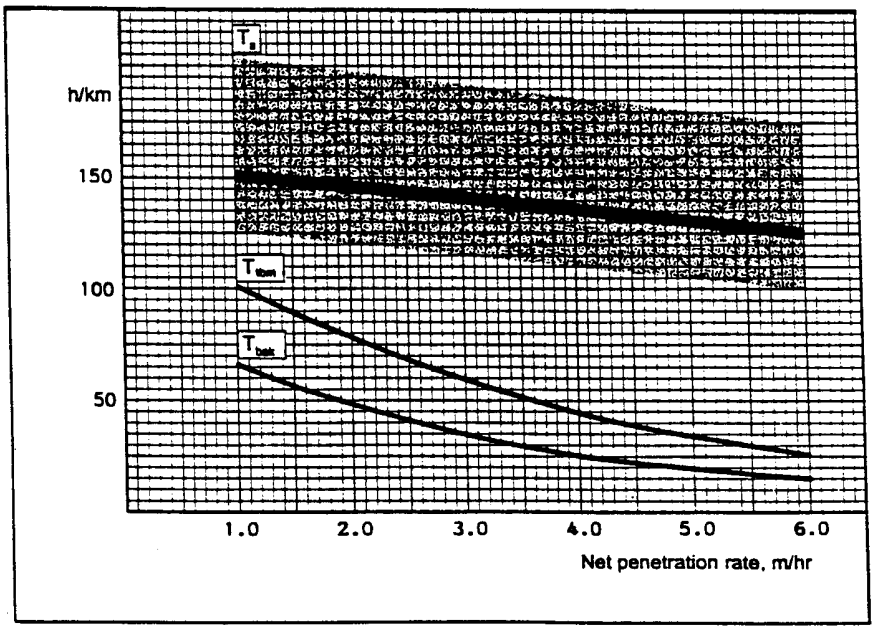



**Fig. A.12 Maintenance as function of net penetration rate**

**A-2.5 Additional Time Consumption**

Estimation of time consumption for a tunnel is based on weekly advance rate, estimated on the basis of net penetration rate and total utilization of the TBM. In addition, extra time must be added for

- assembly and disassembly of TBM and back-up equipment in the tunnel
- excavation of niches, branches, dump stations etc.
- rock support in zones of poor quality
- additional time for unexpected rock mass conditions
- permanent rock support and lining work
- downtime due to major machine breakdowns
- dismantling of tracks, ventilation, invert cleanup etc.

**Example of application**

Geometrical conditions:
Tunnel diameter: f = 4.5 m
Tunnel length: L= 3200 m

Geological conditions:
Type of rock: Mica Schist
Drilling Rate Index: DRI= 60
Degree of fracturing: St II
Angle between tunnel axis and planes of weakness: 45
Fracturing factor. ks = 1.40
Equivalent fracturing factor: $k_{EQV}$ = 1.40 x 1.10 =1.54

Machine parameters:
TBM diameter: f = 4.5 m
Cutter diameter: 483 mm
Gross thrust pr. cutter: Fig. A.6
290 kN/cutter
Cutterhead r.p.m.: Fig. A.7
11.1 rev./min.
Number of cutters: 32
Average cutter spacing: 70 mm
Installed power: 1720 kW

Net penetration rate:
Equivalent thrust: Fig. A.9 and Fig. A.10
$M_{EQV}$ = 290 x 1.00 x 0.975 = 283 kN/cutter
Basic penetration: Fig. A.8 i = 8.40 mm/rev
Net penetration:
8.40 x 11.1 x 60/1000 = 5.59 m/hour

Torque check:
Cutter constant: Fig. A.11

$$Cc = 0.034$$

Cutting coefficient:

$$kc = 0.034 \times 8.400.5 = 0.0985$$

Necessary torque:

$$TREQ = 0.59 \times 2.25 \times 32 \times 290 \times 0.0985 = 1213 \text{ kNm}$$

Necessary power:

$$PN = 1213 \times 2\pi \times 11.1/60 = 1410 \text{ kW}$$

**A-3 Cutter Consumption**

The cutter ring life depends mainly on the following factors:

1. Rock mass properties:
- CUTTER LIFE INDEX (CLI), see A-2, 1. (2)
- Content of abrasive minerals in the rock

2. Machine parameters:
- Cutter diameter
- Cutter type and quality
- Cutter head diameter and shape
- Cutter head rpm
- Number of cutters

The cutter ring life, in boring hours, is proportional to the Cutter Life Index. (CLI) Fig. A.13 shows the basic cutter ring life as a function of CLI and cutter diameter. Corrections must be made for varying cutterhead r.p.m. Also for TBM diameter as Center- and Gauge Cutters have a shorter lifetime than Face Cutters. (Fig. A.14). Corrections must also be made for number of cutters on TBM (Ntbm) deviating from normal (No). Finally correction must be made to quartz-content.(Fig. A.15)

Average life of cutter rings is thus given the following formulas:
Cutter ring life in h/c: $H_H = (H_0 \times k_{f\_} \times k_0 \times k_{RPM} \times k_N)/N_{TBM}$

Cutter ring life in m/c: $H_m = H_H \times I$ (I = net penetration rate)
Cutter ring life in $sm^3$: $Hs\ sm^3 = H_H \times I \times p \times d^2_{TBM}/4$

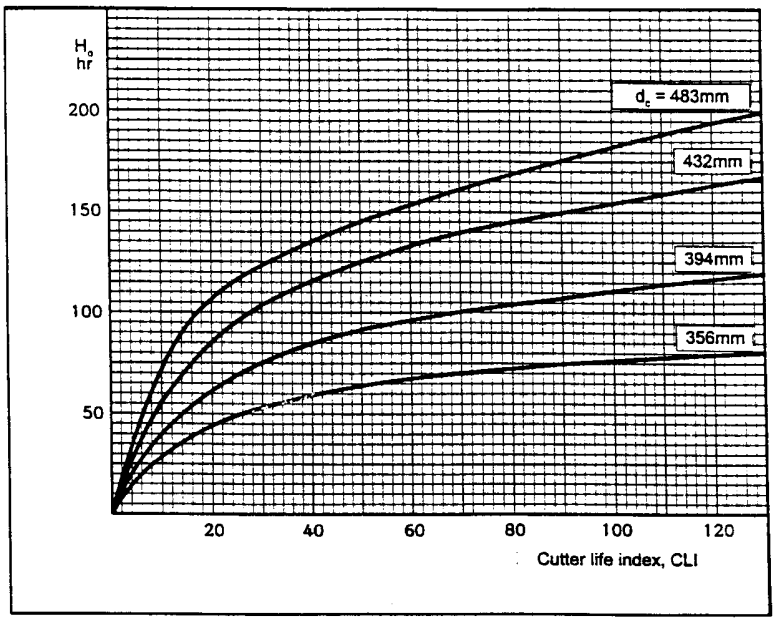



**Fig. A.13 Basic cutter ring life as function of CLI and cutter diameter**

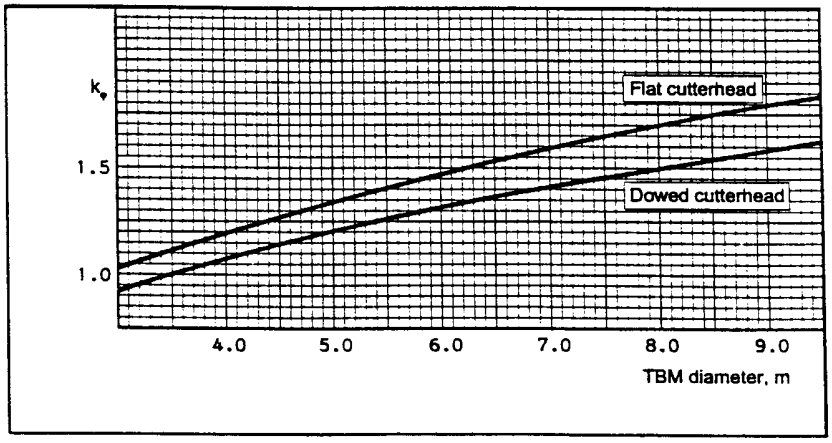



**Fig. A.14 Correction Factor for Cutting Ring Life**

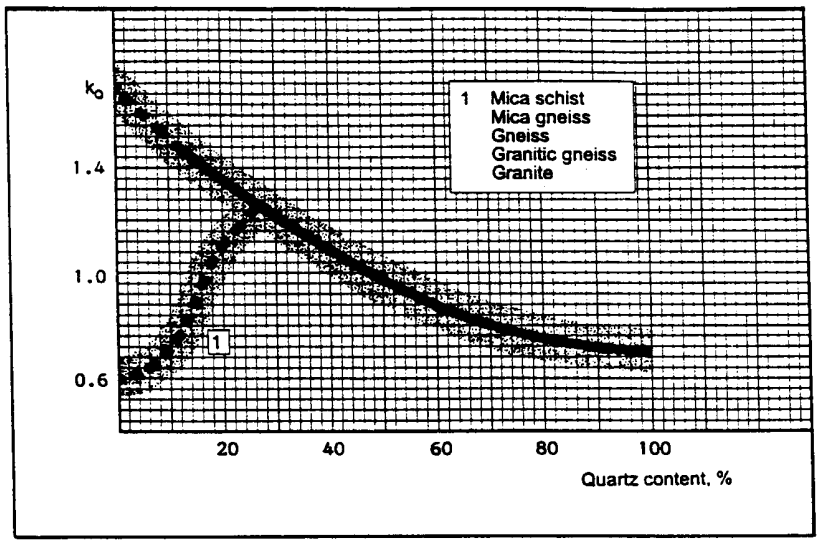



**Fig. A.15 Correction Factor for cutting ring vs. Quartz Content**

## A-4 Troubles and Countermeasures

### A-4.1 Causes for Trouble.

<<Trouble>> is caused by unforeseen incidents or conditions that may be difficult to tackle within estimated tunneling time. Trouble in hard rock boring come from:

- geological conditions
- reasons related to the TBM itself and/or from the rest of the machines and installation, - and/or trouble come as a consequence of lack of experience from similar works and general know-how in tunneling.

1. Geological Causes

a) Water Inflow is always a factor one shall have in mind. It counts for everything from occasional appearance of small amounts of water with no practical consequences, to total inundation with free flowing conditions, some times with material outwash and serious tunneling problems. If caught unaware, these problems are capable of completely disrupting tunneling activity and influencing the time schedules drastically. This is serious to conventional tunneling, - it may be even worse to TBM-tunneling with all the sophisticated electrical installations.

Water may come from groundwater, ores, leakage through the overburden from lakes, rivers etc. or even from underground lakes or from Artesian wells. Inflow of salt water may be damaging even in small amounts and calls for special precautions.

It creates a special atmosphere in the tunnel with damaging effect to the electrical equipment and rust and corrosion to the steel construction if not taken care of.

b) Boring in Hard Rock means normally boring in Sound, Solid Rock, and <<open>> TBMs are normally chosen. Nevertheless it is not unusual to meet Faulty Fractured Zones, Unconsolidated Weak Rock, Swelling Ground, Squeezing Ground and very often so called Mixed Faces which means that face consists partly of hard massive rock and partly of fractured rock. Even one single significant fracture may influence the drillability. Consequences to the boring may naturally vary from minor problems to the penetration rate to full stop with TBM stuck in the tunnel.

Swelling Ground very often comes from the influence of special rock materials as so called swelling clay which starts swelling when exposed to humidity. It may cause down-fall and dangerous conditions. Squeezing Ground is found in tunnels in soft rock with large overburdens, and consequently high rock pressure. Rock deformations may in extreme cases lead to total closing of the tunnel.

c) Even if TBM- technology and –know how is steadily improving and thus extending the frame as far as the geology and the geological parameters are concerned, there are still limits. The drillability is a function of a number of rock parameters, out of which fracturing and rock hardness are the most important. It is rare to get into rock which is so hard and so massive that boring is technically impossible with the most powerful TBMs on the market to day, but it may be a challenge to the economy.

If pre-investigations reveal occurrence of rock with the above properties it will be a matter of calculation to find out if the available TBM is able to do the job, and in case, -what will be the advance rate and what will be the cost. The above calculation model should be used carefully in this case since it is based on experiences from rock with not extreme properties, but it will normally be good enough. If the rock shows up unexpected parameters one might be in trouble if the TBM is too weak, and/or the cutters have insufficient quality.

d) High Temperature Ground is found in different parts of the world as for instance in the Alps, in tropical areas and/or when the tunnel goes with extreme overburden as in mines. The temperature is seldom a real obstacle to the boring itself as long as oil is chosen accordingly and cooling water for motors and cutters are available in sufficient quantities, but rather a challenge to the crew.

e) Combustible gases like methane and dust with high content of coal are dangerous and must be taken care of properly.

2. Machine Related Troubles

As is understood from the above a good result with respect to advance rates and tunnel-meter-costs are to a very great extent dependent on the TBM and the supplementary equipment. The geology related conditions in a tunnel are fixed as such. The result of the tunneling with respect to advance rate and tunnel-meter-cost is therefore in fact a question of doing the right choice of TBM and equipment and to be prepared for conditions as they appear.

The right choice of TBM and supplementary equipment is not only a question of looking at machine specifications. It is also a question to which extent it is possible to utilize the same machine parameters. It is an experience from hard rock boring that the TBMs have more power than can actually be utilized because components like for instance cutters in practice are not strong enough.

Breakdowns due to Main Bearing failure or due to failure on other important and expensive components or parts are naturally disastrous to time schedule and costs. (To change a main bearing may take from four to six weeks, provided the bearing is available.) Downtime caused by unskilled operation of the machinery, bad maintenance and repair, waiting for supply of spares, bad ventilation, cut in power supply, waiting for muck-transport, cutter change and cutter inspection should always be encountered and as far as possible be avoided or minimized.

**A-4.2 Countermeasures**

1. For trouble caused by water inflow there are basically two ways to go.

- To stop the water before it gets into the tunnel by Grouting Ahead of the Face for which purpose boring equipment has to be installed. The equipment should be able to make a 360°funnel with at least 25 m long holes for grouting.
- To take care of the water when it is in the tunnel by Increased Drainage Capacity. What is the best is depending on the amount of water and where it comes from. If the inflow effects change in ground water level and/or pressure grouting may be required. Large inflow of water may cause damage to the machinery, and to the electrical installation in particular, and protection of exposed components may be required.

2. Countermeasures to unusual and unsound ground depends on the actual case
Rock Bolting, Fiber-reinforced Shotcrete alone or together with Rock Bolts, Grouting or in situ Casting with Concrete or may be necessary.
The real trouble comes if the equipment is not built for installation of necessary equipment to carry out the rock support in an efficient way.
Fractures are discontinuities in the rock mass. The fractures are described by thickness, length, distance between the fractures, roughness in planes of weakness, sort of materials found in the fractures, if they are results of bedding or foliation, and strike and dip if there is a definable pattern. Fractures in the rock mass are an advantage with respect to advance rates as long as rock support is not required.
The above factors are strongly into the picture in the so called Q-method which is a method to define the rock mass quality with respect to stability and the need for rock support. Various classes of rock mass quality which go from exceptionally good to exceptionally poor will require from no support at all, spot bolting, systematic bolting, shotcrete etc. to cast concrete lining.

3. Too Hard Rock is normally a cutter-problem. The cutters are spoiling and/or heavily worn and the penetration rate is reduced. Due to frequent cutter inspections and -changes the utility time goes down and consequently also the Gross Advance Rate.
Great efforts are constantly made to increase the cutter quality. Much is achieved by improving the steel quality in the rings and by increasing the size of the cutters and thus be able to use bigger and better bearings.
To change the size of cutters is theoretical, but normally not a practical solution to meet a section of too hard rock in a tunnel.
If the <<too hard rock>> problem seems to be permanent it is a possibility to call for a special study of the rock in order to improve the cutter-result and/or to call for competing suppliers of cutters.
Cutters with tungsten-carbide inserts are expensive, but may be the solution for a short period. Tungsten-carbide inserted cutters can also be used together with normal cutters in positions that are most exposed, for instance as gauge cutters.

4. High Temperatures in the tunnel
In tropical areas the outdoor temperature may also be very high, at least during daytime. Cooling of the ventilation air will therefore be a necessity in such areas. Together with the cooling effect from the evaporation of the flushing water it is absolutely possible to achieve livable temperatures.

5. Combustible Gases
The TBM itself and supplementary machinery and all electrical installation must be insulated to prevent any explosion to come from sparkles or heating. Gas Detection instruments must be installed.
In dimensioning of the ventilation system the occurrence of gases and dust must be taken into consideration.
In countries where the above are frequent occurrences there are normally very strict regulations with regards to what to do to prevent explosion and also what to do if the accident should happen.
Dust with quartz appears frequently in connection with hard rock boring. It is not combustible, but a serious hazard to the health if breathed for a long period. It is partly a ventilation matter to remove the dust from the working area, and partly.

**Germany, Switzerland and Austria**

Tunnelvortriebsmaschinen
Tunnel Boring Machines

Empfehlungen zur Auswahl und Bewertung von Tunnelvortriebsmaschinen

# Recommendations

# for

# Selecting and Evaluating Tunnel Boring machines

DAUB

Deutscher Ausschuss für unterirdisches Bauen (DAUB)
Österreichische Gesellschaft für Geomechanik (ÖGG) und
Arbeitsgruppe Tunnelbau der Forschungsgesellschaft für
das Verkehrs- und Strass enwesen
FGU Fachgruppe für Untertagbau Schweizerischer lngenieur-
und Architekten-Verein

## 1. Purpose of the recommendations

The developments in mined tunneling are characterized by an increased trend towards fully mechanized tunneling with appropriate tunneling machines (TBM) in solid rock and soft ground. The creation of special methods such as face supporting with fluid or slurry as well as the successful utilization of cutter discs for removing rock-like intrusions and boulders have led to a considerable expansion of the field of application and to an increase in the economy of these tunneling systems.

The increasing application of tunneling machines and the related continuous improvement of the various extraction techniques had led to types of machines, which have the capacity to penetrate extremely heterogeneous subsoil, that is respectively a mixture of soft ground and solid rock. The clear distinction between tunnel boring machines (TBM) for solid rock and shield machines (SM) for soft ground, which resulted from their conceptional background and the special engineering and extraction technology, has lost its original significance. Past developments and the progress made in practice have produced tunneling machines, in which the typical features of both techniques have been integrated in a single unit. In this way, the possibility has been created to make available tunneling machines suitable for the entire geotechnical spectrum.

The anticipated geotechnical conditions in conjunction with the course of the route and gradient represent the decisive prerequisites for selecting the tunneling method. By comparison of the cross-section needed for the purpose of the tunnel, its length and the geotechnical conditions with the available technology, the most suitable tunneling machine can be devised. These recommendations apply to inter-relationships, which exist between the geotechnical circumstances and process and engineering techniques.

When selecting tunneling machines, the environmental compatibility of the tunneling methods must also be taken into consideration.

These recommendations should also be seen as an additional aid, designed to serve the engineer in arriving at a decision. A project-related analysis is, however, essential and represents the main basis for the approach. These recommendations do not apply, or only to a certain extent for micro tunneling.

## 2. Geotechnics

The knowledge of the geotechnical conditions is the most important principle for the planning and execution of a tunneling project. The evaluation of general and special maps leads to initial recognition about the geological and hydrogeological conditions and provide pointers for further investigatory measures. By means of suitable preliminary explorations, the nature and features of the subsoil that must be penetrated during the construction of a tunnel can be described. The accuracy of this description depends on the type and extent of these pre-investigations as well as their validity. Extremely variable geological conditions call for more intensive of preliminary surveys.

Conditions which restrict the pre-investigations lead to a limited validity of a geotechnical report. This must be taken into account when assessing the projected geotechnical conditions. The aim of the geotechnical survey must be to present the geological and hydrogeological conditions required for the tunneling project as comprehensively and lucidly as possible.

The subsoil that has to be penetrated is, by and large, examined by means of:

_ investigatory boreholes and the obtaining of bore samples and cores
_ exploration and sample-taking on the surface
_ dynamic penetration tests, pressure probes
_ mechanical borehole examinations, e.g. borehole expansion tests, pressiometer
_ geophysical investigation methods
_ pump and water injection tests
_ exploratory tunnels

Through these investigations and, above all, through the samples that were taken, characteristic values are obtained or derived through further suitable investigations and corresponding evaluations.

The more comprehensively the preliminary investigations are carried out and the more valid they are the better the basis for selecting the tunneling method and the tunneling

machines.
The essential geotechnical parameters are listed in the following:

solid rock
- compressive strength (rock strength)
- tensile strength, cleavage strength
- shearing strength
- break and bedding planes
- degree of decomposition, degree of weathering
- fault zones
- mineralogy/petrography
- proportions of abrasive minerals
- wearing hardness/hardness
- water-bearing and water pressure (under-ground water)
- chemical analysis of the water

soft ground
- grain distribution curves
- angle of friction
- cohesion
- deposit thickness
- compressive strength
- shearing strength
- pore volume
- plasticity
- swelling behavior
- permeability
- natural and artificial intrusions and faults
- water-bearing and water pressure (ground water)
- chemical analysis of the water

special features
- primary stress state
- rock burst
- fault zones
- weakening due to leaching processes
- heaving/swelling rock
- subsidence and subsidence chimneys
- karst manifestations
- gases
- rock temperature
- seismic action

More detailed information relating to investigating the subsoil is contained in DIN 4020-Geotechnical Investigations for Construction Purposes. Further pointers are contained in the “Recommendations for Tunneling - Chapter 3: Geotechnical Investigations” , published by the DGGT.
From the cited geotechnical characteristic values and an overall appraisal of the geological and hydrogeological conditions of the subsoil, generally speaking, the following extremely important technical data can be obtained:
- ease of break-out of the subsoil
- stability of the subsoil
- stability of the face
- measures for supporting the face
- nature and extent of the supporting measures
- time lag between breaking-out and securing the subsoil
- deformation behavior of the subsoil
- influence of underground and/or groundwater
- abrasiveness of the subsoil
- stickiness of the excavated soil
- separability of the excavated soil (when using a supporting fluid)
- suitability for reutilization of the excavated soil

Factors, which influence the environment, must also be observed, such as e.g.:
- surface settlements
- interference with and changes to the groundwater conditions
- suitability of the excavated material for landfill
- contamination of the subsoil and groundwater
- health-jeopardizing influences

On the basis of the listed geotechnical characteristic values and constructional data including the environmentally relevant factors, it is possible the select the construction method and to divide the tunnel over its route into tunneling classes, which closely define the tunneling method, identify the performances to be applied per tunneling class and describe the degree of difficulty. Whereas the selection of the construction method is the prerequisite for allocation into tunneling classes (laid down by the client), the choice of the machine should be left open as far as possible and left up to the responsible contractor (choice of the construction company).

## 3. Construction methods for mined tunnels

### 3.1. Survey

Different construction methods are available for executing a tunnel by mining. They can be split up into the groups-universal headings,

mechanical headings (tunneling machines) and micro-tunnel headings. In this connection, those methods for which the extraction resp, the cutting phase is decisive are allocated to solid rock. In the case of soft ground, on the other hand, the supporting and/or securing of the subsoil is accorded priority(Fig.1).

In conjunction with the special demands placed on a tunnel and taking environmental factors into consideration, a general assessment of the tunneling methods with respect to their suitability in individual cases can be carried out.

The remainder of these recommendations deal exclusively with the process technical features to be considered when using tunneling machines, and essential selection and evaluation criteria for the corresponding geotechnical fields of application.

### 3.2. Explanation of the Construction Methods

The “shotcreting construction method” is an independent method, whose possibilities or rather principles of supporting the cavity combine with various tunneling methods.

Under the term “tunneling with systematically advancing support”, we understand tunneling method which embrace the systematic and thus not simply the partial application of suitable supporting means, which are applied for the advance stabilization of the face area. These include: the forepoling method, methods with pipe screens, screens comprising injection lances, screens with freezing lances, screens comprising horizontal HPG columns.

Large-area freezing or grouting is methods designed to improve the subsoil, which then facilitate the application of a construction method such as shotcreting. The tunneling classification then relates to the improved subsoil conditions.

Whereas the form and size of the cross-section in the case of the “universal headings” can be as desired and in fact, can alter within a length of tunnel, this flexibility does not exist when tunneling machines are applied.

Generally speaking, tunneling machines in accordance with their function are circular and thus possess a given shape. This restricts their application should the utilization of a circular cross-section not be purposeful or necessary and therefore, increases the costs. Tunneling machines have also been developed which do not drive circular cross-sections.

Tunneling machines are, by and large, geared to their diameter. This applies, first and foremost, to shield machines. In the case of tunneling machines for solid rock, a certain variation of the diameter is possible if a shield body is not required.

Recent developments allow shield machines to be modified for different diameter ranges in a fairly straightforward fashion. In addition, shield machines have been devised which are fitted with two or three overlapping cutting wheels staggered one behind the other. In this way, cross-sections which are not circular can be driven. The installations in question are special forms of shield machines for special purposes.

Apart from these machines being geared to a circular form and diameter, the length of the sections to be driven represents a further important feature especially for the economic application of a tunneling machine.

The profile accuracy of the cavity cross-section is particularly high when tunnel machines are used. During heading, care should be taken to ensure that the predetermined driving tolerances are adhered to. Unscheduled deviations from the axis can,

in contrast to universal headings, by and large only be corrected with considerable difficulty.

| Bautechnische Merkmale eines Tunnels<br>Technical features of tunnel<br>Tunnel Bauverfahren<br>Tunneling method | Querschnittsgr §e a tunnel<br>Size of cross-section<br>Umwelt<br>Environment | | Merkmale des Tunnels/Features of tunnel<br>Querschnittsfrom<br>From of cross-section | | Tunnell nge<br>Length of tunnel | | Sicherung Ausbau<br>Lining | | geford. Profilgenauigkeit<br>Required profile accuracy | Grund(G)-Schicht(S)-Wasser<br>Groundwater(G)<br>Underground water(U) | | Umwelt/Environment<br>L rmersch tterungen<br>Noise vibrations | Gas-Staub-Entwickl.<br>Gas dust development | Schutz d.Personals<br>Protection of labour force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | gleichbleibend<br>uniform | ver nderlich<br>changing | gleichbleibend<br>uniform | ver nderlich<br>changing | kurz<br>short | lang<br>long | zweischaling<br>2-shells | einschaling<br>1-shell | gro§<br>high | ohne Zusatzma§n.<br>without extra measures | mit Zusatzma§n.<br>with extra measures | | | |
| Universeller Vortrieb<br>Universal excavation<br>Festgestein/Solid rock<br>Sprengvortrieb<br>Drill+Blast | X | X | X | X | X | X | X | X | 0 | SX | GX | q | q | s |
| Teilschnittmasch.Vortrieb<br>Roadheader | X | X | X | X | X | X | X | X | X | SX | GX | s | q | s |
| Spritzbetonbauw./N T<br>Shotcreting method/NATM | X | X | X | X | X | X | X | X | X | SX | GX | s | s | s |
| Messervortrieb<br>Forepoling | X | 0 | X | 0 | _ | X | X | X | X | 0 | GX | s | s | q |
| Vortrieb mit systematisch voreilender Sicherung<br>Heading with systematic advance support | X | X | X | X | X | X | X | 0 | 0 | 0 | GX | s | s | q |
| Lockergestein/Soft ground<br>Maschineller Vortrieb<br>Mechanical heading<br>Festgestein/Solid rock<br>Tunnelbohrmasch.-Vortr.<br>TBM driving | X | 0 | Kreis<br>circle | 0 | _ | X | X | X | X | SX | GX | s | s | s |
| Schildmasch.-Vortrieb<br>Shield machine driving | X | 0 | Kreis<br>circle | 0 | _ | X | X | X | X | X | X | s | s | q |
| Rohrvortrieb<br>Pipe jacking | X | 0 | Kreis<br>circle | 0 | X | X | _ | X | X | X | X | s | s | q |
| Vorpreßverfahren<br>Jacking method | X | 0 | X | 0 | X | X | 0 | X | X | X | X | s | s | q |
| Lockergestein/Soft ground<br>Microtunnelvortrieb<br>Micro-tunnelling | X | 0 | Kreis<br>circle | 0 | X | 0 | 0 | X | X | X | _ | s | s | q |

Eignung der Bauverfahren: X gut geeignet 0 nicht geeignet - nicht blich
Suitability of the construction methods: X well suited 0 not suited - not usual

Auswirkungen: q gro§ s geringer
Effects: q high s slight

1 Bauverfahren f r Tunnel in geschlossener Bauweise

Construction methods for mined tunnels

## 4. Tunneling machines TM

Tunneling machines (TM) either head the entire tunnel cross-section with a cutter head or cutting wheel full-face or in part segments by means of suitable extraction equipment.
During the excavation phase, the machine is moved forward either continuously or stroke-by-stroke.
A difference is drawn between tunnel boring machines TBM and shield machines SM.
Tunnel boring machines remove the rock at the face, with the support generally being installed afterwards, following up at a distance.
The machines are held in place during the excavation phase by means of grippers pressed laterally against the tunnel walls.
Shield machines generally support the subsoil that is being penetrated and the face by direct means during the excavation phase. The shield is advanced during excavation by jacking against the completed lining.
A systematic compilation of tunneling machines is provided in Fig. 2, which was based on the classification contained in this section.

### 4.1. Tunnel Boring Machines (TBM)

A distinction is drawn between tunnel boring machines without shield body and those with one(Fig.3).

#### 4.1.1. Tunnel boring machines without shields

Tunnel boring machines are employed in solid rock with medium to high face stability. They do not possess a completely closed shield body. Economic application can be strongly influenced and restricted through high wear costs of the cutting tools.
Generally speaking, only a circular cross-section can be broken out by these machines. A rotating cutter head, which is equipped with roller bits (discs), possibly with tungsten carbide bits, is pressed against the face and removes the rock through its notch effect. In order to provide the contact pressure at the cutter head, the machine is held radially by means of hydraulically moveable grippers. Extraction is gentle on the rock and results in an accurate profile.
The machine occupies a large part of the cross-section. Systematic supporting is normally carried out behind the machine (10 to 15 m and more behind the face). In less stable and particularly in friable rock, it must be ensured that the placing of support arches, lagging plates and anchors, in certain cases, even shotcrete, is possible directly behind the cutter head. It should be possible to carry out preliminary investigations and rock strengthening from the machine.
In the case of bore diameters of > 10 m, so-called expansion machines can also be applied. Starting from a continuous pilot tunnel, the profile is expanded in one or two working phases using correspondingly designed cutter heads.
During excavation at the face, small pieces of rock, accompanied by an amount of dust, are produced. As a consequence, devices for restricting the dust development and dedusting are necessary for these machines:
_ wetting with water at the cutter head
_ dust shield behind the cutter head
_ dust removal with dedusting on the back-up
The material transfer and supplies for the machine call for what, in some cases, can be very long back-up facilities.

#### 4.1.2. Tunnel boring machines with shields TBM-S

In solid rock with low stability or friable rock, tunnel boring machines are equipped with a closed shield body. In this case, it is advisable to carry out supporting within the protection of the shield tail skin (segments, pipes, etc.), against which the machine supports itself. The gripper system is then no longer needed.
Otherwise, the explanations already provided for tunnel boring machines also apply here.

### 4.2. Shield Machines SM

A distinction is drawn between Shield Machines with full-face extraction (cutter head) SM-V and shield machines with part extraction (milling boom, excavator)SM-T.
Shield machines are employed in loose soils with or without groundwater, in the case of which generally the subsoil surrounding the cavity and the face have to be supported. The characteristic feature of these machines is the type of face support (Fig. 3).

#### 4.2.1. Shield Machines with full-face excavation SM-V

4.2.1.1 SM-V1 Face without support
If the face is stable, e.g. in clayey soils, so-called open shields can be employed. The

cutter head equipped with tools removes the soil; the loosened soil is carried away by means of conveyor belts or scraper chains.

4.2.1.2 SM-V2 Face with mechanical support

Supporting of the face is carried out via an almost closed cutter head. The plates arranged between the spokes are elastically supported; they are pressed up against the face. Extraction is executed full-face via the cutter head equipped with tools; the loosened soil passes through slits, whose opening width is variable, between the spokes and the supporting plates, into the working chamber.

The material is removed via conveyor belts, scraper chains or by hydraulic means.

Scraper disc shields possess a high degree of mechanization. Through the constant full-face contact of the cutting wheel with the face, high torque is required.

In the case of types of soil, which tend to flow, supporting in the vicinity of the slits is incomplete, which can lead to settlements. It is extremely difficult to remove obstacles.

4.2.1.3 SM-V3 Face with compressed air application

If groundwater is present, it has to be held back in the case of machines belonging to types SM-V1 and SM-V2 unless it can be lowered. Either the whole tunnel is subjected to compressed air or the machine is provided with a bulkhead so that only the working chamber is under pressure. Airlocks are essential in both cases.

Particular attention must be paid to the compressed air leakage via the shield tail seal and the lining.

The support which is realized by the application of compressed air acts directly. Through suitable measures, it is also possible to avoid an accumulation of compressed air, e.g. when sand lenses with water under pressure occur.

4.2.1.4 SM-V4 with fluid support

In the case of these machines, the face is supported by a fluid that is under pressure. Depending on the permeability of the subsoil that is present, effective fluids must be used for supporting, whose density and/or viscosity can be varied. Bentonite suspension has proved to be particularly effective.

The working chamber is closed to the tunnel by a bulkhead. The pressure needed for supporting the face can be regulated with great precision either by means of an air cushion or by controlling the speed of the delivery and feed pumps. Supporting pressure calculations are required.

The soil is removed full-face by means of a cutter head equipped with tools. Hydraulic conveyance with subsequent separation is essential.

If it is necessary to enter the working chamber (tool change, repair work, removing obstacles), the fluid must be replaced by compressed air. The supporting fluid (bentonite, polymer) then forms a slightly air-permeable membrane at the face, whose life span is restricted. This membrane facilitates the supporting of the face through compressed air and should be renewed if need be.

When the machine is at a standstill, mechanical supporting of the face is possible by means of segments, which can be shut, in the cutting wheel or through plates that can be extended from the rear. These solutions are advisable on account of the limited duration of the membrane.

Stones or banks of rock can be reduced to a size convenient for conveyance through discs on the cutting wheel and/or stone crushers in the working chamber.

4.2.1.5 SM-V5 Earth pressure balance face

The face is supported by earth slurry, which is formed from the material that has been removed. The shield's working chamber is closed to the tunnel by means of a bulkhead. More or less closed cutting wheels equipped with tools extract the soil. An extraction screw under pressure carries the soil out of the working area.

The pressure is checked by loadcells, which are distributed over the front side of the bulkhead. Mixing vanes on the rear of the cutting wheel and the bulkhead are intended to ensure that the soil obtains a suitable consistency.

The supporting pressure is controlled through the thrust of the rams and the speed of the conveyor screw. The soil material in the screw or additional mechanical installations must ensure a seal in the extraction equipment, as otherwise the supporting pressure in the working chamber cannot be retained due to the uncontrolled escape of water or soil.

Complete supporting of the face, especially in the upper zone, only then succeeds providing the supporting medium soil- can be transformed into a soft to stiff-plastic mass. In this connection, the percentile share of the fine grain smaller than 0.6 mm has a considerable influence.
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. In such cases, the environmental compatibility of the material for landfill purposes must be taken into consideration.

### 4.2.2. Shield machines with partial axe excavation SM-T

4.2.2.1 SM-T1 Face without support
If the face is perpendicular or stable with a steep slope, it is possible to use this type of shield. The machine merely comprises the shield body and the extraction tool (excavator, milling boom or scarifier). The soil is removed via conveyor belts or scraper conveyors.

4.2.2.2 SM-T2 Face with partial support
The face can be supported by platforms and/or breasting plates.
In the case of platform shields, the front section is divided up by one or a number of platforms on which slope form, which support the face. The soil is removed manually or by mechanical means.
Platform shields possess a low degree of mechanization. Disadvantageous is the danger of major settlements resulting from un-controlled face support.

- Tunnelvortriebs-maschinen TVM *Tunnelling Machines*
  - Tunnelbohrmaschinen TBM *Tunnel Boring Machines*
    - TBM ohne schild TBM *TBM without Shield* — TBM
    - TBM mit Schild TBM-S *TBM with Shield* — TBM-S
  - Schildmaschinen SM *Shielded Machines*
    - Schildmaschinen mit Vollschnittabbau SM-V *Shield Machines with full-face*
      - Ortsbrust ohne Stützung *Face without support* — SM-V1
      - Ortsbrusut mit mechanischer Stützung *Face with mechanical support* — SM-V2
      - Ortsbrust mit Druckluft-Beaufschlagung *Face with compressed air application* — SM-V3
      - Ortsbrust mit Flüssig-Keitsstützung *Face with fluid support* — SM-V4
      - Ortsbrust mit Erddruck-Stützung *Face with earth pressure balance support* — SM-V5
    - Schildmaschinen mit teiltlächigem Abbau SM-T *Shield Machines with part heading*
      - Ortsbrust ohne Stützung *Face without support* — SM-T1
      - Ortsbrust mit Teilstützung *Face with purtial support* — SM-T2
      - Ortsbrust mit Druckluft-Beaufschlagung *Face with compressed air application* — SM-T3
      - Ortsbrust mit Flüssigkeits-Stützung *Face with fluid support* — SM-T4

Sonderformen und Kombinationen siehe Textteil / *Special forms and combinations are provided in the text*

**2 Übersicht Tunnelvortriebsmaschinen(TVM).Sonderformen und Kombinationen sind in Text beschrieben**
**Survey of tunnelling machines(TM). Special forms and combinations are described in the article**

In the case of shield machines with breasting plates, the face is supported through breasting plates, which are mounted on hydraulic cylinders. The breasting plates are partially retracted for removing the soil manually or by mechanical means.
A combination of breasting plates and platforms is possible. If supporting of the roof area is sufficient, extensible breasting plates can be used there.

4.2.2.3 SM-T3 Face with compressed air application
If groundwater is present, this must be held in check in the case of machines of the type SM-T1 and SM-T2. The tunnel is then set under compressed air or the machines are provided with a bulkhead. The material is removed hydraulically or dry via a material lock.

4.2.2.4 SM-T4 Face with fluid support
In the case of this shield type, the working chamber is also closed by a bulkhead. It is filled with a fluid, whose pressure is regulated via the speed of the delivery and feed pumps. The soil is removed via a cutter, which, in similar fashion to suction dredgers, also takes away the fluid-soil mixture.

## 4.3. Adaptable dual purpose shield machines

A large number of tunnels pass through strongly varying subsoil conditions, which can range from rock to loosely bedded soil. As a result, tunneling methods have to be geared to the geotechnical prerequisites and shield machines, which are correspondingly adaptable, employed.
a) Shield machines, in the case of which the extraction method can be changed without modification:
_ earth pressure balance shield SM-V5 _ compressed air shield SM-V3
_ fluid shield SM-V4 _ compressed air shield SM-V3
b) Shield machines, in the case of which the extraction method can be changed through modification. Findings are available with the following combinations:
_ fluid shield SM-V4 _ shield without support SM-V1
_ fluid shield SM-V4 _ earth pressure balance shield SM-V5
_ earth pressure balance shield SM-V5 _ shield without support SM-V1
_ fluid shield SM-V4_ TBM-S

## 4.4. Special forms

### 4.4.1. Finger shields

The shield body is split up into fingers, which can be extended individually. The soil is removed via roadheaders, cutting wheels or excavators. An advantage of finger shields is that they deviate from the circular form and e.g. can also excavate horse-shoe profiles. In the latter case, the base is usually open. The forepoling is also used.

### 4.4.2. Shields with multi-circular cross-sections

These shield types represent the latest state of development for fully mechanized headings. In the case of these machines, the staggered cutting wheels are designed to overlap.

### 4.4.3. Articulated shields

Practically all-existing shields can be provided with an articulating joint. If the ratio of the shield body length to the shield diameter exceeds the value l, generally a joint is incorporated in order to improve the steability. The arrangement can also be necessary if extremely tight curve radii are to be driven.

### 4.4.4. Cowl shield

The shield cutting edge is tapered to approximate the natural angle of slope of the soil. When tunneling under compressed air, this means that safety against blowout is enhanced.

### 4.4.5. Displacement shield

Only suitable for soft-plastic soils. The machine has no extraction tool. It is pressed into the soil, which results in this being partially displaced and partially removed through an aperture in the bulkhead.

### 4.4.6. Telescopic Shields

In order to arrive at higher rates of advance, telescopic shields have been designed.
Essentially, the objective is to install the lining during the removal of the soil.

## 4.5. Supporting and lining

As far as the process techniques referred to in these recommendations are concerned, the tunneling machine together with the support and/or lining represent a single unit in terms of process technology.

### 4.5.1. Tunnel boring machines TBM

Due to the excavation procedure which is gentle on the rock and the advantageous circular form, the extent of the necessary supporting measures is usually less than for example for drill + blast. In less stable rock, the exposed areas have to be supported quickly in order to restrict any disaggregation of the rock and thus retain the rock quality as far as possible.

Should breaks occur in the vicinity of the cutter head, the extent of the necessary supporting measures can increase considerably.

4.5.1.1 Rock bolts

Rock bolts are generally arranged radially in the cross-sectional profile of the tunnel, a rock matrix-oriented set-up enhance the effect of the shear dowels. Installed locally, they prevent the flaking or detaching of rock plates, arranged systematically, they prevent loosening of the exposed tunnel sidewall. Rock bolts are especially suitable for subsequently increasing the lining strength, as they can still be installed at a later stage.

The anchors are installed in the vicinity of the working platform behind the machine or in special cases, directly behind the cutter head.

4.5.1.2 Shotcrete

Shotcrete serves to seal the exposed rock surface either partially or completely (thickness 3 to 5 cm) or provide it with a supporting layer (thickness 10 to 25 cm, in exceptional cases, even more). In order to enhance the loadbearing capacity of the shotcrete lining, it is provided with a single-layer (on The rock side) or two-layers (rock and exposed side) of mesh reinforcement. Alternatively, steel fibber shotcrete can be applied. The shotcrete is generally installed in the vicinity of the working platform behind the machine.

4.5.1.3 Support arches

Support arches serve to effectively support the rock directly after the excavation and to protect the working area. As a consequence, they are, first and foremost, applied in friable and unstable, squeezing rock. Rolled steel sections or lattice girders are used as support arches. Support arches are normally installed directly behind the cutter head in sections in the roof zone or as a closed ring.

### 4.5.2. Tunnel boring machines with shield TBM-S and shield machines SM

In the case of tunnel boring machines with shield or shield machines, the support is installed within the protection of the shield tail. This usually consists of prefabricated segments.

Apart from supporting the surrounding subsoil, it serves in the case of most machines of this type as the abutment for the thrust rams.

The load transfer between the lining and the subsoil is created by grouting the annular void at the shield tail as continuously as possible. This does not apply to lining systems, which are directly pressed against the subsoil.

In general, it must be ascertained whether a lining comprising an inner shell made of reinforced or un-reinforced concrete is needed. Segments and pipes are normally utilised as single skin linings.

4.5.2.1 Concrete and reinforced concrete segments

The customary precast elements are concrete or reinforced concrete segments. Alone the stresses caused by transport and installation makes it necessary for the segments to be reinforced. Segments with steel fibber reinforcement have also been designed in order to strengthen the edges and corners, which cannot be reinforced by rods, through steel fibbers.

4.5.2.2 Cast steel and steel segments

Through the development of casting technology, segments today can be supplied made of cast steel, e.g. with the material designation GGG 50, with low overall thickness, sufficient dimensional accuracy and sufficient elasticity.

In exceptional cases, as e.g. extremely narrow curves and in the vicinity of apertures in the lining, welded steel segments can represent a technical solution for overcoming load con-contortions on the lining.

4.5.2.3 Liner plates

Pre-formed steel plates in the form of liner plates can represent an economic solution as a full surface provisional support in extremely friable rock.

4.5.2.4 Extruded concrete

Extruded concrete is a tunnel lining, which is installed, in a continuous working process as an unreinforced or steel-fibre reinforced concrete support behind the tunneling machine between the shield tail and a mobile inner form. Thus, the extruded concrete in its fresh state already supports the surrounding rock, also in groundwater. An elastically supported stop-end formwork, which is pushed forwards concrete pressure, assures a constant support pressure in the liquid concrete.

4.5.2.5 Timber lagging

In non-water bearing soil, the primary support can comprise a wooden or reinforced concrete slatted construction, which is installed between steel profiles (ribs and lagging), which is assembled protected by the shield tail. When the shield tail releases the steel ribs, they and, in turn, the lagging, are pressed against the soil using hydraulic jacks. The tunneling machine can be advanced by thrusting against this pre-stressed construction.

4.5.2.6 Pipes

Pipe-jacking represents a special method, in the case of which reinforced concrete or steel pipes are thrust forward from a jacking station to serve as a support and/or final lining.

For certain construction projects, rectangular cross-sections are also employed with the jacking method.

4.5.2.7 Reinforced Concrete

Reinforced concrete is only used n conjunction with blade shields. In the same way as shotcrete, reinforced shotcrete can be applied in conjunction with tunneling machines for supporting purposes when they do not transfer the thrusting forces onto the lining. The reinforced concrete is produced in 2.50 to 4.50 m wide sections protected by so-called trailing blades, which are supported on the last concreted section by conventional means with mobile formwork.

## 5. Relationship between geotechnics and tunneling machines

### 5.1. Ranges of application for tunneling machines

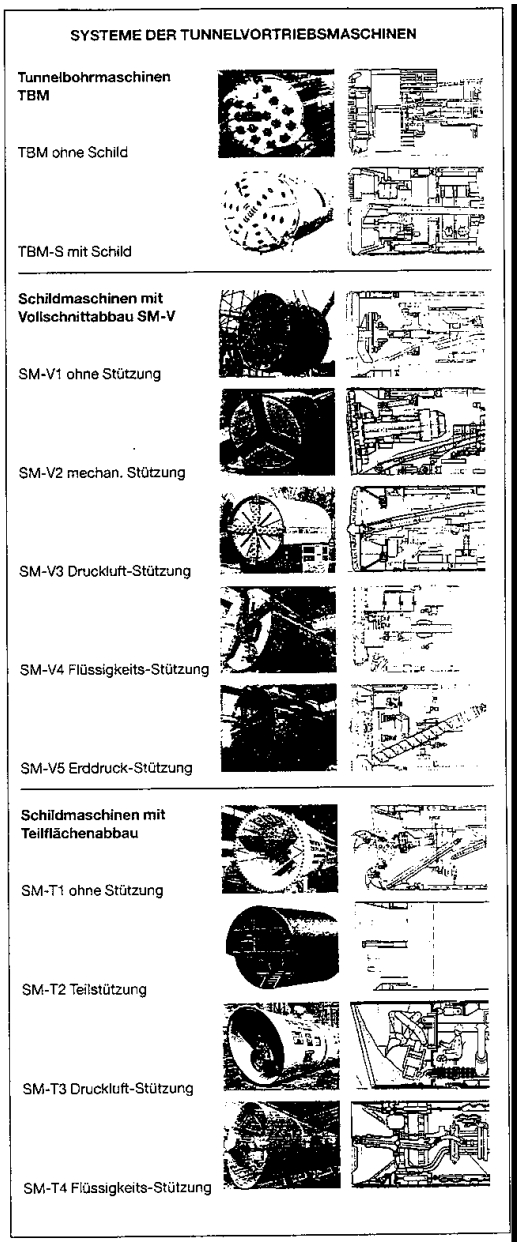
The individual tunneling machines are suitable for certain geotechnical and hydro-geographical ranges of application in con-junction with their process-related and technical features.

The specific types of machines are related to their main ranges of application in Fig.4 with geo-technical terms and parameters as the basis. In addition, it is shown there just how far an extension of the range of application is possible should this present itself as a result of simplified methods, in order to increase the economy or with regard to the heterogeneity of the subsoil that is present.

As one of the most essential influencing factors for the application is the lack or presence of groundwater, the fields of application are divided into subsoil with or without groundwater.

Extremely varied extraction tools can be used for removing the subsoil that is present. They are listed in accordance with their suitability for the geotechnical ranges of application and the machine types.

The forms of supporting and lining suit able for the individual machines are presented under 4.5. As a result, they have not been listed separately in a table.




**3. Systeme der Tunnelvortriebsmaschinen**
**Tunneling machine systems**

## 5.2. Important selection and evaluation criteria

**TBM**

The main range of application is in stable to friable rock, in the case of which underground and fissure water inbursts can be mastered. The uni-axial compressive strength should amount roughly to between 300 and 50 [MN/m$^2$]. Higher strengths, toughness of the rock and a high proportion of abrasion resistant minerals represent economic limits for - application (abrasiveness according to Cerchar, Schimanek, et al). A restriction of the gripper force of the TBM can also place its application in question.

To assess the rock, the cleavage strength _z ≈25 to 5 [MN/m$^2$] and the RQD value are required. Given a degree of decomposition of the rock with RQD of 100 to 50 [%] and a fissure spacing of > 0.6 m the application of a TBM appears assured.

Should the decomposition be higher, the stability has to be checked.

**TBM-S**

The main field of application is in friable to unstable rock, also with inbursts of underground and fissure water. The bonding strength is greatly reduced given possibly the same rock strength in stable rock. This corresponds to a fissure gap of ≈ 0.6 to 0.06 [m] and a RQD value between approx. 50 and 10 [%]. Generally, however, an application of the TBM-S is possible given lower rock compressive strength _D between approx. 50 and 5[MN/m$^2$] and correspondingly less cleavage strength of _z between approx. 5 and 0.5 [MN/m$^2$].

**SM-V1**

This type of machine is mainly used in over-consolidated and thus dry, stable clay soils. In order to make sure that no harmful surface settlements occur even given thin overburdens, the compressive strengths _D of the material should not be less than approx. 1.0 [MN/m$^2$]. The cohesion cu accordingly registers values above approx. 30 [kN/m$^2$].

Only in rock which is relatively immune to overbreak can underground and fissure water ingress be coped with.

**SM-V2**

On account of the full-face supporting cutter head, easily removed, largely dry types of soil can be mastered, first and foremost non-stable cohesive soils or interstratifications comprising cohesive and non-cohesive soils. Major intercalation such as boulders is extremely difficult to cope with.

The cohesion $c_u$ of these soils amounts to between 30 and 5 [kN/m$^2$]. The grain size is restricted upwards due to the slit width in the cutter head. In order to ensure that surface settlements are kept to a minimum, the slit

width and contact pressure have to be optimized.

**SM-V3**
This machine under compressed air working is mainly used when types SM-V1 and SM-V2 have to operate in groundwater. Its main application must be regarded as in soils with interstratification. The air permeability of the rock and the air consumption and the related blow -out danger are the governing criteria for the application of this type of machine.

**SM-V4**
Its main range of application is tunneling in non-cohesive types of soil with or without groundwater.
During the excavation process, a fluid under pressure e.g. bentonite suspension supports the face. Layers of gravel and sand are the typical subsoil. Coarse gravel can in certain cases prevent membrane formation. In the event of high permeability, the supporting fluid must be adapted to suit. Major stratification, which cannot be pumped, is reduced in advance crushers. The proportions of ultra-fine grain < 0.02 mm should amount to ≈ 10%. Higher quantities of ultra-fine material can lead to difficulties during separation.

**SM-V5**
Types of machines with earth pressure balance supporting are especially suitable for with cohesive fractions. In this case, the proportion of ultra-fine grains < 0.06 mm should amount to at least 30 %. In order to produce the desired earth slurry, groundwater has to be present or water must be added. The necessary consistency of the spoil can be improved through the addition of suitable conditioning agents such as bentonite or polymer. In this way too, the danger of sticking is considerably reduced.

**SM-T1**
This type of machine can be used providing the face is thoroughly stable. Refer also to SM-T1.

**SM-T2**
This type of machine can be used when the support due to the material lying on the platforms at a natural sloping angle suffices for a conditional control of deformations during tunnel advance. Breastplates can be used for supporting purposes in the roof and platform zone. Slightly to non-cohesive clay-sand soils with a corresponding angle of friction are the main range of application.

**SM-T3**
The application of this type of machine is given when types SM-T1 and SM-T2 are to be used in groundwater. Either the entire working area, including the excavated tunnel or solely the working chamber is subjected to compressed air.

**SM-T4**
When clay-sand mixtures are to be removed under water, this type of machine is used. The requirements concerning the ground correspond to type SM-T4. Obstacles can be cleared using the cutting boom. Supporting plates are arranged in the roof zone.

| Geo-technische kennwerte Geotechinical Parameters | Baugrund subsoil | Fels/Festgestein/Hard rock/soil standfest bis nachbr chig competent to caving in | Hard rock/soil nachbr chig bis gebr ch caving in to unstable | Boden/Lockergestein/Soft rock/soil bindig standfest cohesive stable | bindig nicht standfest cohesive not stable | Wechsellagerung mixed conditions | nicht bindig non-cohesive |
|---|---|---|---|---|---|---|---|
| Gesteinsfestigkeit Rock Compressive strength | $\sigma_{D}$ [MN/m²] | 300 bis 50 | 50 bis 5 | 1,0 | 0,1 | | |
| Zugfestigkeit Tensile strength | $\sigma_{z}$ [MN/m²] | 25 bis 5 | 5 bis 0,5 | | | | |
| RQD-Wert RQD value | RQD [%] | 100 bis 50 | 50 bis 10 | | | | |
| Kluftabstand Fissure spacing | [m] | >2,0 bis 0,6 | 0,6 bis 0,06 | | | | |
| Koh sion Cohesion | Cu [kN/m²] | | | ≥30 | 30 bis 5 | 30 bis 5 | |
| Kornverteilung Grain distribution | <0,02 [%]<br><0,06 [5] | | | 30<br>≥30 | 30<br>≥30 | | 10 |
| TBM | o.W. | | | | | | |
| TBM | m.W. | | | | | | |
| TBM-S mit Schild | o.W. | | | | | | |
| TBM-S with shield | m.W. | | | | | | |
| SM-V1 ohne St zung | o.W. | | | | | | |
| SM-V1 without support | m.W. | | | | | | |
| SM-V2 mechan.St zung | o.W. | | | | | | |
| SM-V2 mech.support | m.W. | | | | | | |
| SM-V3 mit Druckluft | o.W. | | | | | | |
| SM-V3 with compressed air | m.W. | | | | | | |
| SM-V4 Fl ssigkeitsst tzung | o.W. | | | | | | |
| SM-V4 fluid support | m.W. | | | | | | |
| SM-V5 Erddruck-St tzung | o.W. | | | | | | |
| SM-v5 earth pressure balance support | m.W. | | | | | | |
| SM-T1 ohne St tzung | o.W. | | | | | | |
| SM-T1 without support | m.W. | | | | | | |
| SM-T2 Teilst zung | o.W. | | | | | | |
| SM-T2 partial su | m.W. | | | | | | |
| SM-T3 mit Druckluft | o.W. | | | | | | |
| SM-T3 with compressed air | m.W. | | | | | | |
| SM-T4 Fl ssigkeitsst tzung | o.W. | | | | | | |
| SM-T4 fluid support | m.W. | | | | | | |
| Abbauwerkzeug Extracion tool | V | rollend (Diskenmei§el) rolling (cutter disc) | rollend (Diskenmei§el) rolling (disc bit) | sch lend (Flachmei§el) stripping (flat bit) | sch lend (Flachmei§el) stripping (chisel) | l send/sch lend (Stichel/Flachmei§el) loosening/stripping (cutter/flat bit) | l send (Stichel) loosening (pick) |
| | T | ritzend (Spitzmei§el) notching (pick) | ritzend (Spitzmei§el) notching (point bit) | ritzend (Spitzmei§el) notching (point bit) | sch lend (Flachmei§el) stripping (flat bit) | sch lend (Flachmei§el) stripping (flat bit) | l send (Stichel) loosening (pick) |

o.W.=ohne Grund-bzw.Schichtwasser/groundwater or underground water — Haupteinsatzbereich/Main field of appl

m.W.=mit Grund-bzw.Schichtwasser/groundwater or underground water — Einsatz m glich/application possible

4 Einsatzbereich der Tunnelvortriebsmaschinen
Ranges of application for tunnelling machines

### 5.3. Pointers for special geotechnical and constructional conditions

Due to special marginal conditions, the application of a certain method and/or a tunneling machine can be considerably restricted. By use of suitable measures, however, an application can be made possible, above all, providing these special conditions only occur locally or over a limited zone. The decisive factor is then the economic feasibility.

Through lowering the groundwater, a simplified technique for the tunneling machines can be applied, which e.g. facilitates the removal of obstacles, should these be expected at very frequent intervals.

In the case of strongly fluctuating geotechnical conditions, the possibility of being in a position to adapt the operating mode of the tunneling machine brings advantages. This is, above all, purposeful when lengthy interconnected sections are concerned (see 4.3).

When selecting the suitable tunneling machines, a critical evaluation of eventual additional equipment is advisable, which may be required to cope with any deviations from the projected geotechnical conditions within a certain range.

By means of grouting, freezing, vibrator compaction or soil replacement, the subsoil can be improved. This is suitable for the entire tunnel cross-section but most importantly for the area above the tunnel when only thin overburden is present.

Using compressed air when a thin overburden is present, e.g. below a watercourse, ballast or a waterproofing and ballasting layer should be installed.

When fluid support is used, additional measures are required in order to avoid uncontrollable suspension losses given high permeability of the soil and thin overburden.

Should there be a high frequency of coarse gravels and boulders in the sand, the utilization of a rock crusher enhances the operational safety in the case of fluid supported shield machines in addition to equipping the cutter head with cutter discs.

A tunneling machine is only in the position to head a circular cross-section, which has a constant diameter. However, it is technically possible to expand the driven circular cross-section over short stretches subsequently in such a way that other, above all larger cross-sectional forms are created, e.g. for a subterranean station, employing soil improvements should these be called for.

The greater the proportion of ultra fine material in the subsoil, the more attention has to be paid to spoil separation in the case of fluid supported shield machines.

The requirements on the water content and/or the degree of purity of the separated soil material then govern the limits of the economy of the method.

The operational safety of a method is, among other things, dependent on a tunnel's overburden. This should generally correspond at least to the diameter of the tunnel excavated, if additional measures are to be avoided. This must be accorded special attention in the case of large diameters.

The unrestricted application of certain types of machine is not always assured as the diameter increases and is only possible in conjunction with suitable measures. In the case of tunnel boring machines with large diameters, machines with shield body and systematic placing of segments have proved themselves. As far as earth pressure balance shield machines are concerned, extremely high torques at the cutter head are necessary, which possibly cannot be attained in the case of very large diameters.

As far as earth pressure balance shield machines are concerned, cutter discs can be employed for reducing coarse gravel and boulders. The dimensions of the screw conveyor must be designed in such a fashion the coarse lumps which are present after extraction can be removed. A screw without a shaft is suitable for conveying coarse lumps.

Certain clays or rocks containing clay can cause the cutter head to stick and to form bridges over apertures for removing material. This phenomenon can be counteracted through the proper shape, flushing installations or additives, which reduce the stickiness.

Ingresses of gas require flameproof protection for the tunneling machines or a change of operational mode.

**Italy**

# ITA WORKING GROUP No. 14
# (ITA WG14)

## "MÉCANISATION DE L'EXCAVATION"
## "MECHANIZATION OF EXCAVATION"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## PRÉPARATION DU RAPPORT "RECOMMANDATIONS POUR LE CHOIX DES MACHINES FOREUSES"

## PREPARATION OF THE REPORT "GUIDELINES FOR THE SELECTION OF TBM'S"

**(Contribution from the Italian Tunneling Association "Mechanized Tunneling"working group - GL14, to the ITA WG14)**


World Tunnel Congress'98
Tunnel and Metropolis
24th ITA Annual Meeting
25 - 30 April 1998
Sao Paulo - Brazil

# CONTENTS

# 1. Aim and Scope (deleted)

# 2. Classification and Outline of Tunnel Excavation Machines

## 2.1. Classification of tunnel excavation machines

All over the world there are different classification schemes for tunnel excavation machines (TMs), based on different classification purposes.

The proposed classification scheme represented in fig. l is based on the possibility of dividing TMs on the basis of_

_ ground support system
_ excavation (method and tools)
_ reaction force tool

Following the two machine categories into which all TMs may be grouped, the next paragraphs broadly illustrate all types of TMs.

## .1 - General class f cat on scheme for tunnel ng macn ne

- General classification scheme for tunneling machine

1 - General classification scheme for tunneling machine

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Excavation | | | | Excavation | |
| ion | Excavation | | | Excavation | Excavation | Excavation | Excavation | Excavation | Excavation |
| | Excavation | | | | | | | | |
| | | | | Excavation | Excavation | Excavation | Excavation | | Excavation |
| | | | | Excavation | | Excavation | Excavation | | Excavation |
| | | | | | | Excavation | Excavation | | Excavation |
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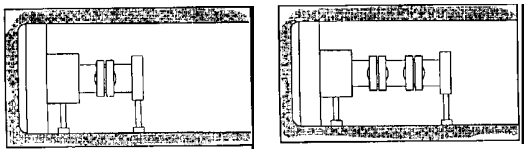
| | | | | | | Excavation | Excavation | | Excavation |
| | Excavation | | Excavation | Excavation | Excavation | Excavation | Excavation | Excavation | Excavation |
| | | | | Excavation | Excavation | Excavation | | | Excavation |
| | | | | Excavation | Excavation | | | | Excavation |
| | | Excavation | Excavation | Excavation | Excavation | Excavation | | | Excavation |
| | | | | Excavation | Excavation | | | | Excavation |
| | | | | Excavation | Excavation | | | | Excavation |
| | | | | Excavation | Excavation | | | | Excavation |
| | | | Excavation | Excavation | Excavation | | | | Earth Pressure Balance Shield-EPBS Special EPBS |
| | | Earth Pressure Balance Shield-EPBS Special | Earth Pressure Balance Shield-EPBS Special EPBS | | | | | | Earth Pressure Balance Shield-EPBS Special EPBS |

## 2.2. Rock tunneling machines

### 2.2.1. Unshielded TBMs



Function principle – A cutterhead, rotating on an axis which coincides with the axis of the tunnel being excavated, is pressed against the excavation face; the cutters (normally disc cutters) penetrate into the rock, pulverizing it locally and creating intense tensile and shear stresses. As the resistance under each disc cutter is overcome, cracks are created which intersect creating chips. Special buckets in the cutterhead allow the debris to be collected and removed to the primary mucking system. The working cycle is discontinuous and includes: 1) excavation for a length equivalent to the effective stroke; 2) regripping; 3) new - excavation.

Main components of the machine - The TBM basically consists of:

_the traveling element which basically consists of the rotating cutting head and the primary mucking system_

_a stationary element which counters the thrust jacks of the cutterhead using one or more pairs of grippers which anchor the TBM against the tunnel walls_

_a rear portion containing the driving gear and back-up elements;

Depending on the type of stationary element it is possible to divide unshielded TBMs into: main beam types or kelly types.

Main field of application - Rock masses whose characteristic range from optimal to moderate with medium to high self-supporting time.

### 2.2.2. Special Unshielded TBMs

#### *2.2.2.1 Reaming Boring Machines - RBMs*

Function principle - The Boring Machine is a TM which allows a tunnel made using a TBM (pilot tunnel) to be widened (reaming).

The function principle on which it is based is identical to that for the unshielded TBM; the working stages are also the same as for the unshielded TBM.

Main components of the machine - The RBM basically consists of:

_the traveling element which basically consists of the reaming head, on which the cutting tools are fitted_and the primary mucking system_

_a stationary element located inside the pilot tunnel opposite the reaming head, which counters the thrust jacks on the cutting head using two pairs of grippers;

_a rear portion containing the engines_the driving gear and back-up elements.

A special type of RBM is the Down Reaming Boring Machine_this machine is used for shaft excavation and enables the top-to-bottom reaming of a pilot tunnel dug using a Raise Borer_see below_.

Main field of application - Rock masses whose characteristics range from optimal to moderate with medium to high self-supporting time.

#### *2.2.2.2 Raise Borer*

Function principle - The Raise Borer is a machine used for shaft excavation which enables the top-to-bottom reaming of a small diameter pilot tunnel created using a drilling rig.

A cutterhead, rotating on an axis, which coincides, with the axis of the tunnel being excavated, is pulled against the excavation face by a drilling rod guided through the pilot tunnel. The cutters provoke crack formation using the same mechanism illustrated for the unshielded TBMs. Debris falls to the bottom of the shaft where it is collected and removed.

Main components of the machine - The Raise Borer basically consists of 3 parts:

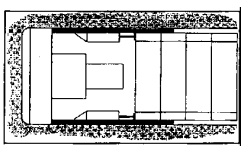
_ the cutterhead (discs or pin discs);

_ the drilling rod which provides torque and pull to the cutterhead;

_ a body, housed outside the shaft, which gives the drilling rod the necessary torque and pull for excavation.

Main field of an application - Rock masses with optimal to poor characteristics.

### 2.2.3. Single Shielded TBMs: SS-TBMs



Function principle - See the section for unshielded TBMs. In this case the working cycle is also -

discontinuous and includes:
l) excavation for a length equivalent to the effective stroke; 2) regripping (using the longitudinal thrust jacks braced against the precast segments of the tunnel lining) and simultaneous laying of tunnel lining using precast segments; 3) new excavation.

Main components of the machine

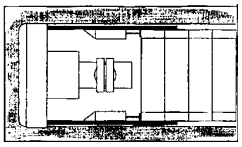
_the cutterhead (discs), which can be connected rigidly to the shield or articulated;

_ the protective shield which is cylindrical or slightly truncated cone-shaped and contains the main components of the machine; the shield may be monolithic (the machine is guided by the thrust system and/- or cutterhead) or articulated (the machine is guided by the thrust system and/or shield articulation);

_ the thrust system which consists of a series of longitudinal/hydraulic jacks placed inside the shield which are braced against the tunnel lining.

Main field of application - Rock masses whose characteristics vary from moderate to poor.

### 2.2.4. Double Shielded TBMs: DS-TBMs



Function principle - Similar to unshielded TBMs, but offers the possibility of a - continuous work cycle owing to the double thrust system, making it more versatile since it can move forward even without laying the tunnel lining of precast - segments.

Main components of the machine:

_ the cutterhead (discs);

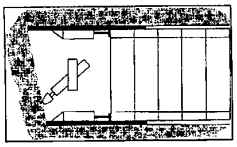
_ the protective shield which is cylindrical or slightly truncated cone-shaped and - articulated, and contains the main machine component;

_ the double thrust system which consists of:

1) a series of longitudinal jacks;
2) a series of grippers, positioned inside the front part of the shield which use the tunnel walls to brace against the thrust jacks.

Main field of application - Rock masses whose characteristics range from excellent to poor.

## 2.3. Soft Ground Tunneling Machines



### 2.3.1. Open Shields

Function principle - The open shield is a TM in which face excavation is - accomplished using a partial section cutterhead.

At the base of the excavating head are hand shields and partly mechanized shields in which excavation is accomplished using a roadheader or using a bucket attached to the shield, and using an automatic unloading and mucking system.

Main components of the machine

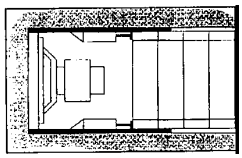
_ the face excavation system;

_ the protective shield whose shape can be altered to suit the type of section to be excavated (non-obligatory circular section);

_ the thrust system consisting of longitudinal jacks.

Main field of application - Rock masses whose characteristics vary from poor to very bad, - cohesive or self-supporting ground in general. It can also be used in ground, which lacks self-supporting capacity using appropriate preconsolidation or presupport of the - excavation face.

### 2.3.2. Mechanically Supported Closed Shields



Function principle - This mechanically supported, closed shield is a TBM in which the cutterhead plays the dual role of acting as the cutterhead and supporting the face using mobile plates, integral to the cutterhead, thrust against the face by special hydraulic jacks. The debris is extracted through adjustable openings or buckets and conveyed to the primary mucking system.

Main components of the machine

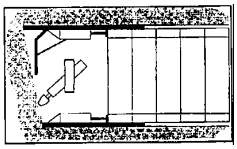
_ the cutterhead (blades and teeth);

_ the protective cylindrical shield containing all the main components of the machine;

_ longitudinal thrust jacks.

Main field of application - Soft rocks, cohesive or partially cohesive ground, self-supporting ground in general. Absence of groundwater.

### 2.3.3. Mechanical Supported Open Shields

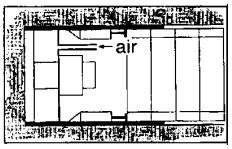


Function principle - Similar to that - described for open - Shields; face stability is achieved using metal plates which thrust alternatively against the face.

Main components of the machine - Similar to those described for open shields; the metal face support plates are located in the upper part of the section and are integral to the shield.

Main field of an application - Soft rocks, cohesive or partially cohesive ground, self-supporting ground in general. Absence of groundwater.

### 2.3.4. Compressed Air Closed Shields




Function principal - In compressed air closed shields the rotating - cutterhead acts as the means of excavation whereas face support is ensured by compressed air at a sufficient level to balance the - hydrostatic pressure of the ground. Debris is extracted from the pressurized excavation chamber using a ball valve-type rotary hopper and then conveyed to the primary mucking system.

Main components of the machine

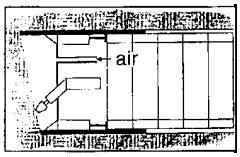
_ the cutterhead (blades and teeth);

_ the protective cylindrical shield containing all the main components of the machine; the front part is closed by a bulk head, which guarantees the separation between the excavation chamber (pressurized), housing the cutterhead, and the zone containing the machine components (unpressurized);

_ longitudinal thrust jacks.

Main field of application - Ground lacking self-supporting capacity and with medium-low permeability ($k \leq 10^{-4}$m/s). Presence of - groundwater. Higher permeability can be locally reduced by injecting bentonite slurry onto the excavation face. The operating limit of the machine is the maximum pressure applicable based on regulations for the use of compressed air in force in different countries.

### 2.3.5. Compressed Air Open Shields




Function principle - As in the case of open shields, face - excavation is achieved using a roadheader; face support is - provided by compressed air in sufficient quantities to balance the hydrostatic pressure of the ground.

Main components of the machine

_face excavation system ( roadheader, excavator);

_ protective shield shaped to fit the type of section to be excavated; the front part, which houses the roadheader, is closed by a bulkhead separating the shield and - excavation chamber (pressurized);

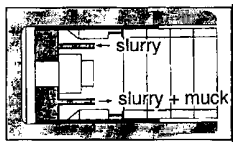
_ longitudinal thrust jacks.

Main field of application - The same as for compressed air closed shields.

### 2.3.6. Slurry shields

#### *2.3.6.1.Slurry shields-SS*

Function principle - The cutterhead acts as the means of - excavation whereas face support is - provided by slurry counterpressure, namely a suspension of bentonite or a clay and water mix (slurry).




This suspension is pumped into the excavation chamber where it reaches the face and penetrates into the ground forming the filter cake, or the impermeable bulkhead (fine ground) or impregnated zone (coarse ground) which guarantees the transfer of - couneterpressure to the excavation face.

Excavated debris by the tools on the rotating cutterhead consists partly of natural soil and partly of the bentonite or clay and water mixture (slurry). This mixture is pumped (hydraulic mucking) from the excavation chamber to a separation plant (which enables the bentonite/clay slurry to be recycled) normally located on the surface.

Main components of the machine

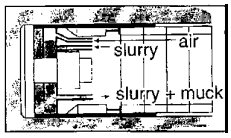
_ cutterhead (discs, blades or teeth);

_ protective shield containing all the main components of the machine; the front part is

sealed by a bulkhead which guarantees the separation between the shield and the excavation chamber (pressurized) containing the cutterhead;
_ longitudinal thrust jacks;
_ mud and debris separation system (normally located on the surface).

Main field of application - Ground with limited self-supporting capacity. In granulometric - terms, slurry shields are mainly suitable for excavation in sand and gravels with silts. The installation of a crusher in the excavation chamber allows any lumps, which would not pass through the hydraulic mucking system to be crushed. The use of disc cutters enables the machine to excavate in rock. Polymers can be used to excavate ground containing much silt and clay. Presence of groundwater.

### *2.3.6.2 Hydroshields HS*

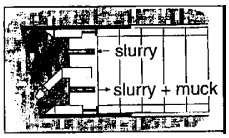



Function principle - Identical to that - described for - uncompensated slurry shields; the only - difference is the way of transferring the counterpressure to the face.

In the closed slurry shield in which the counterpressure is compensated inside the excavation chamber, in addition to the rotating head, there is always a metal buffer which creates a chamber partially filled with air connected to a compressor which can adjust the counterpressure at the face independent of the hydraulic circuit (supply of bentonite slurry and mucking of slurry and natural ground)

Main components of the machine - Similar to those described for closed slurry shields with uncompensated counterpressure.

## 2.3.7. Open slurry shields




Function principle - It is identical to that described for - compressed air open shields. In this case face support is provided by slurry counterpressure. Depending on the function of the cutterhead used, the following types can be identified:

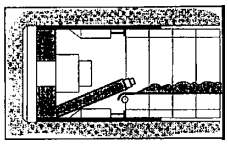
Thixshield: excavation using a roadheader
Hydrojetshield: excavation using high-pressure water jets

Main components of the machine – Similar to those described for compressed air open shields.

Main field of application - Similar to that described for the closed slurry shield.

## 2.3.8. Earth Pressure Balance Shields – EPBS

### *2.3.8.1 Earth Pressure Balance Shields - EPBS.*



Function principle - The cutterhead serves as the means of excavation whereas face support is provided by the - excavated earth which is kept under pressure inside the excavation chamber by the thrust jacks on the shield (which transfer the pressure to the separation bulkhead between the shield and the excavation chamber, and hence to the excavated earth).

Excavation debris is removed from the excavation chamber by a screw conveyor which allows the gradual reduction of pressure.

Main components of the machine
_ cutterhead: rotates with cutting spokes;
_ protective shield similar to that used for closed slurry shields;
_ thrust system: longitudinal jacks which brace against the lining of precast segments.

Main field of application - Ground with limited or no self-supporting capacity. In - granulometric terms, earth pressure balance shields are mainly used for excavating in silts or clays with sand. The use of additives, such as high-density mud or foams, enables excavations in sandy-gravely soil.

### *2.3.8.2 .Special EPBS*

DK shield - Differs from the earth pressure balance shield because of the geometry of the cutterhead whose central cutter projects further than the cutters on the spokes, thus creating a concave cavity.

Double shield (DOT shield) - These are two partially interpenetrated earth pressure balance shields which operate simultaneously on the same plane, creating a “binocular” tunnel.

Flexible Section Shield Tunneling Method -

Earth pressure balance shield in which the excavation system is based on the presence of several rotating cutterheads which enable the construction of non-cylindrical sections.
Elliptical Excavation Face Shield Method - Earth pressure balance shield in which the combined action of a circular cutterhead and additional cutters enables an elliptical section to be excavated.

Triple Circular Face Shield Tunnel - This consists of three shields, operating using earth or slurry pressure balance, which allow large excavation sections to be constructed, such as those required to house an underground railway station.
Vertical Horizontal Continuous Tunnel - This is a slurry pressure balance TM consisting of a main shield, for shaft excavation, which contains a spherical joint housing a secondary shield.
When the main shield has reached the appropriate depth, the spherical joint is rotated 90- and the secondary shield starts tunnel excavation.
Horizontal Sharp Edge Curving Tunnel - Similar to the Vertical-Horizontal Continuous Tunnel, it enables the construction of two tunnels intersecting at right angles.
Double Tube Shield Technology - This is a TM fitted with two concentric shields. The main shield excavates the tunnel with the large section; the secondary shield then excavates the tunnel with the smaller section.

#### 2.3.9. Combined Shields: Mixshield, Polyshield

Function principle - The closed combined shield is a machine, which can be adapted to different excavating conditions mainly by altering the excavation face support system.
The following combinations have already been used:
l ) air pressure balance _ _ no pressure balance,
2 ) slurry pressure balance _ _ no pressure balance,
3 ) earth pressure balance _ _ no pressure balance,
Main components of the machine
_ rotating cutterhead (rotates with cutter spokes more or less closed);
_ protective shield;
_ thrust system:longitudinal jacks.

Main field of application - The versatility of combined closed shields lends them to be used in rocks and soils under the groundwater table with limited or no self -supporting capacity.

## 3. Conditions for Tunnel Construction and Selection of TBM Tunneling Method

### 3.1. Investigations

#### 3.1.1. Introduction

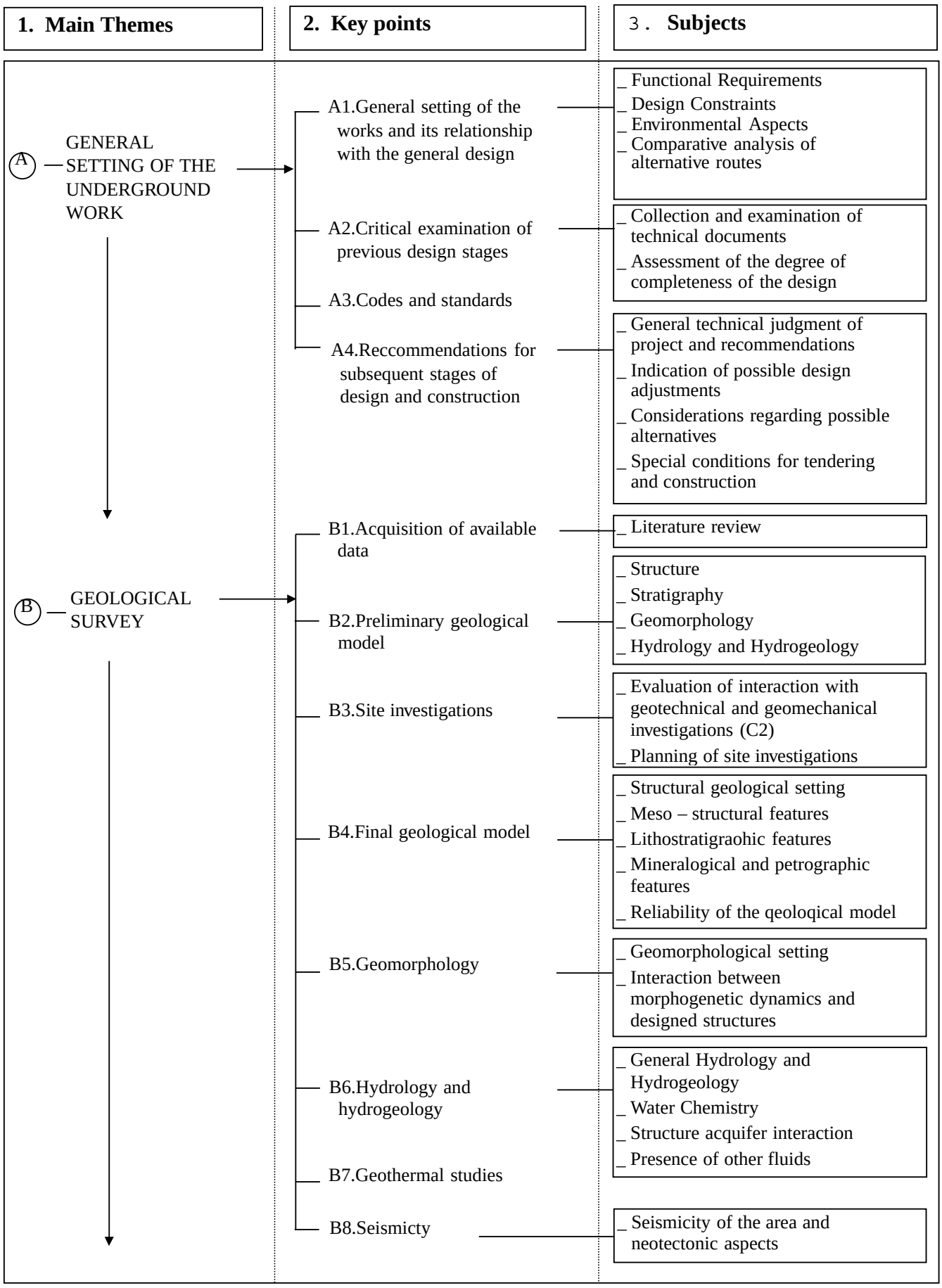
In underground works, construction induces complex and often time-dependent soil-structure interaction. Design must therefore develop both of the basic aspects, which determine the interaction: statics of the excavation and the construction method employed.

The success of a project, in terms of time and costs, strongly depends on the method of excavation employed and the timing of the various construction phases.

The planning of investigation and tests must take into account these considerations and must be inserted into a well-defined design planning.

Figure 3.1 shows the schematic structure of the“Guidelines for Design, Tendering and Construction of Underground Works adopted by the main Italian Engineering Associations in relation to tunneling.
These“guidelines”are based on the identification of the“key points”and their organization into“subjects”representing the various successive aspects of the problem to be analyzed and quantified during design/ - tendering/construction. The degree of detail of each“key point”will depend on the - Peculiarities of the specific project and design stage.
In general planning for design, tendering and construction, as illustrated in Figure 3.2, the various“key points”and“subjects”are linked. The relationship between site investigations (Geological Survey and/or Geotechnical - geomechanical studies) and the Preliminary design of excavation and support (Choice of excavation techniques and support measures) is indicated.

Figure 3.2 Schematic structure of the Guidelines for Design, Tendering and Construction of Underground Works



| 4. Main Themes | 5. Key points | 6. Subjects |
|---|---|---|
| C GEOTECHNICAL GEOMECHANICAL STUDIES | C1.Preliminary | _ Review of data from geological study<br>_ Review of data from literature |
| | C2.Geotechnical and geomechanical investigations | _ Evaluation of the relation-ship with site investigation (B3)<br>_ Planning of investigation and tests<br>_ Summary of results<br>_ Additional investigations |
| | C3.Soil or rock mass characterization | _ Soil and rock-mass structure<br>_ Soil and intact rock characterization<br>_ Mechanical characterization of discontinuities<br>_ Hydraulic properties of soil and rock masses<br>_ Geomechanical classification of rock masses<br>_ Geotechnical and geomechanical models |
| | C4.Natural state of stress | |
| D PREDICTION OF MECHANICAL BEHAVIOR OF THE MASSES | D1.Subdivision of the route into“homogeneous”zones | |
| | D2.Evaluation of the excavation stability conditions for each homogeneous zone | _ Calculation of behavior of face and profile of excavation without support |
| | D3.Surface and underground constraints | _ Effects of underground excavations on the surface<br>_ Effects of excavation on the surrounding mass<br>_ Effects of tunneling on the existing hydrogeologic equilibrium |
| | D4.Preliminary design of methods of excavation and support | _ Study of different methods of excavation and suppout:traditional and mechanized<br>_ Choice of general criteria for construction |

**E — DESIGN CHOICES AND CALCULATIONS**

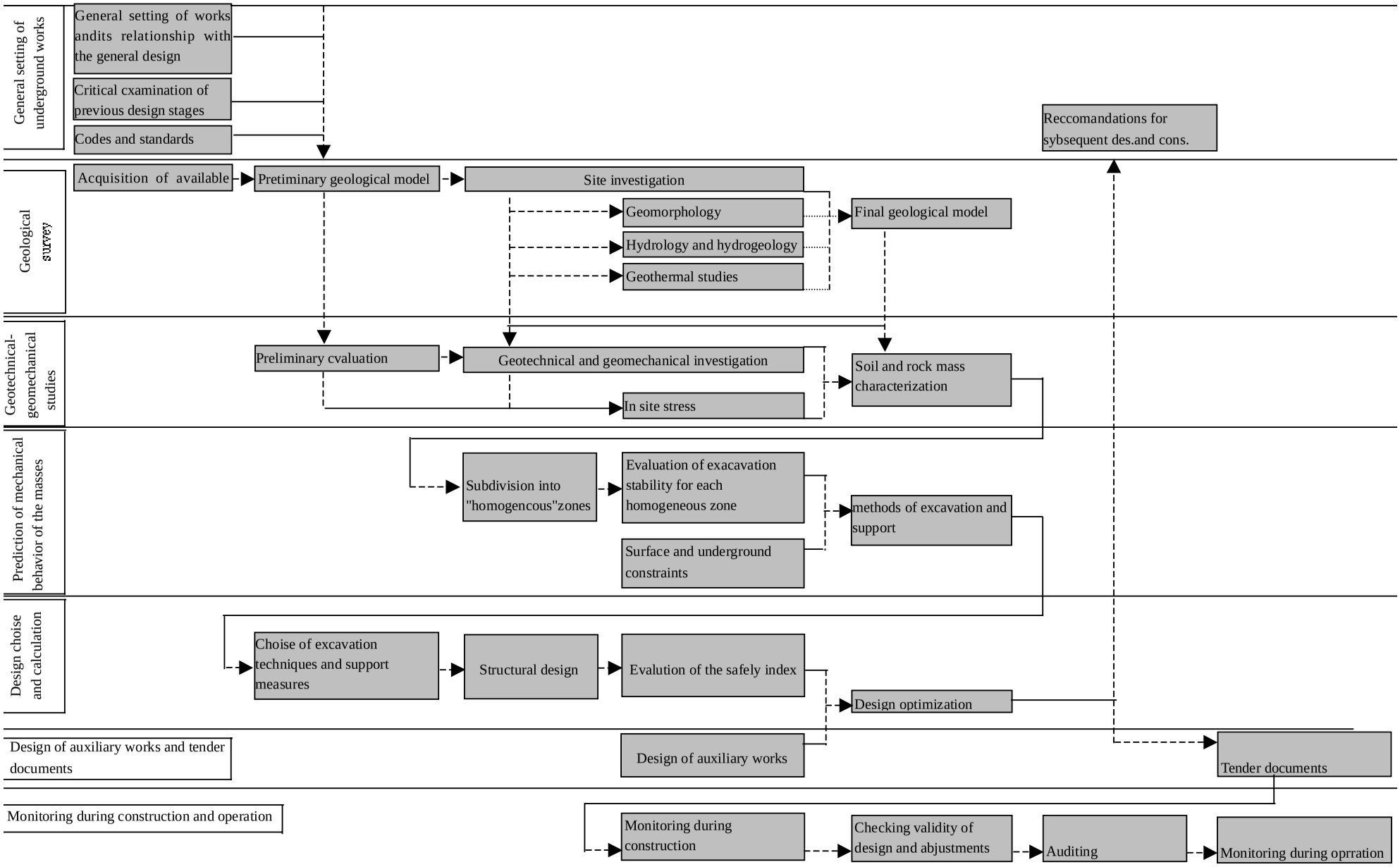
- **E1.Choice of excavation techniques and support measures for each homogeneous zone**
  - Definition of applicable methods of excavation
  - Definition of section type
  - Design of the stabilization interventions
- **E2.Structural design**
  - Design loads
  - Model of construction phases
  - Structural design of final lining
  - Design of finishing
- **E3.Evaluation of safety index**
  - Evaluation of the safety factors
  - Crisis scenarios and collapse hypothesis
  - Definition of counter measures
- **E4.Design optimization**
  - Probabilistic evaluation of construction times and costs of the design solution

**F — DESIGN OF AUXILIARY WORKS AND TENDER**

- **F1.Design of auxiliary works**
  - Design of portals
  - Ventilation systems
  - Monitoring plan
  - Disposal and borrow areas
  - Ancillary works
  - Construction sites and access roads
  - Environmental impact study
- **F2.Tender documents**
  - Technical documents which form part of the contract
  - Plan of safety and coordination

**G — MONITORING DURING CONSTRUCTION AND OPERATION**

- **G1.Monitoring during construction**
  - Geological survey
  - Hydrogeological measurements
  - Geomechanical measurements
  - Monitoring stress-strain response
  - Monitoring the state of stress and strain in the lining
  - Effectiveness of consolidation and stabilization measures
  - Monitoring nearby structures above and below ground
- **G2.Checking validity of design and abjustments during construction**
  - Comparison between design assumption and measurements during construction
  - Adjustments of design according to the observed differences
- **G3.Auditing**
  - Structural auditing
  - System auditing
- **G4.Monitoring during operation**
  - Monitoring of stress and strain in ground-stucture complex
  - Hydrogeological measurements
  - Surveys


General setting of underground works
General setting of works andits relationship with the general design
Critical cxamination of previous design stages
Codes and standards
Reccomandations for sybsequent des.and cons.
Geological survey
Acquisition of available
Pretiminary geological model
Site investigation
Geomorphology
Hydrology and hydrogeology
Geothermal studies
Final geological model
Geotechnical-geomechanical studies
Preliminary cvaluation
Geotechnical and geomechanical investigation
In site stress
Soil and rock mass characterization
Prediction of mechanical behavior of the masses
Subdivision into "homogencous"zones
Evaluation of exacavation stability for each homogeneous zone
Surface and underground constraints
methods of excavation and support
Design choise and calculation
Choise of excavation techniques and support measures
Structural design
Evalution of the safely index
Design optimization
Design of auxiliary works and tender documents
Design of auxiliary works
Tender documents
Monitoring during construction and operation
Monitoring during construction
Checking validity of design and abjustments
Auditing
Monitoring during oprration

### 3.1.2. Parameter selection

In line with the general criteria discussed in the previous section the parameters to be investigated for obtaining useful information for mechanized tunnel design and construction
have been divided in two categories:

1. geological parameters;
2. geotechnical - geomechanical parameters.

In the first category, the parameters are common to all tunnel studies and/or design, not restricted to mechanized tunneling (Table 3.1).

The geotechnical - geomechanical parameters specifically to mechanized tunneling are
presented in Table 3.2.

In accordance also with the work carried out by the French Tunneling Association -
(AFTES),
the parameters have been divided in different groups:

l. state of stress,
2. physical,
3. mechanical,
4. hydrogeological,
5. other parameters.

The following information are reported for each group in Table 3.2:
a) the parameter symbol (s)

b) the relationship with TBM excavation, in terms of:
_ tunnel face and cavity stability
_ cutting head
_ cutting tools
_ mucking system

c) the stage of the work in which the parameter is required, in terms of:

_ FS feasibility study/preliminary design
_ DD detailed design
_ DC construction stage

d) notes related to particular conditions.

Table 3.1: Geological parameters and investigations required for the design of mechanized tunnel excavation

| No. | OBJECTIVE OF INVESTIGATION | INVESTIGATION TYPE |
|---|---|---|
| | **GEOLOGICAL** | |
| 1<br>2 | Regional structural setting<br>Mesostructural and lithostratigraphic features | Topography<br>Photogrammetry<br>Photointerpretation<br>Remote sensing<br>Regional geological studies and mapping<br>Detailed geological studies and mapping |
| 3 | Type of soils/rocks | Detailed geological studies and mapping<br>Boreholes |
| 4 | Soils/rocks structure (fabric, stratification, fracturing) | Detailed geological studies and mapping<br>Boreholes |
| 5<br>6 | Overburden and layers thickness ,<br>Degree and depth of weathering | Detailed geological studies and mapping<br>Geophysical methods<br>Boreholes |
| 7 | Geological structural discontinuities (faults, shear zones, crushed areas, main joints) | Detailed geological studies and mapping<br>Geophysical methods<br>Boreholes |
| 8 | Special formation (salt, gypsum, tale, organic deposits) | Detailed geological studies and mapping ,<br>Boreholes |
| 9 | Karst phenomena: location of cavities, degree of karstification, age and origin, infilling and karst water | Detailed geological studies and mapping<br>Speleological studies<br>Boreholes<br>Micro-gravimetric survey |
| | GEOMORPHOLOGY | |
| 10 | General geomorphological condition | Topography<br>Photogrammetry<br>Photointerpretation<br>Regional geomorphological studies and mapping<br>Detailed geomorphological studies and mapping |
| 11 | Active or potentially active processes | Detailed geomorphological studies and mapping |
| | **HYDROLOGY AND HYDROGEOLOGY** | |
| 12<br><br><br><br><br>13 | Hydrologic condition<br><br><br><br><br>Groundwater features ( swampy ground areas, springs or seepage position, notes on groundwater properties ) | Topography<br>Photogrammetry<br>Photointerpretation<br>Regional hydrological studies and mapping<br>Detailed hydrological studies and mapping<br>Detailed geological studies and mapping<br>Detailed hydrogeological studies and mapping |
| 14 | No. of groundwater bodies, groundwater levels ( and potential groundwater levels ) | Detailed hydrogeological studies and mapping<br>Boreholes |
| 15 | Soil/rock masses permeability types | Detailed hydrogeological studies and mapping |
| | GEOTHERMALCONDITIONS | |
| 16 | Hydrotermal conditions | Regional geological studies |
| 17 | Gas emanations | Regional geological studies and mapping<br>Detailed geological studies and mapping<br>Boreholes |
| | SEISMICDONDITIONS | |
| 18 | Seismicity | Regional geological studies |

Table 3.2: Geo-Parameters related to mechanized tunneling

| No. | PARAMETER | Symbol | Relationship with TBM excavation | | | | Stage of the work in which the parameter is required | | | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Tunnel face and cavity stability | Excavation | | Mucking system | | | | |
| | | | | Cutting head | Cutting tools | | **FS** | **DD** | **DC** | |
| **1** | **STATE OF STRESS** | | | | | | | | | |
| 1.1 | Natural stress | $\sigma_1$, $\sigma_2$, $\sigma_3$, | R | | | | | A | A-O | |
| 1.2 | Vertical stress | $\sigma_v$ | S/R | S/R | | | A | N | | |
| 1.3 | Horizontal/Vertical total stress ratio | Kt_($\sigma_h/\sigma_v$) | S/R | | | | A | N | | |
| 1.4 | Horizontal/Vertical effective stress ratio | $K_O$ | S | S/R | | | A | N | N | |
| 1.5 | Consolidation degree (compaction, decompr.) | | S | | | | A | NO | | |
| **2** | **PHYSICAL** | | | | | | | | | |
| 2.1 | Index properties | | | | | | | | | |
| 2.11 | Volumetric weight | $\gamma$, $\gamma d$,$\gamma s$, | S/R | S/R | | S/R | A | N-O | A | |
| 2.12 | Water content, saturation degree, void ratio | w, $S_i$, e | S/R | S/R | | S/R | A | N-O | A | |
| 2.13 | Plasticity index | $w_l$, $w_n$ | S | S | | | A | N-O | A | Absolutely necessary in soft ground |
| 2.14 | Granulometric characteristics | | S | | S/R | S/R | A | N-O | A | |
| 2.15 | Activity | | | S | S | S | A | N-O | A | |
| 2.16 | Mineralogic and petrographic features | | | | S/R | | A | N-O | A | |
| 2.2 | Global evaluation quality | | | | | | | | | |
| 2.21 | General quality index | | S/R | S/R | | | N-O | | | |
| 2.22 | Alteration index | $A_M$ | R | R | R | | | N-O | N | |
| 2.23 | Quality index | $t_O$ | R | R | R | | | A-O | | |
| 2.3 | ***Discontinuities*** | | | | | | | | | |
| 2.31 | Discontinuities density | RQD,$\lambda$ | R | R | | | N-O | N-O | N | |
| 2.32 | Number of sets | $N_l$, $N_X$ | R | R | | | A | N-O | N | |
| 2.33 | Sets characteristics: | | R | R | | | A | N-O | N | |
| | _ Orientation (dip and dip direction) | | | | | | | | | |
| | _ Spacing | | | | | | | | | |
| | _ Persistence | | | | | | | | | |
| | _ Roughness | | | | | | | | | |
| | _ Aperture | | | | | | | | | |
| | _ Infilling | | | | | | | | | |
| | _ Seepage | | | | | | | | | |
| | _ Shear strength | | | | | | | | | |
| | _ Genesis (foliation, joint) | | | | | | | | | |

| No. | PARAMETER | Symbol | Relationship with TBM excavation | | | | Stage of the work in which the parameter is required | | | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Tunnel face and cavity stability | Excavation | | Mucking system | | | | |
| | | | | Cutting head | Cutting tools | | **FS** | **DD** | **DC** | |
| 2.4 | Weatherability | | | | | | | | | |
| 2.41 | Sensibility to water, solubility | | S/R | S/R | | S/R | A | N-O | A | |
| 2.42 | Sensibility to hydrometric variations | | S/R | S/R | | S/R | A | N-O | A | Not frequently used |
| 2.43 | Sensibility to thermic variations | | S/R | S/R | | | | A | A | |
| 2.5 | Water chemistry | | | | | | | | | |
| 2.51 | Chemical characteristics | | | | | S/R | A | N-O | A | |
| 2.52 | Waste conditions | | | | | S/R | | N | N | |
| **3** | MECHANICAL | | | | | | | | | |
| 3.1 | Strength | | | | | | | | | |
| 3.11 | Shear (short time) | $\tau$ | S/R | S/R | S/R | | N(S) | N-O | A | |
| 3.12 | Uniaxial compressive | $s_f$, $\sigma_c$ | S/R | S/R | S/R | | N(R) | N-O | A | |
| 3.13 | Tensile | $\sigma_t$, $I_S$ | R | R | R | | A-O | N-O | A | |
| 3.14 | Residual | | S/R | | | | A | A-O | A | |
| 3.15 | General strength index | | S/R | S/R | | | | | A | |
| 3.2 | Global evaluation quality | | | | | | | | | |
| 3.21 | Anisotropy elastic constants | | R | R | | | | A | A | |
| 3.22 | Isotropic elastic constants | E, $\upsilon$ | S/R | S/R | | | N-O | N-O | A | |
| 3.23 | Visco-behavior | $E_{(t)}$, $E_{(q)}$ | S/R | | | | A | N-O | A | |
| 3.24 | Swelling | | S/R | S/R | | | N | N-O | A | |
| 3.3 | Dynamic characteristics of soil/rock mass | | | | | | | | | |
| 3.31 | P and S waves velocity | | S/R | | | | A | N-O | A | |
| 3.32 | Deformability modules | | S/R | | | | A | N-O | A | |
| 3.33 | Liquefaction potential | | S | | | | A | N-O | A | |
| **4** | **HYDROGEOLOGICAL** | | | | | | | | | |
| 4.1 | Anisotropy permeability | $k_X$, $k_V$, $k_Z$, | S/R | | | | | A-O | | |
| 4.2 | Isotropic permeability | k | S/R | | | | N-O | N-O | | |
| 4.3 | Piezometric level, hydraulic gradient | H, i | S/R | | | | N | N-O | N-O | |
| 4.4 | Water flow | Q | S/R | | | S/R | | A-O | N-O | |

| No. | PARAMETER | Symbol | Relationship with TBM excavation | | | | Stage of the work in which the parameter is required | | | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Tunnel face and cavity stability | Excavation | | Mucking system | FS | DD | DC | |
| | | | | Cutting head | Cutting tools | | | | | |
| 5,1 | Abrasivity | | | S/R | S/R | | A-O | N-O | | |
| 5,2 | Hardness | | | R | R | | A-O | N-O | | All these parameters are particularly |
| 5,3 | Drillability | | | | R | | | N-O | | required for mechanized tunneling |
| 5,4 | Sticky behavior | | | S/R | S/R | S/R | A-O | N-O | A | |
| 5,5 | Ground friction | | | S/R | | | A | A-O | A-O | |

S=Soil; R=Rock
FS=Feasibility Study/Preliminary Design, DD=Detailed Design; DC=During Construction
N=Necessary; A=Advisable; O=Quantification of this parameter is done through specific tests

Table 3.3: Geo-parameters and related investigations

| No. | PARAMETER | INVESTIGATION TYPE | Location S=site L==Lab. | NOTE |
|---|---|---|---|---|
| **1** | **STATE OF STRESS** | | | |
| 1.1 | Natural stress | Borehole Slotter stressmeter method (R) | S | In borehole test |
| | | Overcoring methods (R) | S | In borehole test |
| | | | S | In borehole test |
| | | Hydraulic Fracturing Technique (R) ' | S | Min. 5-6 tests are required, useful also for soft rock |
| 1.2 | Vertical stress | Dilatometer (S/R) | S | Experimental method |
| 1.3 | Horizontal/Vertical total stress ratio | Aedometer test with lateral pressure control (S) | L | Not frequently used |
| | | | L | Not frequently used |
| | | Triaxial test with lateral deformation control (S) | S | Experimental method |
| | | | S | |
| | | Dilatometer (S/R) | S | |
| 1.4 | Horizontal/Vertical effective stress ratio | Flat jack method (R) | L | |
| 1.5 | Consolidation degree (com action, decompr.) | Marchetti dilatometer (S) | L | |
| | | Oedometric test (S) | | |
| | | Oedometric test (S) | | |
| **2** | PHYSICAL | | | |
| 2.1 | Index properties | | | |
| 1.11 | Unit weight | Density tests (S/R) | L | |
| | | Gamma-densimeter (S) | S | |
| 2.12 | Water content, saturation degree, void | Laboratory index tests (S/R) | L | |
| 2.13 | index | Atterberg limits (S) | L | |
| 2.14 | Plasticity index | Grain-size analyses and sedimentation | L | |
| | Granulometric characteristics | analyses (S) | L | |
| 2.15 | | Petrographic analyses (R) | L | |
| 2.16 | Activity | Mineralogic analyses (S) | L | |
| | Mineralogic and petrographic features | Mineralogic analyses (S/R) | L | |
| | | Petrographic analyses (S/R) | L | |
| | | Chemical analyses (S/R) | | |
| 2.2 | Global evaluation of quality | | | |
| 2.21 | Genera quality index | Geophysical methods: .seismic, geoelectric, micro gravimetric, georadar (S/R) | S | |
| | | Borehole perforation parameters: velocity, torque, pressure (S/R) | S | Qualitative evaluation |
| 2.22 | Alteration index | Visual examination of the material (R) | S | Outcrops, investigation galleries, borehole samples |
| | | Slake durability test (R) | L | |

| No. | PARAMETER | INVESTIGATION TYPE | Lo_ation S=site L=Lab | NOTE |
|---|---|---|---|---|
| 2,23 | Quality index | Sonic waves test (R) | L | |
| | | Mineralogical analysis (R) | L | |
| | | Petrographic analysis (R) | L | |
| 2,3 | **Discontinuities** | | | |
| 2,31 | Discontinuities density | Site measurements (R) | S | Outcrop |
| | | Rock Quality Designation-RQD (R) | S/L | Borehole samples |
| | | Seismic _urvey(R) | S | Qualitative evaluation |
| 2,32 | Number of sets | Site measurements + stereographic analyses (R) | S/L | |
| 2,33 | Sets characteristics: | | | |
| | 1. Orientation (dip and dip direction) | 1. Site measurement | 1. S | |
| | 2. Spacing | 2. Site measurement | 2. S | |
| | 3. Persistence | 3. Site measurement | 3. S | |
| | _. Roughness | 4. Site measurement | 4. S | |
| | 5. Aperture | 5. Site measurement | 5. S | |
| | 6. Infilling | 6. Site observation and_mineralogical test | 6. S | |
| | 7. Seepage | 7. Site measurement | 7. S | |
| | 8. Shear strength | 8. Shear test | 8. L | |
| | 9. Genesis (foliation, bedding, joint) | 9. Geological observations | 9. S | |
| | Weatherability | | | |
| 2,41 | Sensitivity to water, solubility | Site observation (S/R) | S | |
| | | Mineralogical analyses (S/R) | L | |
| | | Swelling test (R) | L | etc.) |
| | | Cyclic tests (wet-dry) (R) | L | |
| | | Solubility test (R) | L | |
| 2,42 | Sensibility to hygrometric variations | Mineralogic analyses (S/R) | L | |
| | | Site observation (S/R) | S | |
| 2,43 | Sensibility to thermic variations | Heating test (S/R) | L | |
| | | Freezing test (S/R) | L | |
| | Water chemistr | | | |
| 2,51 | Chemical characteristics | Chemical analyses: salt content, aggressivity, hardness, pH value, temperature, etc. | L | |
| 2,52 | waste conditions | Chemical analyses | L | |
| **3** | **MECHANICAL** | | | |
| 3,1 | Strength | | | |
| 3,11 | Shear (short time) | Casagrande shear box test, undrained conditions (S) | S/L | |
| | | Direct Shear test (R) | L | |
| | | In situ direct shear test (R) | S | |
| | | Triaxial test (S/R) | S/L | Soils : lower limit values ; rocks : upper limit values |
| | | Scissometer / Vane test (S) | S/L | In clayed borehole samples |

| No. | PARAMETER | INVESTIGATION TYPE | Location S=site L=Lab | NOTE |
|---|---|---|---|---|
| 3,12 | Uniaxial compressive | Uniaxial compression test (S/R) | L | |
| | | Point load test (R) | S/L | Indirect measurement of the parameter |
| 3,13 | Tensile | Direct tensile test (R) | L | |
| | | Brazilian test (R) | L | Indirect measurement of the parameter |
| | | Point load test (R) | S/L | _ndirect measurement of the parameter |
| 3,14 | Residual | Residual strength test (shear, triaxial tests) | S/L | |
| 3,15 | General strength index | Borehole perforation parameter measurements: velocity, torque, pressure (S/R) | | |
| 3.,2 | Deformability | | | |
| 3,21 | Isotropic/Anisotropic el_stic constants | Plate loading test (R/S) | S | Rock surface test |
| | | Directional dilatometer test (S/R) | S | Inside borehole tests |
| | | Uniaxial -Triaxial compressive tests on directional samples (S/R) | L | |
| | | P-S wave measurement (_/R) | S/L | Qualitative measurement |
| | | Deformation measurement (S/R):<br>_. Convergence/dilatancy<br>2. Extensometer<br>3. Inclinome_ers<br>4. Settlements | S | Rock surface test (i.e. experimental-gallery) |
| 3,22 | Visco-behavior | Flat jack method (R) | S | Rock surface test |
| | | Long-time plate loading test (R) | S | Rock surface test |
| | | Creep load test (S) | L | |
| | | Cycle dilatometer test (S/R) | S | Inside borehole tests |
| | | _eformation measurements (S/R) | S | Rock surface test |
| 3,23 | Swelling | Swelling test (S/R) | L/S | |
| 3,3 | Dynamic characteristics of soil/rock mass | | | |
| 3,31 | P and S waves velocity | Seismic survey: cross-hole, down-hole | S | Inside borehole tes_s |
| 3,32 | Deformability modules | Seismic survey: cross-hole, down-hole | S | Inside borehole tests |
| 3,33 | Liquefaction potential | Standard penetration test | S | Inside borehole tests |
| 4 | **HYDROGEOLOGICAL** | | | |
| 4,1 | Anisotropic permeability | Observation during borehole drilling | S | Qualitative determination |
| | | Permeability tests:<br>1. Lefranc<br>2. Lugeon<br>3. Directional, constant or variable water level | S | Inside borehole teests |

| No. | PARAMETER | INVESTIGATION TYPE | Location S=site L=Lab | NOTE |
|---|---|---|---|---|
| 4.2 | Isotropic permeability | Pumping test | S | |
| | | Injection test | S | |
| 4.3 | Piezometric level, hydraulic gradient | Piezometer (open type) | S | |
| | | Piezometer (close type) | S | |
| 4.4 | Water flow | Tunnel measurements | S | |
| | | Springs measurements | S | |
| | **OTHER PARAMETERS** | | | |
| 5.1 | Abrasivity | Abrasivity ISRM | L | |
| | | Cerchar test (R) | L | |
| | | Abrasivity (Norwegian Institure of Technology) | L | |
| | | LCPT test (S/R) | L | |
| 5.2 | Hardness | Hardness ISRM (R) | L | |
| | | Schmith hammer (R) | L | |
| | | LCPT test | L | |
| | | Knoop | S/L | |
| | | Cone Indenter test (NCB) | L | |
| | | Punch test (Colorado Shool of Mines) | L | |
| | | Drop test (Norwegian Institute of Technology) | L | |
| | | Los Angeles test (S/R) | L | |
| 5.3 | Drillability | Siever's test | L | |
| | | Drillability tests | L | |
| 5.4 | Sticky behavior | Mineralogical analyses (S/R) | L | Indirect measurement, related with |
| | | Atterberg limits (S) | L | physical index properties |

In Table 3.3 an international standard is given for each investigation or test related to mechanized tunneling.

Table 3.3: Investigations, test methods and references

| METHODS | REFERENCE |
|---|---|
| SITE INVESTIGATION | |
| Topography,aerotopography,photogrammetry photointerpretation | ISRM 1975 |
| Engineering geological investigations | ISRM 1975 |
| Geophysical methods:<br>_ micro-gravity<br>_ seismic<br>_ geoelectric<br>_ georadar | ASTM D4428-84 |
| Drilling,borehore cameras and television | |
| Trenches,shafts and galleries | |
| SITE TEST | |
| Plate loading test (R) | ISRM11 / ISRM19 / ASTM D4394-84 / ASTM D4395-84 |
| Overcoring methods (R) | ASTM D4623-86 |
| Flat jack method (R) | ASTM D4729-87 |
| Hydraulic fracturing method (R) | ASTM D4645-87 |
| Compression Test (R) | ASTM D4555-90 |
| Direct shear test (R) | |
| Dilatometer (S/R) | |
| Standard penetration test: SPT (S) | ASTM D4971-89 / ASTM D4506 -90 |
| Cone penetration test: CPT (S) | ASTM D1586-84 / ASTM D4633 - 86 |
| Rock Quality Designation (RQD) | ASTM D3441-86 |
| Vane Shear Test (S) | |
| Discontinuities (R) | ASTM D2573-72 |
| Deformation measurements (S/R):<br>1. Convergence/dilatancy<br>2. Extensometer<br>3. Inclinometers<br>4. Settlements | ISRM07 / ISRM14 / ASTM D4554 - 90 |
| Long-time plate bearing test (R) | |
| Creep test (S/R) | |
| Cycle dilatometer test (S/R) | ASTM D4553-90 |
| Deformation measurements (S/R) | |
| Permeability tests:<br>1. Lefranc<br>2. Lugeon<br>3. Directional, constant or variable, water level | ASTM D2434-68 |
| Pumping test | |
| Injection test | |
| Piezometer (open type) | |
| Piezometer (close type) | ASTM D4750-87 |
| Tunnel measurements | |
| LABORATORY - SOIL | |
| Identification tests :<br>_ Volumetric weights (natural, dry, satured)<br>_ natural water content, saturation degree<br>_ porosity, void ratio<br>_ Atterberg limits<br>_ Activity (clay) | ASTM D4318-84 / ASTM D4254-83 / ASTM D3282-88<br>ASTM D2487-90 / ASTM D4404-84 /<br>ASTM D4959-89 / ASTM D854-83<br>ASTM D427-83 / ASTM D2210-90 |

| METHODS | REFERENCE |
|---|---|
| Grain-size analyses and sedimentation analyses | ASTM D422-63 / ASTM D2487-90 / ASTM D1140-54 |
| Gamma-densimeter | |
| Mineralogic analyses (diffractometer) | ISRM 1977 / ASTM D4452-85 |
| Chemical analyses | |
| Permeability | ASTM D2438-90 |
| Oedometric test: | ASTM D4186-90 / ASTM D2435-90 / ISRM 89 |
| _ Natural consolidation | ASTM D2435-90 / ASTM D2166-85 |
| _ compressibility characteristics (consolidation index, edometric compressibility index) | |
| _ permeability | |
| _ swelling pressure/ swelling index | |
| swelling test (Huder-Amberg) | |
| Shear test: | ASTM D3080-90 / ASTM D2435-90 |
| _ total coesion | |
| _ total frictional angle | |
| Triaxial test: | ASTM D4767-88 / BS1377 / ASTM D2850-87 |
| _ drained coesion | |
| _ drained frictional angle | |
| _ undrained coesion | |
| _ total coesion | |
| _ total frictional angle | |
| LABORATORY - ROCK | |
| Index laboratory tests: | ISRM09 |
| _ Density | |
| _ natural water content | |
| _ porosity | |
| Slake durability test | ISRM09 / ASTM D4644-87 |
| Petrographic analyses | ISRM01 |
| Mineralogic analyses | |
| Chemical analyses | |
| Uniaxial compression test (R) | ISRM08 / ASTM D3148-86 / ASTM D2938-86 |
| Point load test (R) | ISRM16 / ISRM25 |
| Triaxial test (R) | ISRM02 / ISRM13 / ASTM D2664-86 |
| | ASTM D4767 / BS1377 / AGI 1994 |
| | ISRM05 / ASTM D2936-84 / ASTM D3967-86 |
| Direct Shear test (R) | ISRM24 |
| Direct tensile test (R) | |
| Brazilian test (R) | |
| Creep | ASTM D4341-84 / ASTM D4406-84 / ASTM D4405-84 |
| Sonic waves test (R) | ASTM D2845-90 / ISRM03 |
| Swelling test (R) | ISRM09 |
| Cyclic tests (wet-dry) (R) | |
| Solubility test (R) | |
| Thermal expansion test (S/R) | ASTM D4611-86 |
| Frozing test (S/R) | |
| Abrasivity | |
| _ Abrasivity | ISRM04 |
| _ Cerchar test (CAI index) | West 1989 |
| _ Abrasivity test (AV – AVS) | NIT 1990 |
| Hardness | |
| _ Hardness | ISRM04 |
| _ Schmith hammer | ISRM 1977 |
| _ Knoop | |
| _ Cone Indenter (INCB) | National Coal Board, UK, 1964 |
| _ Punch test | |
| _ Los Angeles test (S/R) | |

| METHODS | REFERENCE |
|---|---|
| Drillability | |
| • Sievers test | NIT 1990 |
| • Drillability test | |
| • Resistance to crushing : Drop test | NIT 1990 |
| LABORATORY - WATER | |
| Chemical analyses: | |
| • salt content / organic materials | Standard Methods for examination of wa |
| • aggressivity_ | waters. American Public Health Associa |
| • hardness | |
| • pH value | |
| • temperature | |

### 3.1.3. Monitoring during construction

The deterministic design of a tunnel is based on judgment in selecting the most probable values within the ranges of possible values of engineering properties. As construction - progresses the geotechnical - geomechanical conditions are observed, work performance is monitored and the design judgments can be evaluated or, if necessary, updated. Thus, engineering observations during tunnel works are often an integral part of the design process, and geotechnical - geomechanical - instrumentation is a tool, which assists with these observations.

From a general point of view, the scope of the monitoring scheme is to:

A. control the stability and stress - strain conditions of the structures in the new underground construction;

B. control the stability and stress-strain conditions of the existing structures which potentially interfere with the new construction; and

C. control ground movement around the new underground constructions;

D. monitor environmental aspects.

The design of the general monitoring scheme comprises the following activities:

1. identification of the significant parameters which need to be monitored in consideration of:
- construction geometries and materials;
- stability of existing structures (surface and/or underground) and their potential interference with the new construction;
- geotechnical – geomechanical parameters of the ground and their range of variation;
- geo-structural calculations and structural analysis; and
- construction sequence.

2. definition of the adequate types of instruments;

3. specification of the caution and alarm values for each parameter to be monitored;

4. definition of the counter – measures in case that caution and/or alarm leveis are exceeded.

The different investigation/monitoring possibilities are
- from ground surface, or from underground
- before, during and after excavation.

In the following subsections we will only examine the underground investigation/- monitoring systems specifically related to TBM tunneling (investigation before - excavation and monitoring during excavation from underground).

### 3.1.4. TBM tunneling monitoring system

Monitoring systems are used to study the stress-strain behavior of the surrounding ground and lining during and after - construction.

The use of a TBM for the construction of a tunnel does not permit continuous, direct observation of the ground being excavated. Therefore, all the necessary geological-geomechanical information required both during the construction phase for evaluating the ground conditions ahead of the excavation face and subsequently for the purpose of documentation when the work is completed, are normally obtained using indirect methods.

Usually the studies on the interaction between the soil/rock mass and the TBM aim to characterize the quality of the ground mass, above all, to assess its borability.

However, the current problem is an inverse one: given that there is no question that the ground can be excavated, efforts must be focused on the characterization itself through analysis and elaboration of all construction parameters that could possibly be recorded.

Through precise and objective documentation of what the TBM encounters during excavation it is possible to derive the principal - characteristics of the soil/rock mass because variations in TBM behavior are usually correlated with changes in the geotechnical-geomechanical situations.

It is important to underline right from the outset that the prerequisites for making a correct evaluation of the ground mass using all the construction parameters that can possibly be recorded may be summed up as follows:
- the use of a TBM fitted with appropriate instrumentation.
- in this approach skilled engineering geologists with experience should be employed to collect and interpret all the relevant data.
- The data collected should be stored in a dynamic database so that multiple-parameter correlation can be not only established but also continuously updated in quasi-real time, as well as offering the possibility to carry out ground conditions extrapolation and forecasting.

From a tunnel excavated by TBM it is possible to investigate the ground ahead of the tunnel face using the methods listed it Table 3.4.

The TBM monitoring systems which can be used to collect data during tunnel construction are listed in Table 3.5.

Table 3.4: Types of soil/rock mass investigations used ahead TBM face

| INVESTIGATION TYPE | NOTE |
|---|---|
| Direct investigation | |
| Boreholes with core recovery | Horizontal boreholes are normally performed through the TBM cutting head; inclined boreholes are normally possible immediately behind the cutting head in open TBM, through the shield in shielded TBM. Radial boreholes are possible in all TBM types through the lining.<br><br>The objective of boreholes is to:<br><br>_ determine the lithological nature of the ground to be excavated through by the TBM.<br>_ determine the presence of water<br>_ determine thepresence of voids (karst) and/or decompressed zones;<br><br>The drilling is realized with a rig positioned behind the TBM cutting head. In the case of shielded TBMs, it is also possible to utilize a“preventer”system to avoid the ingress of groundwater to the tunnel during execution of the drilling.<br><br>Horizontal and/or inclined boreholes with core-recovery is not commonly used because the time and drilling diameter required. |
| Boreholes without core recovery | The method of no-core-recovery with registration of the following drilling parameters using a data-logger.<br><br>_ drilling rate (**VA**, m/h) ;<br>_ pressure on drill bit (**PO**,bar) ;<br>_ pressure of the drilling fluid (**PI,** bar) ;<br>_ torque (**CR**, bar) ;<br><br>It is possible to use either a drilling hammer or a tricone bit. The diameter of the drill hole may be limited to 75mm, whereas the drilling rods may be of the aluminum type in order to reduce potential problems associated with the advance of the TBM later in the case that the drilling rods might be completely lost in the drill hole. |
| Geostructural mapping of the face and/or of the sidewalls | The mapping must be performed using the same methodologies adopted for the face mapping in tunnels excavated by conventional methods.<br><br>This type of investigation can be performed only when the TBM stops excavation and thus it can be executed at more or less regular intervals in function of the various construction needs. The mapping involves the collection of all geological, structural and geomechanical data of the soil/rock mass. The purpose of this kind of investigation is:<br><br>_ direct characterization and classification of the soil/rock mass;<br>_calibration of all construction parameters which may permit indirect characterization of the rock mass. |
| **Indirect investigation** | |
| Georadar (in borehole) | |
| Other borehole logs | Gamma ray log<br>Neutron logs<br>Geoelectric logs |
| Seismic methods | Tunnel Seismic Prediction method (TSP)<br>Soft Ground Sonic Probing System (SSP) |

Table 3.5: TBM monitoring systems

| Category | | Parameter | UdM | TBMtype |
|---|---|---|---|---|
| Excavation | Cutting head | Power | kW | All TBM |
| | | Torque | Knm | |
| | | Thrust | KN | |
| | | Rotation speed | RPM | |
| | | Penetration rate | mm/s | |
| | Cutting tools | Consumption | - | |
| | | Wedge position | mm | |
| | | | | |
| Support in the excavation chamber | | Air pressure | kPa | Closed slurry shield (hydroshield) Compressed air close shield |
| | | Air discharge | $m^3/h$ | |
| | | Slurry pressure | kPa | Closed slurry shield |
| | | Slurry level | mm | |
| | | Earth pressure | kPa | Earth pressure balance shield |
| | | | | |
| Mucking | Amount | Slurry discharge | $m^3/h$ | Closed slurry shield |
| | | Slurry density | $kg/dm^3$ | |
| | | Discharge | $m^3/h$ | |
| | | Density | $kg/dm^3$ | |
| | | Weight | kN | Unshielded, single-double shielded TBM, mec. supported, comp. air, closed slurry and EPB shields |
| | | Amount | $m^3$ | |
| | Charact. | Petrographic characteristics | - | All TBM (in slurry shield or EPB shield TBM is not required) |
| | | Grain-size distribution | - | |
| | | mechanical parameters | - | |
| | | | | |
| Other parameters | | Shield position (x, y, z) | m | All TBM |
| | | Gripper thrust | kN | Open TBM and some double shielded TBM |
| | | Gripper stroke | mm | |
| | | Jack thrust | kN | Single-double shielded TBM, mec. suppoted, comp. air, closed slurry and EPB shields TBM |
| | | Jacks stroke | mm | |
| | | Injection (through the shield) pressure | kPa | Closed slurry and EPB shield |
| | | Injection (through the shield) amount | $m^3$ | |
| | | Concrete injection pressure | kPa | Shielded TBM with extruded concrete lining system |
| | | Concrete injection amount | $m^3$ | |
| | | | | |
| Construction data | Performance | Excavation cycle (min. - med. - max.) | h | All TBM |
| | | Advance rate per shift/day/week/month | m | |
| | | Lining rings per shift/day/week/month | N° | |
| | TBM stops | Planned (holidays, tools change, other ordinary maintenance) | h | |
| | | Due to machine problem (mechanical, electrical, etc.) | h | |
| | | Due to unpredicted rock mass behavior, (water inflow, tunnel face and /or cavity instabilities, squeezing ground, karst, etc.) | h | |
| | | Due to lining problems | h | |
| | | Diverse (back-up problems, others) | h | |
| | | Due to mucking system problems (slurry circuit, screw conveyor, belt conveyor, muck cars, etc.) | h | |

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# AFTES

## NEW RECOMMENDATIONS ON

# CHOOSING MECHANIZED TUNNELLING TECHNIQUES

A.F.T.E.S. will be pleased to receive any suggestions concerning these recommendations

Version 1 - 2000 -approved by the Technical Committee of 23 November 1999 Translated in 2000

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## INTRODUCTION

The first recommendations on mechanized tunnelling techniques issued in 1986 essentially concerned hard-rock machines.

The shape of the French market has changed a great deal since then. The development of the hydropower sector which was first a pioneer, then a big user of mechanized tunnelling methods has peaked and is now declining. In its place, tunnels now concern a range of generally urban works, i.e. sewers, metros, road and rail tunnels.

Since most of France's large urban centres are built on the flat, and often on rivers, the predominant tunnelling technique has also switched from hard rock to loose or soft ground, often below the water table.

To meet these new requirements, France has picked up on trends from the east (Germany and Japan).

Faced with France's extremely varied geology, project owners, contractors, engineers, and suppliers have adapted these foreign techniques to their new conditions at astonishing speed.

Now, this new French technical culture is being exported throughout the world (Germany, Egypt, United Kingdom, Australia, China, Italy, Spain, Venezuela, Denmark, Singapore, etc.).

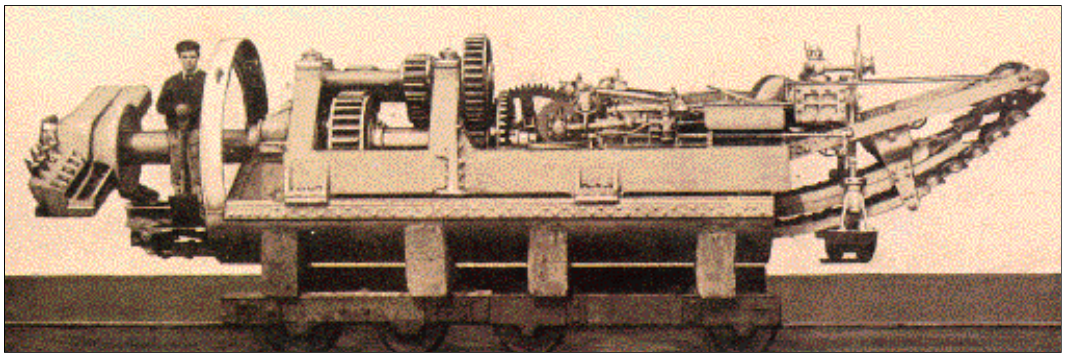
This experience forms the basis for these recommendations, drawn up by a group of 25 professionals representing the different bodies involved.

Before the large number of parameters and selection criteria, this group soon realized that it was not possible to draw up an analytical method for choosing the most appropriate mechanized tunnelling method, but rather that they could provide a document which:

1) clarifies the different techniques, describing and classifying them in different groups and categories,

2) analyzes the effect of the selection criteria (geological, project, environmental aspects, etc.),

3) highlights the special features of each technique and indicates its standard scope of application, together with the possible accompanying measures.In other words, these new recommendations do not provide ready-made answers, but guide the reader towards a reasoned choice based on a combination of technical factors.



Beaumont machine, 1882. First attempt to drive a tunnel beneath the English Channel.

# CONTENTS

# 1 - PURPOSE OF THESE RECOMMENDATIONS

These recommendations supersede the previous version which was issued in 1986 and which dealt essentially with hard-rock or "main-beam" tunnel boring machines (TBMs).

The scope of this revised version has been broadened to include all (or nearly all) types of tunnelling machines.

The recommendations are intended to serve as a technical guide for the difficult and often irreversible choice of a tunnel boring machine consistent with the expected geological and hydrogeological conditions, the environment, and the type of the tunnel project.

To start with, the different kinds of machines are classified by group, category, and type. Since all the machines share the common characteristic of excavating tunnels mechanically, the first criterion for classification is naturally the machine's ability to provide immediate support to the excavation.

This is followed by a list of the parameters which should be analyzed in the selection process, then by details of the extent to which these parameters affect mechanized tunnelling techniques, and finally a series of fundamental comments on the different kinds of machine.

By combining these parameters, decision-makers will arrive at the optimum choice.

The principal specific features of the different groups and categories of techniques are then outlined, and the fundamental fields of application of each category are explained.

Lastly, accompanying techniques, which are often common to several techniques and vital for proper operation of the machine, are listed and detailed. It should be noted that data logging techniques have meant remarkable progress has been made in technical analysis of the problems that can be encountered.

Since health and safety are of constant concern in underground works, a special chapter is devoted to the matter.

# 2 - MECHANIZED TUNNELLING TECHNIQUES

## *2.1 - DEFINITION AND LIMITS*

For the purposes of these recommendations, "mechanized tunnelling techniques" (as opposed to the so-called "conventional" techniques) are all the tunnelling techniques in which excavation is performed mechanically by means of teeth, picks, or discs. The recommendations therefore cover all (or nearly all) categories of tunnelling machines, ranging from the simplest (backhoe digger) to the most complicated (confinement-type shield TBM).

The mechanized shaft sinking techniques that are sometimes derived from tunnelling techniques are not discussed here.

For drawing up tunnelling machine supply contracts, contractors should refer to the recommendations of AFTES WG 17, "Pratiques contractuelles dans les travaux souterrains ; contrat de fourniture d'un tunnelier" (Contract practice for underground works; tunnelling machine supply contract) (TOS No. 150 November/December 1998).

## *2.2 - BASIC FUNCTIONS*

### 2.2.1 - Excavation

Excavation is the primary function of all these techniques.

The two basic mechanized excavation techniques are:

- Partial-face excavation
- Full-face excavation

With partial-face excavation, the excavation equipment covers the whole sectional area of the tunnel in a succession of sweeps across the face.

With full-face excavation, a cutterhead - generally rotary - excavates the entire sectional area of the tunnel in a single operation.

### 2.2.2 - Support and opposition to hydrostatic pressure

Tunnel support follows excavation in the hierarchy of classification.

"Support" here means the immediate support provided directly by the machine (where applicable).

A distinction is made between the techniques providing support only for the tunnel walls, roof, and invert (peripheral support) and those which also support the tunnel face (peripheral and frontal support).

There are two types of support: passive and active. Passive or "open-face" support reacts passively against decompression of the surrounding ground. Active or "confinement-pressure" support provides active support of the excavation.

Permanent support is sometimes a direct and integral part of the mechanized tunnelling process (segmental lining for instance). This aspect has been examined in other AFTES recommendations and is not discussed further here.

Recent evolution of mechanized tunnelling techniques now enables tunnels to be driven in unstable, permeable, and water-bearing ground without improving the ground beforehand. de ceux-ci.This calls for constant opposition to the hydrostatic pressure and potential water inflow. Only confinement-pressure techniques meet this requirement.

### 2.2.3 - Mucking out

Mucking out of spoil from the tunnel itself is not discussed in these recommendations. However, it should be recalled that mucking out can be substantially affected by the tunnelling technique adopted. Inversely, the constraints associated with mucking operations or spoil treatment sometimes affect the choice of tunnelling techniques.

The basic mucking-out techniques are:

- haulage by dump truck or similar
- haulage by train
- hydraulic conveyance system
- pumping (less frequent)
- belt conveyors

## *2.3 - MAIN RISKS AND ADVANTAGES OF MECHANIZED TUNNELLING TECHNIQUES*

The advantages of mechanized tunnelling are multiple. They are chiefly:

- enhanced health and safety conditions for the workforce,
- industrialization of the tunnelling process, with ensuing reductions in costs and lead-times,
- the possibility some techniques provide of crossing complex geological and hydrogeological conditions safely and economically,
- the good quality of the finished product (surrounding ground less altered, precast concrete lining segments, etc.)

However, there are still risks associated with mechanized tunnelling, for the choice of technique is often irreversible and it is often impossible to change from the technique first applied, or only at the cost of immense upheaval to the design and/or the economics of the project.

Detailed analysis of the conditions under which the project is to be carried out should substantially reduce this risk, something for

which these recommendations will be of great help. The experience and technical skills of tunnelling machine operators are also an important factor in the reduction of risks.

## 3 - CLASSIFICATION OF MECHANIZED TUNNELLING TECHNIQUES

It was felt to be vital to have an official classification of mechanized tunnelling techniques in order to harmonize the terminology applied to the most common methods.

The following table presents this classification. The corresponding definitions are given in Chapter 4.

The table breaks the classification down into groups of machines (e.g. boom-type unit) on the basis of a preliminary division into types of immediate support (none, peripheral, peripheral and frontal) provided by the tunnelling technique.

To give more details on the different techniques, the groups are further broken down into categories and types.

## 4 - DEFINITION OF THE DIFFERENT MECHANIZED TUNNELLING TECHNIQUES CLASSIFIED IN CHAPTER 3

### *4.1 - MACHINES NOT PROVIDING IMMEDIATE SUPPORT*

#### 4.1.1 - General

Machines not providing immediate support are necessarily those working in ground not requiring immediate and continuous tunnel support.

#### 4.1.2 - Boom-type tunnelling machine

Boom-type units (sometimes called "tunnel heading machines") are machines with a selective excavation arm fitted with a tool of some sort. They work the face in a series of sweeps of the arm. Consequently the faces they excavate can be both varied and variable. The penetration force of the tools is resisted solely by the weight of the machineLa réaction à.

This group of machines is fitted with one of three types of tool:

- Backhoe, ripper, or hydraulic impact breaker
- In-line cutterhead (roadheader)
- Transverse cutterhead (roadheader)

AFTES data sheets: No. 8 – 14 (photo 4.1.2)

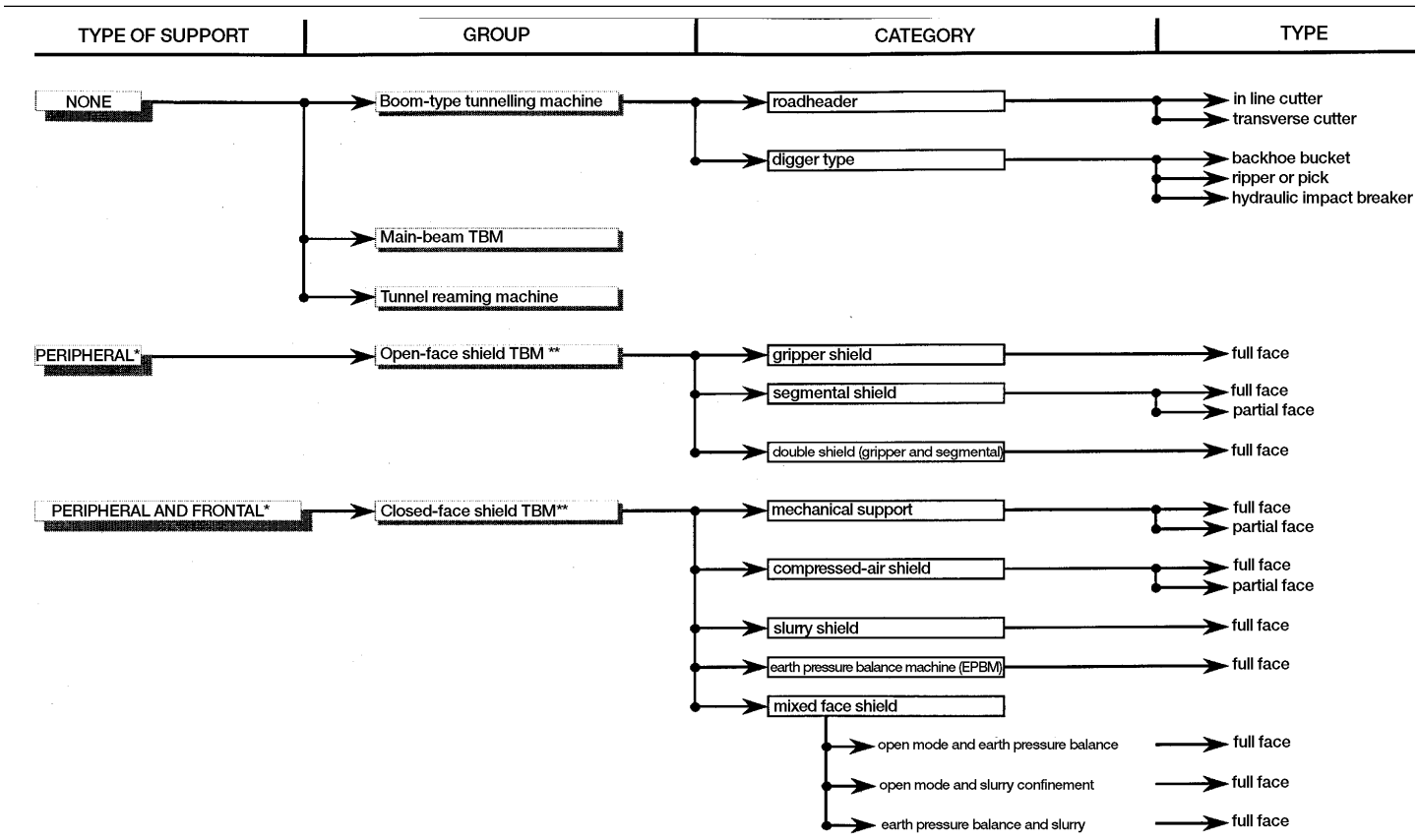
#### 4.1.3 - Main-beam TBM

A main-beam TBM has a cutterhead that excavates the full tunnel face in a single pass.

The thrust on the cutterhead is reacted by bearing pads (or grippers) which push radially against the rock of the tunnel wall.

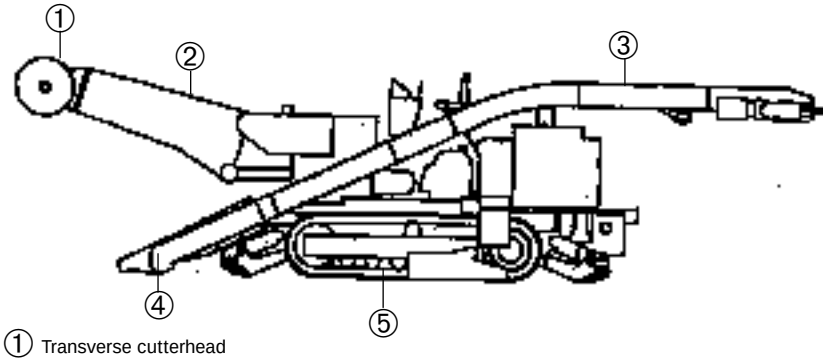
The machine advances sequentially, in two phases:

- Excavation (the gripper unit is stationary)
- Regripping




*For microtunnellers (diameter no greater than 1200 mm), refer to the work of the ISTT.
**Machines used in pipe-jacking and pipe-ramming are included in these groups.

CLASSIFICATION OF MECHANIZED TUNNELLING TECHNIQUES




1 Transverse cutterhead
2 Boom
3 Muck conveyor
4 Loading apron
5 Crawler chassis

Schéma 4.1.2

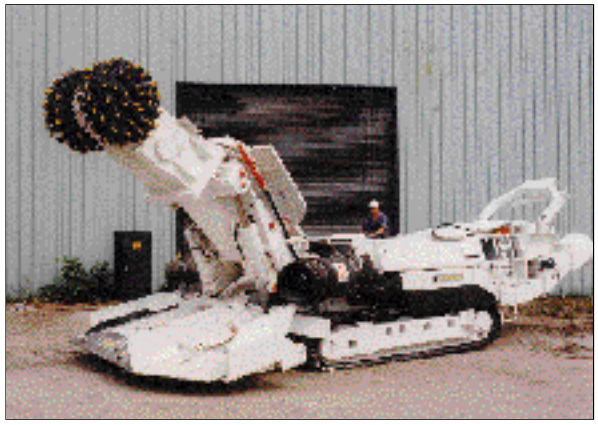


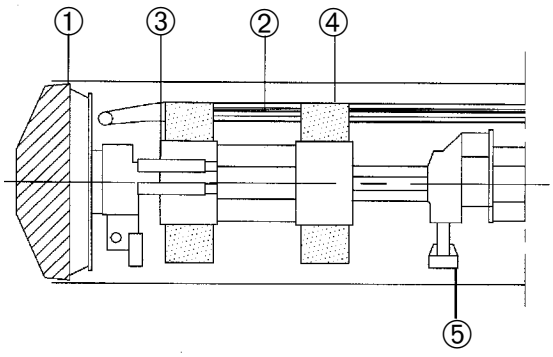
Photo 4.1.2 - Roadheader

Spoil is collected and removed rearwards by the machine itself.

This type of TBM does not play an active role in immediate tunnel support.

AFTES data sheets: No. 1 to 7, 10 to 13, 15 to 24, 26 to 30, 67(photo 4.1.3)

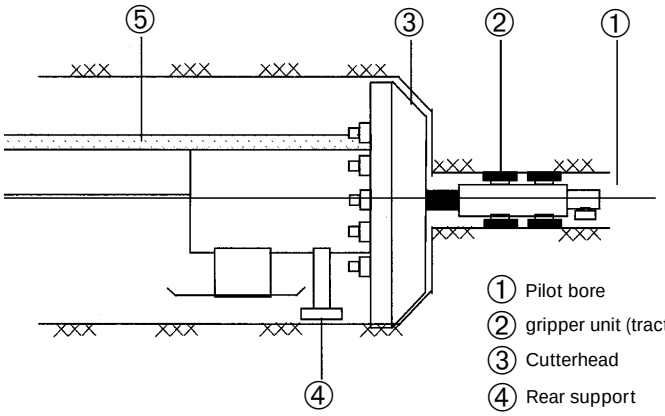
Photo 4.1.3 - Lesotho Highlands Water Project




1 Canopy/Hood/Roof
2 Rear gripper
3 Front gripper
4 Muck conveyor
5 Rear lift leg

## 4.1.4 - Tunnel reaming machine

A tunnel reaming machine has the same basic functions as a main-beam TBM. It bores the final section from an axial tunnel (pilot bore) from which it pulls itself forward by means of a gripper unit.




1 Pilot bore
2 gripper unit (traction)
3 Cutterhead
4 Rear support
5 Muck conveyor

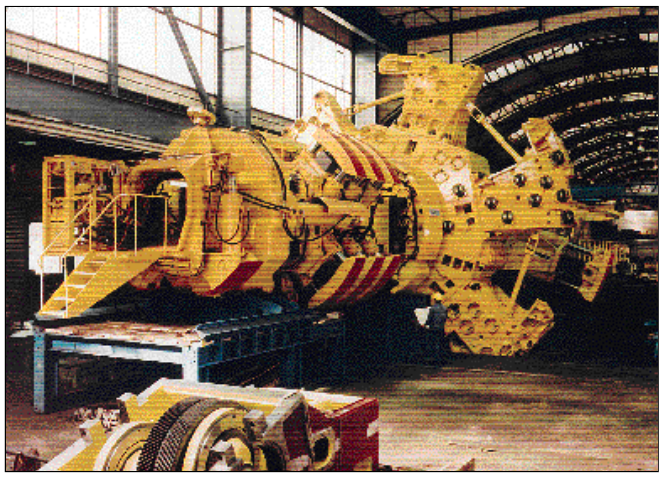


Photo 4.1.4 - Sauges tunnel (Switzerland)

## *4.2 - MACHINES PROVI - DING IMMEDIATE PERIPHE - RAL SUPPORT*

### 4.2.1 - General

Machines providing immediate peripheral support only belong to the open-face TBM group.

While they excavate they also support the sides of the tunnel. The tunnel face is not supported. d'aucune façon.

They can have two types of shield:

- one-can shield,
- shield of two or more cans connected by articulations.

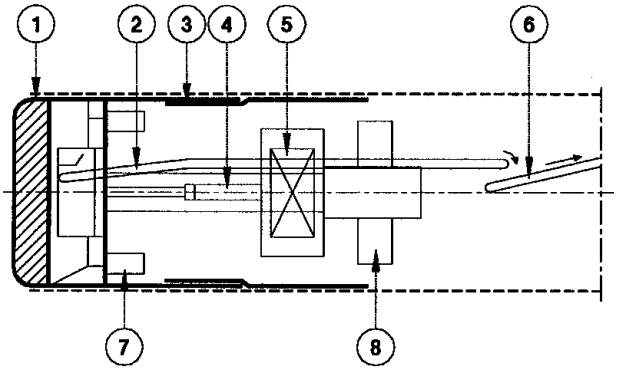
The different configurations for peripheral-support TBMs are detailed below.

### 4.2.2 - Open-face gripper shield TBM

A gripper shield TBM corresponds to the definition given in § 4.1.32 except that it is mounted inside a cylindrical shield incorporating grippers.

The shield provides immediate passive peripheral support to the tunnel walls.

AFTES data sheet: N° 25 ▼




① Cutterhead
② Muck extraction conveyor
③ Télescopic section
④ Thrust ram
⑤ Grippers (radial thrust)
⑥ Muck transfer conveyor
⑦ Motor
⑧ Segment erector

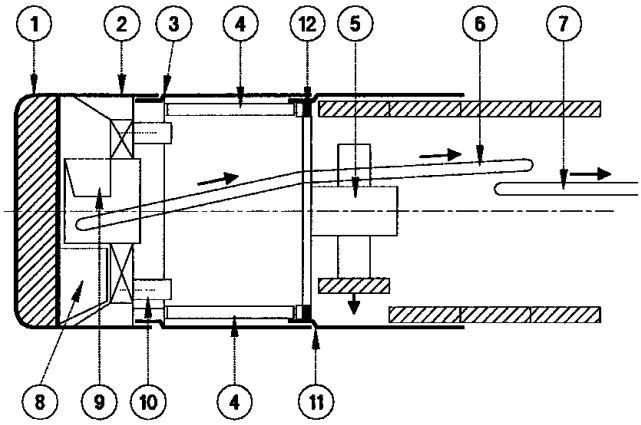

Photo 4.2.2 - Main CERN tunnel

### 4.2.3 - Open-face segmental shield TBM

An open-face segmental shield TBM is fitted with either a full-face cutterhead or an excavator arm like those of the different boom-type units. To advance and tunnel, the TBM's longitudinal thrust rams react against the tunnel lining erected behind it by a special erector incorporated into the TBM.

AFTES data sheets: No. 31 - 32 - 41 - 66

▼




a Cutterhead
b Shield
c Articulation (option)
d Thrust ram
e Segment erector
f Muck extraction conveyor
g Muck transfer conveyor
h Gathering arm
i Muck hopper
j Motor
k Tailskin articulation (option)
l Thrust ring

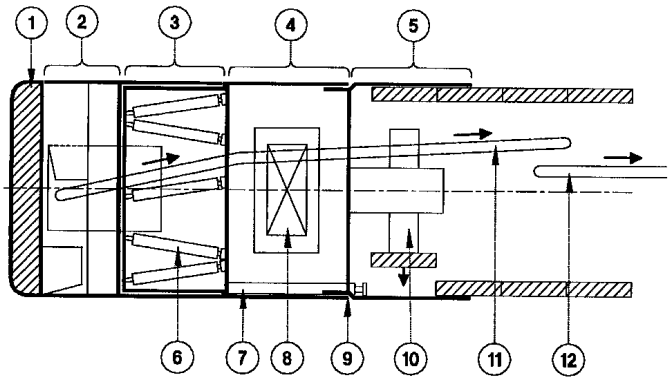
Photo 4.2.3
Athens metro

### 4.2.4 - Double shield

A double shield is a TBM with a full-face cutterhead and two sets of thrust rams that react against either the tunnel walls (radial grippers) or the tunnel lining. The thrust method used at any time depends on the type of ground encountered. With longitudinal thrust, segmental lining must be installed behind the machine as it advances.

The TBM has three or more cans connected by articulations and a telescopic central unit which relays thrust from the gripping/thrusting system used at the time to the front of the TBM.

AFTES data sheets: No. 65 – 68 – 71




a Cutterhead
b Front can
c Telescopic section
d Gripper unit
e Tailskin
f Main thrust rams
g Longitudinal thrust rams
h Grippers
i Tailskin articulation (option)
j Segment erector
k Muck extraction conveyor
l Muck transfer conveyor

Photo 4.2.4 - Salazie water transfer project (Reunion Island)

## *4.3 - MACHINES PROVIDING IMMEDIATE PERIPHERAL AND FRONTAL SUPPORT SIMULTANEOUSLY*

### 4.3.1 - General

The TBMs that provide immediate peripheral and frontal support simultaneously belong to the closed-faced group.

They excavate and support both the tunnel walls and the face at the same time.

Except for mechanical-support TBMs, they all have what is called a cutterhead chamber at the front, isolated from the rearward part of the machine by a bulkhead, in which a confinement pressure is maintained in order to actively support the excavation and/or balance the hydrostatic pressure of the groundwater.

The face is excavated by a cutterhead working in the chamber.

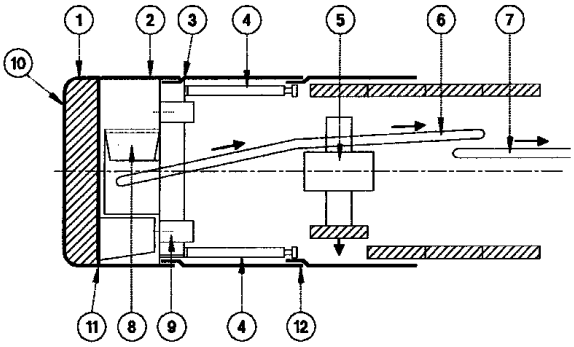
The TBM is jacked forward by rams pushing off the segmental lining erected inside the TBM tailskin, using an erector integrated into the machine.

### 4.3.2 - Mechanical-support TBM

A mechanical-support TBM has a full-face cutterhead which provides face support by constantly pushing the excavated material ahead of the cutterhead against the surrounding ground.

Muck is extracted by means of openings on the cutterhead fitted with adjustable gates that are controlled in real time.

AFTES data sheets: No. 38 – 39 – 40 – 51 – 58 – 64




a Cutterhead
b Shield
c Articulation (option)
d Thrust ram
e Segment erector
f Muck extraction conveyor
g Muck transfer conveyor
h Muck hopper (with optional gate)
i Cutterhead drive motor
j Gated cutterhead openings
k Peripheral seal between cutterhead and shield
l Tailskin articulation (option)

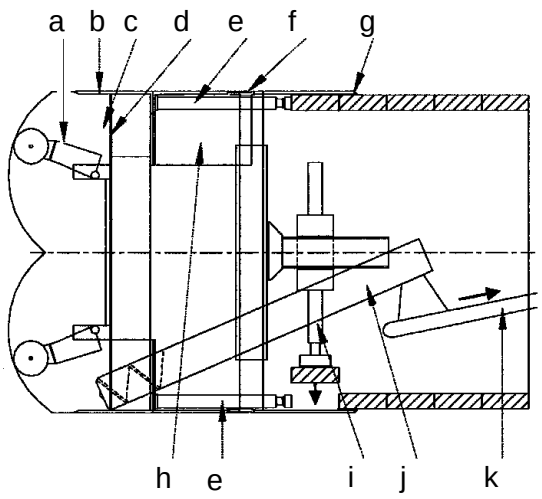

Photo 4.3.2
RER Line D (Pa ris)

### 4.3.3 - Compressed-air TBM

A compressed-air TBM can have either a full-face cutterhead or excavating arms like those of the different boom-type units. Confinement is achieved by pressurizing the air in the cutting chamber.

Muck is extracted continuously or intermittently by a pressure-relief discharge system that takes the material from the confinement pressure to the ambient pressure in the tunnel.

AFTES data sheets: No. 37 – 42 – 43 – 53 – 54 – 70



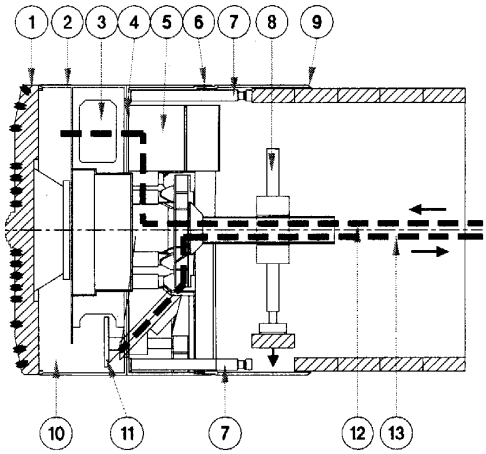

a Excavating arm
b Shield
c Cutting chamber
d Airtight bulkhead
e Thrust ram
f Articulation (option)
g Tailskin seal
h Airlock to cutting chamber
i Segment erector
j Screw conveyor (or conveyor and gate)
k Muck transfer conveyor

Photo 4.3.3 - Compressed air TBM - Boom type

### 4.3.4 - Slurry shield TBM

A slurry shield TBM has a full-face cutterhead. Confinement is achieved by pressurizing boring fluid inside the cutterhead chamber. Circulation of the fluid in the chamber flushes out the muck, with a regular pressure being maintained by directly or indirectly controlling discharge rates.

AFTES data sheets:
No. 33 – 34 – 35 – 36 – 44 – 50 – 52 – 56 – 57 - 60 – 62 – 63 – 69 – 76 – Cairo – Sydney




a Cutterhead
b Shield
c Air bubble
d Watertight bulkhead
e Airlock to cutterhead chamber
f Tailskin articulation (option)
g Thrust ram
h Segment erector
i Tailskin seal
j Cutterhead chamber
k Agitator (option)
l Slurry supply line
m Slurry return line

Photo 4.3.4 - Cairo metro

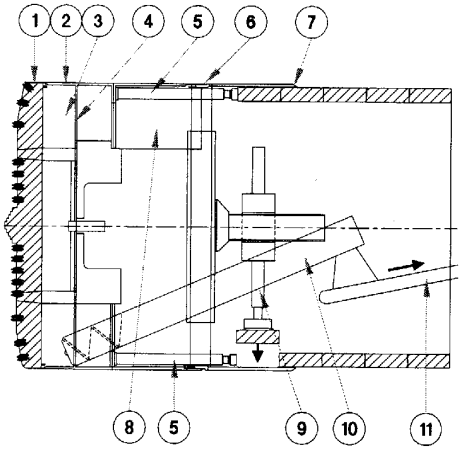
### 4.3.5 - Earth pressure balance machine

An earth pressure balance machine (EPBM) has a full-face cutterhead. Confinement is achieved by pressurizing the excavated material in the cutterhead chamber. Muck is extracted from the chamber continuously or intermittently by a pressure-relief discharge system that takes it from the confinement pressure to the ambient pressure in the tunnel.

EPBMs can also operate in open mode or with compressed-air confinement if specially equipped.

AFTES data sheets: No. 45 – 46 - 47 – 48 – 49 – 55 – 59 – 61 – 72 – 73 – 74* - 77 to 85

*TBMs also working with compressed-air confinement




a Cutterhead
b Shield
c Cutterhead chamber
d Airtight
e Thrust ram
f Articulation (option)
g Tailskin seal
h Airlock to cutterheau chamber
i Segment erector
j Screw conveyor
k Muck transfer conveyor

Photo 4.3.5 - CaluireTunnel, Lyons (France)

### 4.3.6 - Mixed-face shield TBM

Mixed-face shield TBMs have full-face cutterheads and can work in closed or open mode and with different confinement techniques.

Changeover from one work mode to another requires mechanical intervention to change the machine configuration.

Different means of muck extraction are used for each work mode.

There are three main categories of machine:

- Machines capable of working in open mode, with a belt conveyor extracting the muck, and, after a change in configuration, in closed mode, with earth pressure balance confinement provided by a screw conveyor;
- Machines capable of working in open mode, with a belt conveyor extracting the muck, and, after a change in configuration, in closed mode, with slurry confinement provided by means of a hydraulic mucking out system (after isolation of the belt conveyor);
- Machines capable of providing earth pressure balance and slurry confinement.

TBMs of this type are generally restricted to large-diameter bores because of the space required for the special equipment required for each confinement method.

AFTES data sheets: A86 Ouest (Socatop), Madrid metro packages 2 & 4, KCR 320 (Hong Kong)

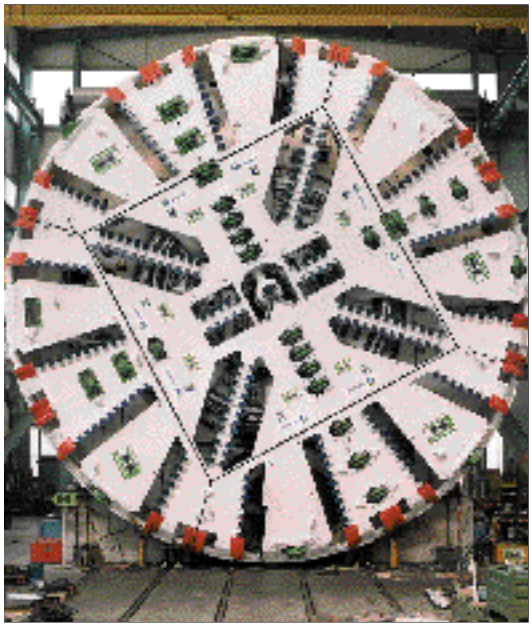


Photo 4.3.6a
A86 Oues tunnel (Socatop)

Photo 4.3.6b - A86 Ouest tunnel (Socatop)
Madrid metro

## 5 - EVALUATION OF PARAMETERS FOR CHOICE OF MECHANIZED TUNNELLING TECHNIQUES

### *5.1.GENERAL*

It was felt useful to assess the degree to which elementary parameters of all kinds affect the decision-making process for choosing between the different mechanized tunnelling techniques.

The objectives of this evaluation are:

• to rank the importance of the elementary selection parameters, with some indication of the basic functions concerned.

• to enable project designers envisaging a mechanized tunnelling solution to check that all the factors affecting the choice have been examined.

• to enable contractors taking on construction of a project for which mechanized tunnelling is envisaged to check that they are in possession of all the relevant information in order to validate the solution chosen.

This evaluation is presented in the form of two tables (Tables 1 and 2).

Table 1 (§ 5.2.) indicates the degree to which each of the elementary selection parameters affects each of the basic functions of mechanized tunnelling techniques (all techniques combined).

Table 2 (§ 5.3) indicates the degree to which each of the elementary selection parameters affects each individual mechanized tunnelling technique.

These evaluation tables are complemented by comments in the appendix.

The list of parameters is based on that drawn up by AFTES recommendations work group No. 7 in its very useful document "Choix des paramètres et essais géotechniques utiles à la conception, au dimensionnement et à l'exécution des ouvrages creusés en souterrain" (Choice of geotechnical parameters and tests of relevance to the design and construction of underground works). This initial list has been complemented by factors other than geotechnical ones.

## 5.2 - EVALUATION OF THE EFFECT OF ELEMENTARY SELECTION PARAMETERS ON THE BASIC FUNCTIONS OF MECHANIZED TUNNELLING TECHNIQUES

| Elementary parameters \ Basic function | SUPPORT | | OPPOSITION TO HYDROSTATIC PRESSURE | EXCAVATION | MUCKING OUT, EXTRACTION, TRANSPORT STOCKPILING |
|---|---|---|---|---|---|
| | Frontal | Peripherical | | | |
| | A | B | C | D | E |
| 1. NATURAL CONTRAINTS | 2 | 2 | SO | 1 | 0 |
| 2. PHYSICAL PARAMETERS | | | | | |
| 2.1 Identification | 2 | 1 | 2 | 2 | 1 |
| 2.2 Global appreciation of quality | 2 | 2 | 0 | 1 | 0 |
| 2.3 Discontinuities | 2 | 2 | 2 | 1 | 0 |
| 2.4 Alterability | 1 | 1 | SO | 1 | 1 |
| 2.5 Water chemistry | 1 | 0 | SO | 0 | 1 |
| 3. MECHANICAL PARAMETERS | | | | | |
| 3.1 Strength Soft ground | 2 | 2 | SO | 1 | 0 |
| Hard rock | 1 | 1 | SO | 2 | 0 |
| 3.2 Deformability | 2 | 2 | SO | 0 | 0 |
| 3.3 Liquefaction potential | 0 | 0 | 0 | 0 | 0 |
| 4. HYDROGEOLOGICAL PARAMETERS | 2 | 2 | 2 | 1 | 0 |
| 5. OTHER PARAMETERS | | | | | |
| 5.1 Abrasiveness - Hardness | 0 | 0 | 0 | 2 | 1 |
| 5.2 Propensity to stick | 0 | 0 | 0 | 2 | 2 |
| 5.3 Ground/machine friction | 0 | 1 | 0 | 0 | 0 |
| 5.4 Présence of gas | 0 | 0 | 0 | 0 | 0 |
| 6. PROJECT CHARACTERISTICS | | | | | |
| 6.1 Dimensions, shape | 2 | 2 | 2 | 1 | 2 |
| 6.2 Vertical alignment | 0 | 0 | 0 | 0 | 2 |
| 6.3 Horizontal alignment | 0 | 0 | 0 | 0 | 1 |
| 6.4 Environment | | | | | |
| 6.4.1 Sensitivity to settlement | 2 | 2 | 2 | 0 | 0 |
| 6.4.2 Sensitivity to disturbance and work constraints | 0 | 0 | 0 | 0 | 2 |
| 6.5 Anomalies in ground | | | | | |
| 6.5.1 Heterogeneity of ground in tunnel section | 1 | 1 | 0 | 2 | 0 |
| 6.5.2 Natural/artificial obstacles | 0 | 0 | 0 | 1 | 0 |
| 6.5.3 Voids | 2 | 2 | 2 | 0 | 0 |

2 : Decisive 1 : Has effect 0: No effect SO: Not applicable

See comments on this table in Appendix 1

Table 1

## 5.3 - EVALUATION DE L'INFLUENCE DES PARAMETRES ELEMENTAIRES DE CHOIX POUR LES SOLUTIONS DE TECHNIQUES D'EXCAVATION MECANISEE

| Solution / Paramètres élémentaires | Machine n'assurant pas de soutènement | | Machine assurant un soutènement laté- | | | Machine assurant un soutènement latéralet frontal | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Machine à attaque ponctuelle | Aléseur et tunnelier à appui latéral | Bouclier mécanisé ouvert à appui radial | Bouclier mécanisé ouvert à appui longitudinal | | Bouclier mécanisé à soutène-ment méca- | Bouclier mécanisé à confinement d'air comprimé | | Bouclier mécanisé à confinement de boue | Bouclier mécanisé à confinement de terre |
| | | | | A attaque pleine face | A attaque ponctuelle | | A attaque pleine face | A attaque ponctuelle | | |
| 1. NATURAL CONTRAINTS | 0 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 1 |
| 2. PHYSICAL PARAMETERS | | | | | | | | | | |
| 2.1 Identification | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 2.2 Global appreciation of quality | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 2.3 Soft ground/hard rock discontinuities | 1/2 | 1/2 | SO/2 | 1/2 | 1/2 | 1/2 | 2/2 | 2/2 | 2/2 | 1/2 |
| 2.4 Alterability | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2.5 Water chemistry | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 3. MECHANICAL PARAMETERS | | | | | | | | | | |
| 3.1 Strength | | | | | | | | | | |
| For soft ground | 2 | 2 | SO | 2 | 2 | 2 | 1 | 2 | 1 | 1 |
| For hard ground | 2 | 1 | 1 | SO | 2 | 1 | 1 | 2 | 1 | 1 |
| 3.2 Deformability | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3.3 Liquefaction potential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4. HYDROGEOLOGICAL PARAMETERS | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 5. OTHER PARAMETERS | | | | | | | | | | |
| 5.1 Abrasiveness - Hardness | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 ou 2 |
| 5.2 Propensity to stick | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5.3 Ground/machine friction | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 5.4 Presence of gas | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 6. PROJECT CHARACTERISTICS | | | | | | | | | | |
| 6.1 Dimensions, shape | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| 6.2 Vertical alignment | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 6.3 Horizontal alignment | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 6.4 Environment | | | | | | | | | | |
| 6.4.1 Sensitivity to settlement | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| 6.4.2 Sensitivity to disturbance and work constraints | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 à 2 | 1 |
| 6.5 Anomalies in ground | | | | | | | | | | |
| 6.5.1 Heterogeneity of ground | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 à 2 |
| 6.5.2 Natural/artificial obstacles | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 à 2 |
| 6.5.3 Voids | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

2: Decisive 1: Has effect 0: No effect SO: Not applicable

See comments on this table in Appendix 2

Table 2

# 6 - SPECIFIC FEATURES OF THE DIFFERENT TUNNELLING TECHNIQUES

## *6.1 - MACHINES PROVIDING NO IMMEDIATE SUPPORT*

### 6.1.1 - Specific features of boom-type tunnelling machines

*a) General*

Boom-type tunnelling machines are generally suited to highly cohesive soils and soft rock. They consist of an excavating arm or boom mounted on a self-propelling chassis. There is no direct relationship between the machine and the shape of the tunnel to be driven; the tunnel cross-sections excavated can be varied and variable. The face can be accessed directly at all times. Since these machines react directly against the tunnel floor, the floor must have a certain bearing capacity.

*b) Excavation*

The arms or booms of these machines are generally fitted with a cutting or milling head which excavates the face in a series of sweeps. These machines are called roadheaders. The maximum thrust on the roadheader cutterhead is directly related to the mass of the machine. The cutters work either transversally (perpendicular to the boom) or in-line (axially, about the boom axis). In most cases the spoil falling from the face is gathered by a loading apron fitted to the front of the machine and transported to the back of the machine by belt conveyor. This excavation method generates a lot of dust which has to be controlled (extraction, water spray, filtering, etc.).

In some cases the cutterhead can be replaced by a backhoe bucket, ripper, or hydraulic impact breaker.

*c) Support and opposition to hydrostatic pressure*

There is no tunnel support associated with this type of machine. It must be accompanied by a support method consistent with the shape of the tunnel and the ground conditions encountered (steel ribs, rockbolts, shotcrete, etc.).

This type of machine cannot oppose hydrostatic pressure, so accompanying measures (ground improvement, groundwater lowering, etc.) may be necessary.

*d) Mucking out*

Mucking out can be associated with this kind of machine or handled separately. It can be done directly from the face.

### 6.1.2 - Specific features of main-beam TBMs

*a) General*

The thrust at the cutterhead is reacted to one or two rows of radial thrust pads or grippers which take purchase directly on the tunnel walls. As with shield TBMs, a trailing backup behind the machine carries all the equipment it needs to operate and the associated logistics. Forward probe drilling equipment is generally fitted to this type of TBM. The face can be accessed by retracting the cutterhead from the face when the TBM is stopped.

The machine advances sequentially (bore, regrip, bore again).

*b) Excavation*

These full-face TBMs generally have a rotary cutterhead dressed with different cutters (disc cutters, drag bits, etc.). Muck is generally removed by a series of scrapers and a bucket chain which delivers it onto a conveyor transferring it to the back of the machine. Water spray is generally required at the face both to keep dust down and to limit the temperature rise of the cutters.

*c) Support and opposition to hydrostatic pressure*

Tunnel support is independent of the machine (steel ribs, rockbolts, shotcrete, etc.) but can be erected by auxiliary equipment mounted on the beam and/or backup. If support is erected from the main beam, it must take account of TBM movement and the gripper advance stroke. The cutterhead is not generally designed to hold up the face. A canopy or full can is sometimes provided to protect operators from falling blocks.

This kind of TBM cannot oppose hydrostatic pressure. Accompanying measures (groundwater lowering, drainage, ground improvement, etc.) are required if the expected pressures or inflows are high.

*d) Mucking out*

Mucking out is generally done with wagons or by belt conveyor. It is directly linked to the TBM advance cycle.

### 6.1.3. Specific features of tunnel reaming machines

*a) General*

Tunnel reaming machines work in much the same way as main-beam TBMs, except that the cutterhead is pulled rather than pushed. This is done by a traction unit with grippers in a pilot bore. As with all main-beam and shield machines, the cutterhead is rotated by a series of hydraulic or electric motors. The tunnel can be reamed in a single pass with a single cutterhead or in several passes with cutterheads of increasing diameter.

*b) Excavation*

See Chapter 6.1.2 § b) (main-beam TBM).

*c) Support and opposition to hydrostatic pressure*

The support in the pilot bore must be destructible (glass-fibre rockbolts) or removable (steel ribs) so that the cutterhead is not damaged. The final support is independent of the reaming machine, but can be erected from its backup.

For details on opposition to the hydrostatic pressure, see Chapter 6.1.2 § c (main-beam TBM).

*d) Mucking out*

See Chapter 6.1.2.§ d) (main-beam TBM).

## *6.2 - SPECIFIC FEATURES OF MACHINES PROVIDING IMMEDIATE PERIPHERAL SUPPORT*

### 6.2.1 - Specific features of open-face gripper shield TBMs

*a) General*

An open-face gripper shield TBM is the same as a main-beam TBM except that it has a cylindrical shield.

The thrust of the cutterhead is reacted against the tunnel walls by means of radial pads (or grippers) taking purchase through openings in the shield or immediately behind it. As with other TBM types, a backup trailing behind the TBM carries all the equipment it needs to operate, together with the associated logistics.

The TBM does not thrust against the tunnel lining or support.

*b) Excavation*

See Chapter 6.1.2 § b) (main-beam TBM).

*c) Support and opposition to hydrostatic pressure*

The TBM provides immediate passive peripheral support. It also protects workers from the risk of falling blocks. If permanent tunnel support is required, it consists either of segments (installed by an erector on the TBM) or of support erected independently.

This type of machine cannot oppose hydrostatic pressure, so accompanying measures (ground improvement, groundwater lowering, etc.) may be necessary when working in water-bearing or unstable terrain.

*d) Mucking out*

See Chapter 6.1.2 § d) (main-beam TBM).

### 6.2.2 - Specific features of open-face segmental shield TBMs

*a) General*

An open-face shield segmental TBM has either a full-face cutterhead or an excavating arm like those of the different boom-type tunnelling machines. The TBM is thrust forward by rams reacting longitudinally against the tunnel lining erected behind it.

*b) Excavation*

TBM advance is generally sequential:

1) boring under thrust from longitudinal rams reacting against the tunnel lining

2) retraction of thrust rams and erection of new ring of lining.

*c) Support and opposition to hydrostatic pressure*

The TBM provides passive peripheral support and also protects workers from the risk of falling blocks.

The tunnel face must be self-supporting. Even a full-face cutterhead can only hold up the face under exceptional conditions (e.g. limitation of collapse when the TBM is stopped).

Temporary or final lining is erected behind the TBM by an erector mounted on it. It is against this lining that the rams thrust to push the machine forward.

This type of machine cannot oppose hydrostatic pressure, so accompanying measures (ground improvement, groundwater lowering, etc.) may be necessary when working in water-bearing or unstable terrain.

*d) Mucking out*

Muck is generally removed by mine cars or belt conveyors. Mucking out is directly linked to the TBM advance cycle.

### 6.2.3 - Specific features of double shield TBMs

Double shield TBMs combine radial purchase by means of grippers with longitudinal purchase by means of thrust rams reacting against the lining. A telescopic section at the centre of the TBM makes it possible for excavation to continue while lining segments are being erected.

Excavation proceeds as follows: with the rear section of the TBM secured by the grippers, the front section thrusts against it by means of the main rams between the two sections, and tunnels forward. A ring of segmental lining segments is erected at the same time. The grippers are then released and the longitudinal rams thrust against the tunnel lining to shove the rear section forward. The rear section regrips and the cycle is repeated.

## 6.3 - SPECIFIC FEATURES OF TBMS PROVIDING IMMEDIATE FRONTAL AND PERIPHERAL SUPPORT

### 6.3.1 - Specific features of mechanical-support shield TBMs

*a) General*

Mechanical-support shield TBMs ensure the stability of the excavation by retaining excavated material ahead of the cutterhead. This is done by partially closing gates on openings in the head.

*b) Excavation*

The face is excavated by a full-face cutterhead.

*c) Support and opposition to hydrostatic pressure*

Real-time adjustment of the openings in the cutterhead holds spoil against the face.

Frontal support is achieved by holding spoil against the face (in front of the cutterhead).

The shield provides immediate passive peripheral support.

The tunnel lining is erected:

• either inside the TBM tailskin, in which case it is sealed against the tailskin (tail seal) and back grout is injected into the annular space around it,

• or behind the TBM tailskin (expanded lining, segments with pea-gravel backfill and grout).

This type of machine cannot oppose hydrostatic pressure as a rule, so accompanying measures (ground improvement, groundwater lowering, etc.) may be necessary when working in water-bearing or unstable terrain.

*d) Mucking out*

Mucking out is generally by means of mine cars or belt conveyors.

### 6.3.2 - Specific features of compressed-air TBMs

*a) General*

With compressed-air TBMs, only pressurization of the air in the cutter chamber opposes the hydrostatic pressure at the face.

Compressed-air confinement pressure is practically uniform over the full height of the face. On the other hand, the pressure diagram for thrust due to water and ground at the face is trapezoidal. This means there are differences in the balancing of pressures at the face. The solution generally adopted involves compressing the air to balance the water pressure at the lowest point of the face. The greater the diameter, the greater the resulting pressure differential; for this reason the use of compressed-air confinement in large-diameter tunnels must be studied very attentively.

Compressed-air TBMs are generally used with moderate hydrostatic pressures (less than 0.1 MPa).

*b) Excavation*

The face can be excavated by a variety of equipment (from diggers to full-face cutterheads dressed with an array of tools). In the case of rotating cutterheads, the size of the spoil discharged is controlled by the openings in the cutterheadla roue.

Muck can be extracted from the face by a screw conveyor (low hydrostatic pressure) or by an enclosed conveyor with an airlock.

*c) Support and opposition to hydrostatic pressure*

Mechanical immediate support of the tunnel face and walls excavation is provided by the cutterhead and shield respectively.

The hydrostatic pressure in the ground is opposed by compressed air.

*d) Mucking out*

Muck is generally removed by conveyor or by wheeled vehicles (trains, trucks, etc.).

### 6.3.3 - Specific features of slurry shield TBMs

*a) General*

The principle of slurry shield TBM operation is that the tunnel excavation is held up by means of a pressurized slurry in the cutterhead. The slurry entrains spoil which is removed through the slurry return line.

The tunnel lining is erected inside the TBM tailskin where a special seal (tailskin seal) prevents leakage.

Back grout is injected behind the lining as the TBM advances.

*b) Excavation*

The face is excavated by a full-face cutterhead dressed with an array of cutter tools. Openings in the cutterhead (plus possibly a crusher upline of the first slurry return line suction pump) control the size of spoil removed before it reaches the pumps.

*c) Support and opposition to hydrostatic pressure*

Frontal and peripheral support of the tunnel excavation are the same, i.e. by means of the slurry pressure generated by the hydraulic mucking out system.

In permeable ground ($K \geq 5 \times 10^{-5}$ m/s) it is possible to pressurize the chamber by creating a 'cake' of thixotropic slurry (bentonite, polymer, etc.), generally with relative density of between 1.05 and 1.15, on a tunnel face and walls.

With such a 'cake' in place it is possible for workers to enter the pressurized cutterhead (via an airlock).

The TBM can be converted to open mode, but the task is complex.

As for tunnel support, the hydrostatic pressure is withstood by forming a 'cake' to help form a hydraulic gradient between the hydrostatic pressure in the ground and the slurry pressure in the cutterhead chamber.

Together with control of the stability of the excavation and of settlement, opposition to hydrostatic pressure is a design consideration for the confinement pressure; the confinement pressure is regulated either by direct adjustment of the slurry supply and return pumps or by means of an "air bubble" whose level and pressure are controlled by a compressor and relief valves. With an "air bubble" in the cutterhead chamber the confinement pressure can be measured and regulated within a very narrow range of variation.

*d) Mucking out*

Muck is removed by pumping it through the pipes connecting the TBM to the slurry separation and recycling plant.

In most cases the muck is often treated outside the tunnel, in a slurry separation plant. This does introduce some risks associated with the type of spoil to be treated (clogging of plant, difficulties for disposal of residual sludge).

The pump flowrate and the treatment capacity of the separation plant determine TBM progress.

#### 6.3.4 - Specific features of earth pressure balance machines

*a) General*

The principle of EPBM operation is that the excavation is held up by pressurizing the spoil held in the cutterhead chamber to balance the earth pressure exerted. If necessary, the bulked spoil can be made more plastic by injecting additives from the openings in the cutterhead chamber, the pressure bulkhead, and the muck-extraction screw conveyor. By reducing friction, the additives reduce the torque required to churn the spoil, thus liberating more torque to work on the face. They also help maintain a constant confinement pressure at the face.

Muck is extracted by a screw conveyor, possibly together with other pressure-relief devices.

The tunnel lining is erected inside the TBM tailskin, with a tailskin seal ensuring there are no leaks. Back grout is injected behind the lining as the TBM advances.

*b) Excavation*

The tunnel is excavated by a full-face cutterhead dressed with an array of tools. The size of spoil removed is controlled by openings in the cutterhead which are in turn determined by the dimensional capacity of the screw conveyor.

The power at the cutterhead has to be high because spoil is constantly churned in the cutterhead chamber.

*c) Support and opposition to hydrostatic pressure*

Face support is uniform. It is obtained by means of the excavated spoil and additives which generally maintain its relative density at between 1 and 2. Peripheral support can be enhanced by injecting products through the shield.

For manual work to proceed in the cutterhead chamber, it may be necessary to create a sealing cake at the face through controlled substitution (without loss of confinement pressure) of the spoil in the chamber with bentonite slurry.

L'architecture de ce type de tunnelier permet un passage rapide du mode fermé en mode ouvert.

The hydrostatic pressure is withstood by forming a plug of confined earth in the chamber and screw conveyor; the pressure gradient between the face and the spoil discharge point is balanced by pressure losses in the extraction and pressure-relief device.

Care must be take over the type and location of sensors in order to achieve proper measurement and control of the pressure in the cutterhead chamber.

*d) Mucking out*

After the muck-extraction screw conveyor, spoil is generally transported by conveyors or by wheeled vehicles (trains, trucks).

The muck is generally "diggable", enabling it to be disposed of without additional treatment; however, it may be necessary to study the biodegradability of the additives if the disposal site is in a sensitive environment.

The architecture of this type of TBM allows for rapid changeover from closed to open mode and vice versa.

## 7 - APPLICATION OF MECHANIZED TUNNELLING TECHNIQUES

### *7.1 - MACHINES NOT PROVIDING IMMEDIATE SUPPORT*

#### 7.1.1 - Boom-type tunnelling machines

Boom-type units are generally suitable for highly cohesive soils and soft rock. They reach their limits in soils with compressive strength in excess of 30 to 40 MPa, which corresponds to class R3 to R5 in the classification given in Appendix 3 (depending on the degree of cracking or foliation). The effective power of these machines is directly related to their weight.

When these machines are used in water-bearing ground, some form of ground improvement must be carried out beforehand to overcome the problem of significant water inflow.

When excavating clayey soils in water, the cutters of roadheaders may become clogged or balled; in such terrain, a special study of the cutters must carried out to overcome the problem. It may be advisable to use a backhoe instead.

These techniques are particularly suitable for excavating tunnels with short lengths of different cross-sections, or where the tunnel is to be driven in successive headings.

The tunnel support accompanying this method of excavation is independent of the machine used. It will be adapted to the conditions encountered (ground, environment, etc.) and the shape of the excavation.

#### 7.1.2 - Main-beam TBMs

Main-beam TBMs are particularly suited to tunnels of constant cross-section in rock of strength classes R1 to R4 (see rock classification in Appendix 3).

For the lower strength classes (R3b-R4), the bearing surface of the grippers is generally increased in order to prevent them punching into the ground. If there is a risk of alteration of the tunnel floor due to water, laying a concrete invert behind the machine will faci-

litate movement of the backup. To provide short-term stabilization of the excavation, it will be necessary to have rapid support-erection systems that will be independent of but nevertheless compatible with the TBM.

For the higher strength classes (R1-R2a), all the boreability parameters must be taken into account in the TBM design.

In hard and abrasive ground in particular, it is recommended that every precaution be taken to allow for cutters to be replaced in perfect safety.

A system for spraying water on the tunnel face will cool the cutters and keep dust down. It can be complemented by dust screens, extraction, and filters.

Main-beam TBMs are generally fitted with destructive drilling rigs for forward probe drilling, together with drill data-logging equipment. The probe holes are drilled when the TBM is not working.

The design of these machines does not allow them to support non-cohesive soils as they advance, or to oppose hydrostatic pressure. For this reason accompanying measures such as drainage and/or consolidation of the ground are necessary before the machines traverse a geological accident. Consequently the TBM must be equipped to detect such features and to treat the ground ahead of the face when necessary.

### 7.1.3 - Tunnel reaming machines

Tunnel reamers are suitable for excavating large horizontal or inclined tunnels (upwards of 8 m in diameter) in rock (R1 to R3, sometimes R4 and R5).

The advantages of reaming a tunnel from a pilot bore are as follows:

- The ground is investigated as the pilot bore is driven
- Any low-strength ground encountered can be consolidated from the pilot bore before full-diameter excavation
- The ground to be excavated is drained
- The pilot bore can be used for dewatering and ventilation
- Temporary support can be erected independently of the machine.

## 7.2 - MACHINES PROVIDING IMMEDIATE PERIPHERAL SUPPORT

### 7.2.1 - Open-face gripper shield TBMs

Open-face gripper shield TBMs are particularly suitable for tunnelling in rock of strength classes between R1 and R3

The shield provides immediate support for the tunnel and/or protects the workforce from falling blocks.

The shield can help get through certain geological difficulties by avoiding the need for support immediately behind the cutterhead.

Application of this technique can be limited by the ability of the ground to withstand the radial gripper thrust.

The general considerations outlined in § 7.1.2 also apply here.

### 7.2.2 - Open-face segmental shield TBMs

An open-face segmental shield TBM requires full lining or support along the length of the tunnel against which it can thrust to advance.

Its field of application is soft rock (strength classes R4 and R5) and soft ground requiring support but in which the tunnel face holds up.

The general considerations outlined in § 7.1.2 also apply here.

This type of TBM can traverse certain types of heterogeneity in the ground. It also enables the tunnel support to be industrialized to some extent. On the other hand, the presence of the lining and shield can give rise to difficulties when crossing obstacles such as geological accidents, since they hinder access to the face for treatment or consolidation of the ground.

### 7.2.3 - Open-face double shield TBMs

Open-face double shield TBMs combine the advantages and disadvantages associated with radial grippers and longitudinal thrust rams pushing off tunnel lining: they need either a lining or ground of sufficient strength to withstand gripper thrust.

This greater technical complexity is sometimes chosen when lining is required so that boring can proceed (with gripper purchase) while the lining ring is being erected.

## 7.3 - MACHINES PROVIDING IMMEDIATE FRONTAL AND PERIPHERAL SUPPORT

### 7.3.1 - Mechanical-support shield TBMs

The difference between mechanical-support shield TBMs and open-face segmental shield TBMs lies in the nature of the cutterhead. Mechanical-support TBMs have:

- openings with adjustable gates
- a peripheral seal between the cutterhead and the shield.

Face support is achieved by holding spoil ahead of the cutterhead by adjusting the openings. It does not provide 'genuine' confinement, merely passive support of the face.

Its specific field of application is therefore in soft rock and consolidated soft ground with little or no water pressure

### 7.3.2 - Compressed-air TBMs

Compressed-air TBMs are particularly suitable for ground of low permeability with no major discontinuities (i.e. no risk of sudden loss of air pressure).

The ground tunnelled must necessarily have an impermeable layer in the overburden.

Compressed-air TBMs tend to be used to excavate small-diameter tunnels.

Their use is not recommended in circumstances where the ground at the face is heterogeneous (unstable ground in the roof which could cave in). They should be prohibited in organic soil where there is a risk of fire.

In the case of small-diameter tunnels, it may be possible to have compressed air in all or part of the finished tunnel.

### 7.3.3 - Slurry shield TBMs

Slurry shield TBMs are particularly suitable for use in granular soil (sand, gravel, etc.) and heterogeneous soft ground, though they can also be used in other terrain, even if it includes hard-rock sections.

There might be clogging and difficulty separating the spoil from the slurry if there is clay in the soil.

These TBMs can be used in ground with high permeability (up to 10-2 m/s), but if there is high water pressure a special slurry has to be used to form a watertight cake on the excavation walls. However, their use is usually restricted to hydrostatic pressures of a few dozen MPa.

Generally speaking, good control of slurry quality and of the regularity of confinement pressure ensures that surface settlement is kept to the very minimum.

Contaminated ground (or highly aggressive water) may cause problems and require special adaptation of the slurry mix design.

The presence of methane in the ground is not a problem for this kind of TBM.

If the tunnel alignment runs through contrasting heterogeneous ground, there may be difficulties extracting and processing the spoil.

#### 7.3.4 - Earth pressure balance machines

EPBMs are particularly suitable for soils which, after churning, are likely to be of a consistency capable of transmitting the pressure in the cutterhead chamber and forming a plug in the muck-extraction screw conveyor (clayey soil, silt, fine clayey sand, soft chalk, marl, clayey schist).

They can handle ground of quite high permeability (10–3 to 10-4 m/s), and are also capable of working in ground with occasional discontinuities requiring localized confinement.en l'absence

In hard and abrasive ground it may be necessary to use additives or to take special measures such as installing hard-facing or wearplates on the cutterhead and screw conveyor.a vitesse de progression de l'usure par

In permeable ground, maintenance in the cutterhead chamber is made complex because of the need to establish a watertight cake at the face beforehand, without losing confinement pressure.

## 8 - TECHNIQUES ACCOMPANYING MECHANIZED TUNNELLING

### *8.1 - PRELIMINARY INVESTIGATIONS FROM THE SURFACE*

#### 8.1.1 - Environmental impact assessment

At the preliminary design stage an environmental impact assessment should be carried out in order to properly assess the dimensional characteristics proposed for the tunnel, particularly its cross-section, sectional area, and overburden.

In addition, the effect and sensitivity of settlement-especially in built-up areas-should be given special attention. This is a decisive factor in choosing the tunnelling and support methods, the tunnel alignment, and the cross-section.

The environmental impact assessment should be thorough, taking account of the density of existing works and the diversity of their behaviours.

For existing underground works, the compatibility of the proposed tunnelling and support methods or the adaptations required (special treatment or accompanying measures) should be assessed through special analysis.

#### 8.1.2 - Ground conditions

The purpose of preliminary investigations is not just for design of the temporary and permanent works, but also to check the feasibility of the project in constructional terms, i.e. with respect to excavation, mucking out, and short- and long-term stability.

Design of the works involves determining shape, geological cross-sections, the physical and mechanical characteristics of the ground encountered by the tunnel, and the hydrogeological context of the project as a whole.

Project feasibility is determined by the potential reactions of the ground, including details of both the formations traversed and of the terrain as a whole, with respect to the loadings generated by the works, i.e. with respect to the excavation/confinement method adopted.

Depending on the context and the specific requirements of the project, the synopsis of investigation results should therefore deal with each of the topics detailed in the AFTES recommendations on the choice of geotechnical tests and parameters, irrespective of the geological context (cf.: T.O.S No. 28, 1978, re-issued 05/93 – review in progress; and T.O.S No. 123, 1994).

If the excavation/confinement method is only chosen at the tender stage, and depending on the confinement method chosen by the Contractor, additional investigations may have to be carried out to validate the various options adopted.

#### 8.1.3 - Resources used

Depending on the magnitude and complexity of the project, preliminary investigations - traditionally based on boreholes and borehole tests - may be extended to "large-scale" observation of the behaviour of the ground by means of test adits and shafts.

Advantage can be taken of the investigation period to proceed with tests of the tunnelling and support methods as well as any associated treatments.

If there are to be forward probe investigations, matching of the boring and investigation methods should be envisaged at the preliminary investigation stage.

In the event of exceptional overburden conditions and difficult access from the surface, directional drilling investigation (mining and/or petroleum industry techniques) of long distances (one kilometre or more) along the tunnel alignment may be justified, especially if it is associated with geophysical investigations and appropriate in situ testing.

### *8.2 - FORWARD PROBING*

The concept of forward probing must be set against the risk involved. This type of investigation is cumbersome and costly, for it penalizes tunnelling progress since—in the case of full-face and shield TBMs—the machine has to be stopped during probing (with current-day technology). It should therefore be used only in response to an explicit and absolute requirement to raise any uncertainty over the conditions to be expected when crossing areas where site safety, preservation of existing works, or the durability of the project might be at risk.

Irrespective of the methodology selected, it must give the specialists implementing it real possibilities for avoiding difficulties by implementing corrective action in good time.

The first condition that forward probing must meet in order to achieve this objective is that it give sufficiently clear and objective information about the situation ahead of the face (between 1 and 5 times the tunnel diameter ahead), with a leadtime consistent with the rate of tunnel progress.

The second condition is that in terms of quality it must be adapted to the specific requirements of the project (identification of clear voids, of decompressed areas, faults, etc.). These criteria should be determined jointly by the Designer, Engineer, and Contractor and should be clearly featured in specifications issued to the persons carrying out the investigations.

During tunnelling, analysis of results is generally the responsibility of the investigations contractor, but the interpretation of data, in correlation with TBM advance parameters (monitoring), should in principle be the responsibility of the contractor operating the TBM.

## 8.3 - GROUND IMPROVE - MENT

Prior ground improvement is sometimes necessary, particularly in order to cross:

• singular features such as break-ins and breakouts, including on works along the route (shafts, stations, etc.)

• discontinuities and fault zones identified beforehand

• permeable water-bearing ground.

If the problem areas are of limited extent, ground improvement will sometimes enable a less sophisticated - and therefore less costly - tunnelling technique to be adopted.

Since ground improvement is long and costly to carry out from the tunnel (especially when the alignment is below the water table), the work is generally done from the surface (in the case of shallow overburden).

These days, however, there is a trend for TBMs to be fitted with the basic equipment (such as penetrations in the bulkhead and / or cans) enabling ground improvement to be carried out from the machine should water-bearing ground not compatible with the tunnelling technique adopted be encountered unexpectedly. This can also be the case when local conditions prohibit treatment from the surface.

When confinement-type TBMs are used, geological and hydrogeological conditions often require special treatment for break-ins and breakouts. This point should not be overlooked, neither at the preliminary design stage (surface occupation, ground and network investigations, works schedule) nor during the construction phase, for this is one of the most difficult phases of tunnelling.

Special attention should be given to the compatibility of ground treatment with the tunnelling process (foaming, reaction with slurry and additives, etc.)

The most commonly used ground improvement techniques are:

• permeation-grouted plug of bentonite-cement and / or gel

• diaphragm-wall box

• total replacement of soil by bentonite-cement

• jet-grouted plug

## 8.4 - GUIDANCE

Guidance of full-face TBMs is vital. The performance of the guidance system used must be consistent with the type of TBM and lining, and with the purpose of the tunnel.

The development of shield TBMs incorporating simultaneous erection of precast segmental lining has led to the design of highly sophisticated guidance systems, because with tunnel lining it is impossible to remedy deviation from the correct course. Consequently, the operator (or automatic operating system) must be given real-time information on the position of the face and the tunnelling trend relative to the theoretical alignment. However, when considering the construction tolerance it must be remembered that the lining will not necessarily be centred in the excavation, and that it may be subject to its own deformation (offset, ovalization, etc.). The generally accepted tolerance is an envelope forming a circle about 20 cm larger in diameter than the theoretical diameter.

Whatever the degree of sophistication of the guidance system, it is necessary to:

• reliably transfer a traverse into the tunnel and close it as soon as possible (breakout into shaft, station, etc.)

• carry out regular and precise topographical checks of the position of the TBM and of the tunnel

• know how quickly (speed and distance) the TBM can react to modifications to the trajectory it is on.

## 8.5 - ADDITIVES

### a) General

Mechanized tunnelling techniques make use of products of widely differing physical and chemical natures that can all be labelled "conditioning fluids and slurries". Before any chemical additives are used, it should be checked that they present no danger for the environment (they will be mixed in with the muck and could present problems when it is disposed of) or for the workforce (particularly during pressurized work in the cutterhead chamber where the temperature can be high).

### b) Water

Water will be present in the ground in varying quantities, and will determine the soil's consistency, as can be seen from different geotechnical characterization tests or concrete tests (Atterberg limits for clayey soils and slump or Abrams cone test for granular soils). It can be used alone, with clay (bentonite), with hydrosoluble polymers, or with surfactants to form a conditioning fluid (slurry or foam).

### c) Air

By itself air cannot be considered to be a boring additive in the same way as water or other products; its conditioning action is very limited. When used in pressurized TBMs - if the permeability of the ground does not prohibit it - air helps support the tunnel. As a compressible fluid, air helps damp confinement-pressure variations in the techniques using slurry machines with "air bubbles" and EPB machines with foam. As a constituent of foam, air also helps fluidify and reduce the density of muck, and helps regulate the confinement pressure in the earth-pressure-balance process.

### d) Bentonite

Of the many kinds of clay, bentonite is most certainly the best-known drilling or boring mud. It has extremely high swell, due to the presence of its specific clayey constituent, montmorillonite, which gives it very interesting colloidal and sealing qualities.

In the slurry-confinement technique, the rheological qualities of bentonite (thixotropy) make it possible to establish a confinement pressure in a permeable medium by sealing the walls of the excavation through pressurized filtration of the slurry into the soil (formation of a sealing cake through a combination of permeation and membrane), and to transport muck by pumping.

Bentonite slurry can also be used with an EPB machine, to improve the consistency of the granular material excavated (homogenization, plastification, lubrication, etc.).

In permeable ground, the EPB technique uses the same principle of cake formation before work is carried out in the pressurized cutterhead chamber.

### e) Polymers

Of the multitude of products on the market, only hydrosoluble or dispersible compounds are of any interest as tunnelling additives. Most of these are well known products in the drilling industry whose rheological properties have been enhanced to meet the specific requirements of mechanized tunnelling.

These modifications essentially concern enhanced viscosifying power in order to better homogenize coarse granular materials, and enhanced lubrifying qualities in order to limit sticking or clogging of the cutterhead and mucking out system when boring in certain types of soil.

Polymers may be of three types:

• natural polymers (starch, guar gum, xan-

than gum, etc.)

• modified natural or semi-synthetic polymers (CMC [carboxymethylcellulose], etc.)

• synthetic polymers (polyacrylamides, polyacrylates, etc.)

*f) Foams (surfactants)*

Foams are two-phase systems (a gas phase and a liquid phase containing the foaming agent) which are characterized physically by their expansion factor (volume occupied by the air in the foam relative to the volume of liquid).

Foams are easy to use. They are similar to aerated slurries, combining the advantages of a gas (compressibility, practically zero density, etc.) and of a slurry (fluidification, lubrication, pore filling, etc.). With EPB machines they are used to facilitate confinement and sometimes excavation and mucking out as well.

## *8.6 - DATA LOGGING*

The acquisition and restitution of TBM operating parameters is undoubtedly the biggest factor in the technical progress of mechanized tunnelling in the last ten years.

It makes for objective analysis of the operating status and dysfunctions of the machine and its auxiliaries.

The status of the machine at any given time is short-lived and changes rapidly. Without data logging, this gave rise to varied and often erroneous interpretations in the past.

Logging gives a "true" technical analysis that is indispensable for smooth operation on projects in difficult or sensitive sites.

Data logging also provides a basis for computerized control of TBM operation and automation of its functions (guidance, mucking out, confinement pressure regulation, etc.).

Data logging also provides an exact record of operating statuses and their durations (cf. recommendation on analysis of TBM operating time and coefficients, TOS No. 148, July 98).

They also constitute operating feedback that can be used to optimize TBM use.

## *8.7 - TUNNEL LINING AND BACKGROUTING*

### 8.7.1 - General

In the case of segmental TBMs, the lining and its backgrouting are inseparable from the operation of the machine.

Without any transition and in perfectly controlled fashion, the lining and backgrout must balance the hydrostatic pressure, support the excavation peripherally, and limit surface settlement.

Because of their interfaces with the machine, they must be designed in parallel and in interdependence with the TBM.

### 8.7.2 - Lining

The lining behind a shield TBM generally consists of reinforced concrete segments. Sometimes (for small-diameter tunnels) cast-iron segments are used. More exceptionally the lining is slipcast behind a sliding form.

Reinforced concrete segments are by far the most commonly used. The other techniques are gradually being phased out for economic or technical reasons.

The segments are erected by a machine incorporated into the TBM which grips them either mechanically or by means of suction.

The following AFTES recommendations examine tunnel lining:

• Recommandations sur les revêtements préfabriqués des tunnels circulaires au tunnelier (Recommendations on precast lining of bored circular tunnels), TOS No. 86

• Recommandation sur les joints d'étanchéité entre voussoirs (Recommendations on gaskets between lining segments), TOS No. 116, March/April 1993

• Recommandations "pour la conception et le dimensionnement des revêtements en voussoirs préfabriqués en béton armé installés à l'arrière d'un tunnelier" (Recommendations "on the design of precast reinforced concrete lining segments installed behind TBMs") drawn up by AFTES work group No. 18, published in TOS No. 147, May/June 1998.

### 8.7.3 - Backgrouting

This section concerns only mechanized tunnelling techniques involving segmental lining.

Experience shows the extreme importance of controlling the grouting pressure and filling of the annular space in order to control and restrict settlement at the surface and to securely block the lining ring in position, given that in the short term the lining is subject to its selfweight, TBM thrust, and possibly flotational forces.

Grouting should be carried out continuously, with constant control, as the machine advances, before a gap appears behind the TBM tailskin.

In the early days backfilling consisted of either pea gravel or fast-setting or fast-hardening cement slurry or mortar that was injected intermittently through holes in the segments.

Since management of the grout and its hardening between mixing and injection is a very complex task, there has been a constant trend to drop cement-based products in favour of products with retarded set (pozzolanic reaction) and low compressive strength. Such products are injected continuously and directly into the annular space directly behind the TBM tailskin by means of grout pipes routed through the tailskin.

# 9 - HEALTH AND SAFETY

Mechanization of tunnelling has very substantially improved the health and safety conditions of tunnellers. However, it has also induced or magnified certain specific risks that should not be overlooked. These include:

• risk of electrical fire or spread of fire to hydraulic oils

• risk of electrocution

• risks during or subsequent to compressed-air work

• risks inherent to handling of heavy parts (lining segments)

• mechanical risks

• risk of falls and slips (walkways, ladders, etc.)

## *9.1 - DESIGN OF TUNNELLING MACHINES*

Tunnelling machines are work items that must comply with the regulations of the Machinery Directive of the European Committee for Standardization (CEN).

These regulations are aimed primarily at designers—with a view to obtaining equipment compliant with the Directive—but also at users.

The standards give the minimum safety measures and requirements for the specific risks associated with the different kinds of tunnelling machines. Primarily they apply to machines manufactured after the date of approval of the European standard.

• At the time of writing only one standard had been homologated:

- NF EN 815 "Safety of unshielded tunnel boring machines and rodless shaft boring machines for rock" (December 1996)

• Three are in the approval process:

- Pr EN 12111 "Tunnelling machines - Roadheaders, continuous miners and impact

rippers – Safety requirements”

- Pr EN 12336 “Tunnelling machines – Shield machines, horizontal thrust boring machines, lining erection equipment - Safety requirements ”

- Pr EN 12110 “Tunnelling machines – Airlocks – Safety requirements ”

## *9.2 - USE OF TUNNELLING MACHINES*

Machine excavation of underground works involves specific risks linked essentially to atmospheric pollution (gas, toxic gases, noise, temperature), flammable gases and other flammable products in the ground, electrical equipment (low and high voltage), hydraulic equipment (power or control devices), and compressed-air work (work in large-diameter cutterhead chambers under compressed air, pressurization of whole sections of small-diameter tunnels).

A variety of bodies dealing with safety on public works projects have drawn up texts and recommendations on safety. In France, these include OPPBTP, CRAM, and INRS, for example.

All their requirements should be incorporated into the General Co-Ordination Plan and Health and Safety Plan at the start of works.

## APPENDICES 1, 2, 3, AND 4

1. Comments on Table No. 1 in Chapter 5
2. Comments on Table No. 2 in Chapter 5
3. Ground classification table
4. Mechanized tunnelling project data sheets

APPENDIX 1

## COMMENTS ON TABLE NO. 1 IN CHAPTER 5.

### *1 - Natural constraints*

*Support (columns A and B)*

*With knowledge of natural constraints:*

• a choice can be made from among the tunnelling technique groups (from boom-type units to confinement-type TBMs)

• relaxation of stresses can be managed (from simple deformation-convergence to failure).

## 2 - PHYSICAL PARAMETERS

### *2.1 - Identification*

❑ Face support (column A)

With knowledge of physical parameters:

• the support method can be assessed, and the tunnelling technique group chosen

• the requirement for face support can be assessed.

❑ Peripheral support (column B)

With knowledge of physical parameters the requirement for peripheral support around the machine can be assessed.

❑ Opposition to hydrostatic pressure (column C)

With knowledge of physical parameters and of grain and block sizes, the permeability of the terrain can be assessed, leading to a proposal for the way hydrostatic pressure could be controlled.

❑ Excavation (column D)

Of the parameters concerned, grain and block size are decisive for assessing the excavation method (design of cutterhead, cutters, etc.).

### *2.2 - Global appreciation of quality*

❑ Support (columns A and B)

Global appreciation of quality provides additional information for identification that concerns only the sample. This data defines more global information at the scale of the soil horizon concerned.

### *2.3 - Discontinuities*

❑ Support (columns A and B)

This data concerns rock and coherent soft ground. With knowledge of discontinuities a choice can be made among the tunnel technique groups (from boom-type units to confinement-type TBMs).

❑ Opposition to hydrostatic pressure (column C)

With knowledge of discontinuities the crack permeability and water pressure to be taken into account for the project can be assessed. This enables the type of technique to be chosen.

❑ Excavation (column D)

In conjunction with knowledge of block sizes, knowledge of discontinuities (nature, size, and frequency) can be decisive or merely have an effect on the excavation method to be adopted.

## 3 - MECHANICAL PARAMETERS

### *3.1 - Strength*

❑ Support (columns A and B)

With knowledge of mechanical parameters a preliminary choice can be made from among the tunnelling technique groups (from boom-type units to confinement-type TBMs).

❑ Excavation (hard rock)(column D)

Knowledge of mechanical parameters is particularly important for defining the architecture of the machine and helps determine its technical characteristics (torque, power, etc.) and the choice of cutting tools.

### *3.2 - Deformability*

❑ Support (columns A and B)

With knowledge of deformability the relaxation of stresses can be assessed and taken into account (from simple deformation or convergence to failure).

### *3.3 - Liquefaction potential*

❑ Support and mucking out (columns A, B and E)

Knowledge of the liquefaction potential has an effect in seismic zones and in cases where the technique chosen might set up vibrations in the ground (blasting, etc.).

## 4 - HYDROGEOLOGICAL PARAMETERS

❑ Support, opposition to hydrostatic pressure, and excavation (Columns A, B, C and D)

Knowledge of these parameters is decisive in appreciating control of the stability of the tunnel, both at the face and peripherally, and therefore in choosing the method from the various tunnelling techniques. In the case of tunnels beneath deep overburden it is not easy to obtain these parameters. They should be estimated with the greatest care and analyzed with caution.

## 5 - OTHER PARAMETERS

❑ Excavation and mucking out (Columns D and E)

The parameters of abrasiveness and hardness are decisive or have an effect in appreciation of the excavation and mucking-out methods to be used. These parameters should be

APPENDIX 2

*Comments on Table No. 1 in Chapter 5*

## 1 - NATURAL CONSTRAINTS

The stress pattern in the ground is very important in deep tunnels or in cases of high anisotropy. If the rate of stress release is high, with main-beam TBMs, shield TBMs, and reaming machines, it may cause:

- jamming of the machine (jamming of the cutterhead or body)
- rockburst at the face or in tunnel walls, roof, or invert.

With slurry-shield TBMs or EPBMs it is rare for the natural stress pattern to be decisive in the choice of machine type since they are generally used for shallow tunnels.

## 2 - PHYSICAL PARAMETERS

### *2.1 - Identification*

The type of ground plays a decisive role in the choice and design of a shield TBM. Consequently the parameters characterizing the identification of the ground must be examined carefully when choosing the excavation/ support method.

The most important of the identification parameters are **plasticity** and - for hardness, clogging potential, and abrasiveness - **mineralogy** which are particularly decisive in the selection of shield TBM components.

Chemical analysis of the soil can be decisive in the case of confinement-type shield TBMs because of the effect soil might have on the additives used in these techniques.

### *2.2 - Global appreciation of quality*

Global appreciation of quality results from combining parameters which are easy to measure in the laboratory or in situ (borehole logs, RQD) and visual approaches.

Weathered zones and zones with contrasting hardness can cause specific difficulties for the different tunnelling techniques, e.g. face instability, insufficient strength for grippers, confinement difficulties.

The degree of weathering of rock has an effect but is not generally decisive for slurry shields and EPBMs. In all cases it has an effect for cutterhead design.

### *2.3 - Discontinuities*

For rock, knowledge of the situation regarding discontinuities is decisive (orientation and density of the network), for it will affect the choice of the tunnelling and support technique as well as the tunnelling speed.

With open-face main-beam TBMs and shields and mechanical-support TBMs, attention should be given to the risk of jamming of the machine induced by the density of a network of discontinuities which could quite rapidly lead to doubtful stability of the terrain. The existence of unconsolidated infilling material can aggravate the resulting instability.

The presence of major discontinuities can have a major effect on the choice of tunnelling technique.

Slurry shields and compressed-air TBMs are generally more sensitive to the presence of discontinuities than EPBMs. If there are major discontinuities (high density of fracturation), the compressed-air confinement TBM may have to be eliminated from the possible range.

In general the overall permeability of the terrain should be examined in conjunction with its discontinuities before selecting the type of confinement.

### *2.4 - Alterability*

Alterability characteristics concern terrain that is sensitive to water. Alterability data should be obtained at the identification stage.

Special attention should be given to alterability when mechanized tunnelling is to take place in water-sensitive ground such as certain molasses, marls, certain schists, active clays, indurated clays, etc.

Alterability has an effect on confinement-type TBMs; it can result in changes being made to the design of the machine and the choice of additives.

### *2.5 - Water chemistry*

Problems related to the aggressivity or the degree of pollution of water may arise in very specific cases and have to be dealt with regardless of the tunnelling principles adopted.

With confinement-type TBMs this parameter may be decisive because of its effect on the quality of the slurry or additives.

## 3 - MECHANICAL PARAMETERS

### *3.1 - Strength*

In the case of rock, the essential mechanical criteria are the compressive and tensile strength of the terrain, for they condition the efficacy of excavation.

In soft ground, the essential criteria are cohesion and the angle of friction, for they condition the hold-up of the face and of the excavation as a whole.

The very high strengths of some rocks exclude the use of boom-type tunnelling machines (unless they are highly cracked). Gripper-type tunnel boring and reaming machines are very sensitive to low-strength ground and may require special adaptation of the gripper pads. For main-beam and shield TBMs alike, the machine architecture, the installed power at the cutterhead, and the choice and design of cutting tools and cutterhead are conditioned by the strength of the ground.

If there is any chance of tunnel bearing capacity being insufficient, special treatment may be necessary for the machine to advance.

### *3.2 - Deformability*

Deformability of the terrain may cause jamming of the TBM, especially in the event of convergence resulting from high stresses (see paragraph 1, " Natural constraints" ).

In the case of tunnel reamers and open-face or mechanical-support TBMs, this criterion affects the appreciation of the risks of cutterhead or shield jamming.

In the case of excessively deformable material, the design of TBM gripper pads will have to be studied carefully. The

deformability of the surrounding ground also affects TBM guidance. If the tunnel lining is erected to the rear of the tail-skin, attention should be paid to the risk of deferred deformation.

In ground that swells in contact with water, the resulting difficulties for advancing the machine are comparable for both slurry shield and EPB machines, in so far as the swelling is due to the diffusion and absorption of water within the decompressed ground around the tunnel. Compressed-air TBMs are less sensitive to this phenomenon.

### 3.3 - Liquefaction potential

Not applicable, except if there is a risk of earthquake or if the ground is particularly sensitive (saturated sand, etc.).

## 4 - HYDROGEOLOGICAL PARAMETERS

The purpose of examining the hydrogeological parameters of the terrain is to ensure that it will remain stable in the short term. The presence of high water pressures and/ or potential inflow rates entraining material will prohibit the use of boom-type machines and open-face or mechanical-support machines unless accompanying measures such as ground improvement, groundwater lowering, etc. are carried out.

Water pressure is also decisive when geological accidents (e.g. mylonite) have to be crossed, irrespective of whether or not they are infilled with loose soil.

Ground permeability and hydrostatic pressure are decisive for TBMs using compressed-air, slurry, or EPB confinement. Compressed-air machines may even be rejected because of these factors, and they are particularly decisive for EPBMs when there are likely to be sudden variations in permeability. For slurry shield TBMs, the effects of these parameters are attenuated by the fact that a fluid is used for mucking out.

## 5 - OTHER PARAMETERS

### 5.1 - Abrasiveness - Hardness

Excessively high abrasiveness and hardness make it impossible or uneconomic to use boom-type tunnelling machines.

Abrasiveness and hardness can be decisive with respect to tool wear, the structure of the cutterhead, and extraction systems (screw conveyor, slurry pipes, etc.). However, the expected wear can be countered by using boring and/ or extraction additives and/ or protection or reinforcement on sensitive parts.

### 5.2 - Sticking - Clogging

When the potential the material to be excavated has to stick or clog is known, the cutters of boom-type units, tunnel reamers, or shield TBMs can be adapted or use of an additive envisaged.

This parameter alone cannot exclude a type of shield TBM; it is therefore not decisive for face-confinement shields. However, the trend for the ground to stick must be examined with respect to the development of additives (foam, admixtures, etc.) and the design of the equipment for churning and mixing the sticky spoil (agitators, jetting, etc.).

The transport of muck by trains and/ or conveyors is particularly sensitive to this parameter.

### 5.3 - Ground/machine friction

For shield TBMs the problem of ground friction on the shield can be critical in ground where convergence is high.

Where there is a real risk of TBM jamming (convergence, swelling, dilitancy, etc.) this parameter has a particularly important effect on the design of the shield.

The lubrication provided by their bentonite slurry makes slurry shield TBMs less susceptible to the problems of ground/ machine friction.

### 5.4 - Presence of gas

The presence of gas in the ground can determine the equipment fitted to the machine.

## 6 - PROJECT CHARACTERISTICS

### 6.1 - Dimensions and sections

Boom-type units can excavate tunnels of any shape and sectional area. Shield TBMs, main-beam machines, and reamers can excavate tunnels of constant shape only. The sectional area that can be excavated is related to the stability of the face.

The sectional area of tunnels is decisive for large-diameter EPBMs (power required at the cutterhead).

The length of the project can have an effect on slurry shield TBMs (pumping distance).

### 6.2 - Vertical alignment

The limits imposed on tunnelling machines by the vertical profile are generally those of the associated logistics. Main-beam tunnel boring and reaming machines can be adapted to bore inclined tunnels, but the requirement for special equipment takes them beyond the scope of these recommendations.

With boom-type units and open-face or mechanical-support TBMs, water inflow can cause problems in downgrade drives.

### 6.3 - Horizontal alignment

- The use of boom-type units imposes no particular constraints.
- The use of main-beam tunnel boring and reaming machines and of shield TBMs is limited to certain radii of curvature (even with articulations on the machines).
- With shield TBMs the alignment after/ before break-ins and breakouts should be straight for at least twice the length of the shield (since it is impossible to steer the machine when it is on its slide cradle).

### 6.4 - Environment

#### 6.4.1 - Sensitivity to settlement

Since boom-type units, tunnel reamers, main-beam TBMs, and open-face shield TBMs do not generally provide any immediate support, they can engender settlement at the surface. Settlement will be particularly decisive in urban or sensitive zones (transits below routes of communication such as railways, pipelines, etc.).

Sensitivity to settlement is generally decisive for all TBM types and can lead to exclusion of a given technique.

Open-face or mechanical-support shield TBMs are not suitable for use in very

deformable ground. If the tunnel lining is erected to the rear of the tailskin, attention should be paid to the risk of deferred deformation of the surrounding ground.

With confinement-type TBMs, control of settlement is closely linked to that of confinement pressure.

With compressed-air shields the risk of settlement lies in loss of air (sudden or gradual).

With slurry shield TBMs the risk lies in the quality of the cake and in the regulation of the pressure. In relation to this, the "air bubble" confinement pressure regulation system performs particularly well.

With EPBMs the risk lies in less precise regulation of the confinement pressure. Moreover, the annular space around the shield is not properly confined, unless arrangements are made to inject slurry through the cans.

### 6.4.2 - Sensitivity to disturbance and work constraints

Slurry shield machines require a large area at the surface for the slurry separation plant. This constraint can have an effect on the choice of TBM type or even be decisive in intensively built-up zones.

The additives introduced into the cutterhead chamber of shield TBMs (bentonite, polymer, surfactant, etc.) may imply constraints on disposal of spoil.

## 6.5 - Anomalies in ground

### 6.5.1 - Ground/accident heterogeneity

Mixed hard rock/ soft ground generally implies face-stability and gripping problems for tunnelling techniques with no confinement, and also introduces a risk of caving-in of the roof where the ground is softest.

### 6.5.2 - Natural and artificial obstacles

For "open" techniques it is essential to be able to detect geological accidents. For confinement techniques attention should be paid to the presence of obstacles, whether natural or artificial. Obstacles can have an effect on the choice of machine, depending on the difficulties encountered in overcoming the obstacle and the need to work from the cutterhead chamber.

Compressed-air work necessary for detecting and dealing with obstacles requires replacement of the products in the cutterhead chamber (products depending on the confinement method) with compressed air.

The work required for replacing them is:

- ❑ faster and simpler with a compressed-air TBM (in principle)
- ❑ easy with a slurry shield TBM
- ❑ longer and more difficult with an earth pressure balance machine (extraction of the earth and substitution with slurry to form a sealing film, followed by removal of the bulk of the slurry and replacement with compressed air).

### 6.5.3 - Voids

Depending on their size, the presence of voids can engender very substantial deviation from the design trajectory, especially vertically. They can also be a source of disturbance to the confinement pressure, particularly with compressed-air or slurry shield TBMs.

## APPENDIX 3

*Ground classification table (cf. GT7)*

| Catégory | Description | Examples | RC (Mpa) |
|---|---|---|---|
| R1 | Very strong rock | Strong quartzite and basalt | > 200 |
| R2a | Strong rock | Very strong granite, porphyry, very strong sandstone and limestone | 200 à 120 |
| R2b | | Granite, very resistant or slightly dolomitized sandstone and limestone, marble, dolomite, compact conglomerate | 120 à 60 |
| R3a | Moderately strong rock | Ordinary sandstone, siliceous schist or schistose sandstone, gneiss | 60 à 40 |
| R3b | | Clayey schist, moderately strong sandstone and limestone, compact marl, poorly cemented conglomerate | 40 à 20 |
| R4 | Low strength rock | Schist or soft or highly cracked limestone, gypsum, highly cracked or marly sandstone, puddingstone, chalk | 20 à 6 |
| R5 a | Very low strength rock and consolidated cohesive soils | Sandy or clayey marls, marly sand, gypsum or weathered chalk | 6 à 0,5 |
| R5b | | Gravelly alluvium, normally consolidated clayey sand | < 0,5 |
| R6a | Plastic or slightly consolidated soils | Weathered marl, plain clay, clayey sand, fine loam | |
| R6b | | Peat, silt and little consolidated mud, fine non-cohesive sand | |

## APPENDIX 3

*Mechanized tunnelling data sheets (up to 31/12/99).*

| N° fiche | Project | *Project type (AITES) | TOS issue** | Date | Bored length (m) | Bored diameter (m) | Geology | |
|---|---|---|---|---|---|---|---|---|
| 1 | Echaillon | D | 68 | 1972-1973 | 4362 | 5.80 | Gneiss, flysch, limestone | Wirth |
| 2 | La Coche | D | 77 | 1972-1973 | 5287 | 3.00 | Limestone, sandstone, breccia | Robbins |
| 3 | CERN SPS | H | 64 | 1973-1974 | 6551 | 4.80 | Molasse | Robbins |
| 4 | RER Châtelet-Gare de Lyon | C | 64 | 1973-1975 | 5100 | 7.00 | Limestone | Robbins |
| 5 | Belledonne | D | 64 | 1974-1978 | 9998 | 5.88 | Schist, sedimentary granite | Wirth |
| 6 | Bramefarine | D | 67 | 1975-1977 | 3700 | 8.10 | Limestone, schist | Robbins |
| 7 | Lyons metro - Crémaillère | C | 64 | 1976 | 220 | 3.08 | Gneiss, granite | Wirth |
| 8 | Galerie du Bourget | C | 67 | 1976-1978 | 4845 | 6 m2 | Limestone, molasse | Alpine |
| 9 | Monaco - Service tunnel | H | 64 | 1977 | 913 | 3.30 | Limestone, marne | Robbins |
| 10 | Grand Maison - Eau Dolle | D | 64 | 1978 | 839 | 3.60 | Gneiss, schist, dolomite | Wirth |
| 11 | Western Oslofjord | G | 77 | 1978-1984 | 10500 | 3.00 | Slate, limestone, igneous rock | Bouygues |
| 12 | Brevon | D | 66 | 1979-1981 | 4150 | 3.00 | Limestone, dolomite, other calcareous rock (malm) | Bouygues |
| 13 | Grand Maison (penstocks and service shaft) | D | 75 | 1979-1982 | 5466 | 3.60 | Gneiss, schist | Wirth |
| 14 | Marignan aqueduct | F | 66 | 1979-1980 | 480 | 5.52 m2 | Limestone | Alpine |
| 15 | Super Bissorte | D | 73 | 1980-1981 | 2975 | 3.60 | Schist, sandstone | Wirth |
| 16 | Pouget | D | 66 | 1980-1981 | 3999 | 5.05 | Gneiss | Wirth |
| 17 | Grand Maison - Vaujany | D | 75 | 1981-1983 | 5400 | 7.70 | Liptinite, gneiss, amphibolite | Robbins |
| 18 | Vieux Pré | D | 68 | 1981-1982 | 1257 | 2.90 | Sandstone, conglomeratee | Bouygues |
| 19 | Haute Romanche Tunnel | D | 73 | 1981-1982 | 2860 | 3.60 | Limestone, schist, crystalline sandstone | Wirth |
| 20 | Cilaos | F | 80 | 1982-1984 | 5701 | 3.00 | Basalt, tuff | Wirth |
| 21 | Monaco - tunnel No. 6 | A | 66 | 1982 | 183 | 5.05 | Limestone, dolomite | Wirth |
| 22 | Ferrières | D | 79 | 1982-1985 | 4313 | 5.90 | Schist, gneiss | Wirth |
| 23 | Durolle | D | 79 | 1983-1984 | 2139 | 3.40 | Granite, quartz, microgranite | Wirth |
| 24 | Montfermy | D | 80 | 1983-1985 | 5040 | 3.55 | Gneiss, anatexite, granite | Robbins |
| 25 | CERN LEP (machines 1 and 2) | H | 82 | 1985-1986 | 14680 | 4.50 | Molasse | Wirth |
| 26 | CERN LEP (machine 3) | H | 82 | 1985-1987 | 4706 | 4.50 | Molasse | Wirth |
| 27 | Val d'Isère funicular | B | 97 | 1986 | 1689 | 4.20 | Limestone, dolomite, cargneule (cellular dolomite) | Wirth |
| 28 | Calavon and Luberon | F | 97 | 1987-1988 | 2787 | 3.40 | Limestone | Wirth |
| 29 | Takamaka II | D | 101 | 1985-1987 | 4803 | 3.20 | Basalt, tuff, agglomerates | Bouygues |
| 30 | Oued Lakhdar | D | 101 | 1986-1987 | 6394 | 4.56 / 4.80 | Limestone, sandstone, marl | Wirth |
| 31 | Paluel nuclear power plant | E | 105 | 1980-1982 | 2427 | 5.00 | Chalk | Zokor |
| 32 | Penly nuclear power plant | E | 105 | 1986-1988 | 2510 | 5.15 | Clay | Zokor |
| 33 | Lyons river crossing - metro line D | C | 106 | 1984-1987 | 2 x 1230 | 6.50 | Recent alluvium and granitic sand | Bade |
| 34 | Lille metro, line 1b - Package 8 | C | 106 | 1986-1987 | 1000 | 7.65 | White chalk and flint | FCB/ Kawasaki |
| 35 | Lille metro, Line 1b - Package 3 | C | 106 | 1986-1988 | 3259 | 7.70 | Clayey sand and silt | Herrenknecht |
| 36 | Villejust tunnel | B | 106 | 1986-1988 | 4805 + 4798 | 9.25 | Fontainebleau sand | Bade/ Theelen (2 machines) |
| 37 | Bordeaux: Cauderan-Naujac | G | 106 | 1986-1988 | 1936 | 5.02 | Sand, marl and limestone | Bessac |
| 38 | Caracas metro: package PS 01 | C | 107 | 1986-1987 | 2 x 1564 | 5.70 | Silty-sandy alluvium, gravel, and clay | Lovat |
| 39 | Caracas metro: package CP 03 | C | 107 | 1987 | 2 x 2131 | 5.70 | Weathered micaschist and silty sand | Lovat |
| 40 | Caracas metro: package CP 04 | C | 107 | 1987-1988 | 2 x 714 | 5.70 | Micaschist | Lovat |
| 41 | Singapore metro: package 106 | C | 107 | 1985-1986 | 2600 | 5.89 | Sandstone, marl and clay | Grosvenor |
| 42 | Bordeaux: "boulevards" main sewers Ø3800 | G | 113 | 1989-1990 | 1461 | 4.36 | Karstic limestone and alluvium | Bessac |
| 43 | Bordeaux: Avenue de la Libération Ø2200 | G | 113 | 1988-1989 | 918 | 2.95 | Karstic limestone and alluvium | Bessac |
| 44 | St Maur-Créteil, section 2 | G | 113 | 1988-1990 | 1530 | 3.35 | Old alluvium and boulders | FCB |
| 45 | Crosne-Villeneuve St Georges | G | 113 | 1988-1990 | 911 | 2.58 | Weathered marl and indurated limestone | Howden |
| 46 | Channel Tunnel T1 | B | 114 | 1988-1990 | 15618 | 5.77 | Blue chalk | Robbins |
| 47 | Channel Tunnel T2-T3 | B | 114 | 1988-1991 | 20009 +18860 | 8.78 | Blue chalk | Robbins/ Kawasaki |

*AITES classification of project types

A road tunnels - B rail tunnels - C metros - D hydropower tunnels - E nuclear and fossil-fuel power plant tunnels - F water tunnels - G sewers- H service tunnels - I access inclines - J underground storage facilities - K mines -

*(APPENDIX 3)*

| N° fiche | Project | *Project type (AITES) | TOS issue** | Date | Bored length (m) | Bored diameter (m) | Geology | |
|---|---|---|---|---|---|---|---|---|
| 48 | Channel Tunnel T4 | B | 114 | 1988-1989 | 3162 | 5.61 | Grey and white chalk | Mitsubishi |
| 49 | Channel Tunnel T5-T6 | B | 114 | 1988 -1990 | 2 x 3265 | 8.64 | Grey and white chalk | Mitsubishi |
| 50 | Sèvres - Achères: Package 3 | G | 121 | 1989 -1991 | 3550 | 4.05 | Coarse limestone, sand, upper Landenian clay (fausses glaises), plastic clay, Montian marl, chalk | Herrenknecht |
| 51 | Sèvres - Achères: Packages 4 and 5 | G | 121 | 1988 -1990 | 3312 | 4.8 | Sand, upper Landenian clay (fausses glaises), plastic clay, Montian marl and limestone, chalk | Lovat |
| 53 | Orly Val: Package 2 | C | 124 | 1989 - 1990 | 1160 | 7.64 | Marl with beds of gypsum | Howden |
| 54 | Bordeaux Caudéran - Naujac Rue de la Liberté | G | 126 | 1991 | 150 | 3.84 | Karstic limestone | Bessac |
| 55 | Bordeaux Amont Taudin | G | 126 | 1991 | 500 | 2.88 | Alluvium and karstic limestone | Howden |
| 56 | Rouen "Métrobus" | C | 126 | 1993 | 800 | 8.33 | Black clay, middle Albian sand and Gault clay | Herrenknecht |
| 57 | Toulouse metro: Package 3 | C | 131 | 1989 -1991 | 3150 | 7.65 | Clayey-sandy molasse and beds of sandstone | FCB / Kawasaki |
| 58 | Toulouse metro: Packages 4 and 5 | C | 131 | 1990 -1991 | 1587 +1487 | 5.6 | Molasse | Lovat |
| 59 | Lille metro: Line 2 Package 1 | C | 132 | 1992 - 1994 | 5043 | 7.65 | Flanders clay | FCB |
| 60 | Lille metro: Line 2 Section b | C | 132 | 1992 - 1993 | 1473 | 7.65 | Chalk, clay, and sandy chalk | FCB |
| 61 | St Maur: VL3c main sewer | G | 133 | 1992 - 1994 | 1350 | 3.5 | Very heterogenous plastic clay, sand, coarse limestone,andupper Landenian clay | Herrenknecht |
| 62 | Lyons metro: Line D Vaise - Gorge de Loup | C | 133 | 1993 - 1995 | 2 x 875 | 6.27 | Sand, gravel, and clayey silt | Herrenknecht |
| 63 | METEOR Line 14 | C | 142 | 1993 - 1995 | 4500 | 8.61 | Sand, limestone, marl,upper Lutetian marl/limestone (caillasses) | HDW |
| 64 | RER Line D Chatelet / Gare de Lyon | C | 142 | 1993 - 1994 | 2 x 1600 | 7.08 | Coarse limestone | Lovat |
| 65 | Cleuson Dixence Package D Inclined shaft | D | 142 | 1994 - 1996 | 2300 | 4.77 | Limestone, quartzites, schist, sandstone | Robbins |
| 66 | Cleuson Dixence Inclined shaft | D | 142 | 1994 - 1996 | 400 | 4.4 | Limestone, schist, sandstone | Lovat |
| 67 | Cleuson Dixence Package B Headrace tunnel | D | 153 | 1994 - 1996 | 7400 | 5.6 | Schist and gneiss | Wirth |
| 68 | Cleuson Dixence Package C Headrace tunnel | D | 152 | 1994 - 1996 | 7400 | 5.8 | Schist, micachist, gneiss, and quartzite | Robbins |
| 69 | EOLE | B | 146 | 1993 - 1996 | 2 x 1700 | 7.4 | Sands, marl and 'caillasse' marl/limestone, sandstone and limestone | Voest Alpine |
| 70 | South-east plateau outfall sewer (EPSE) | G | 146 | 1994 - 1997 | 3925 | 4.42 | Molasse sand, moraine, alluvium | NFM |
| 71 | Cadiz: Galerie Guadiaro Majaceite | F | 148 | 1995 - 1997 | 12200 | 4.88 | Limestone, consolidated clay | NFM/ MHI |
| 72 | Lille metro Line 2 Package 2 | C | 148 | 1995 - 1997 | 3962 | 7.68 | Flanders clay | FCB |
| 73 | North Lyons bypass, Caluire tunnel, North tube | A | 150 | 1994 - 1996 | 3252 | 11.02 | Gneiss, molasse, sands and conglomerate | NFM |
| 74 | North Lyons bypass, Caluire tunnel, South tube | A | 150 | 1997 - 1998 | 3250 | 11.02 | Gneiss, molasse, sand, and conglomerate | NFM |
| 75 | Storebaelt rail tunnels | B | 150 | 1990 - 1995 | 14824 | 8.78 | Clay and marl | Howden |
| 76 | Strasbourg tram line | C | 150 | 1992 - 1993 | 1198 | 8.3 | Sands and graviers | Herrenknecht |
| 77 | Thiais main sewer Package 1 | G | 154 | 1987 - 1989 | 4404 | 2.84 | Marl and clay | Lovat |
| 78 | Antony urban area main sewer | G | 154 | 1989 | 1483 | 2.84 | Alluvium, limestone, marl | Lovat |
| 79 | Fresnes transit | G | 154 | 1991 | 280 | 2.84 | Marl and alluvium | Lovat |
| 80 | Main sewer beneath CD 67 road in Antony | G | 154 | 1991 | 670 | 2.84 | Marl | Lovat |
| 81 | Duplication of main sewer, Rue de la Barre in Enghien | G | 154 | 1992 - 1993 | 807 | 2.84 | Sand, marly limestone, marl | Lovat |
| 82 | Bièvre interceptor | G | 154 | 1993 | 1000 | 2.84 | Marl and alluvium | Lovat |
| 83 | Duplication of main sewer, Ru des Espérances - 8th tranche | G | 156 | 1993 - 1994 | 1387 | 2.54 | Limestone, sand | Lovat |
| 84 | Duplication of main sewer, Ru des Espérances - 9th tranche | G | 156 | 1995 - 1996 | 1200 | 2.54 | Coarse limestone, marly limestone | Lovat |
| 85 | Duplication of main sewer, Ru des Espérances - 10th tranche | G | 156 | 1996 - 1997 | 469 | 2.54 | Marly limestone | Lovat |