AFTES

NEW RECOMMENDATIONS ON

CHOOSING MECHANIZED TUNNELLING TECHNIQUES

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

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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.

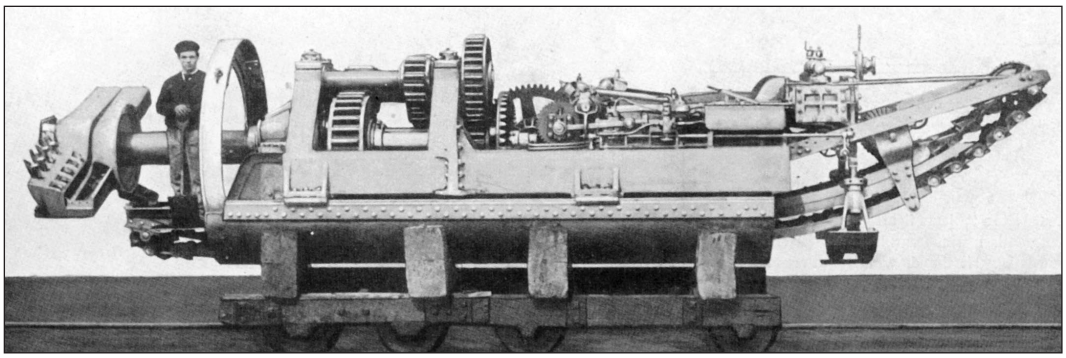
Before the large number of parameters and selection criteria, this group soon realized that it was not possible to draw up an analytical method for choosing the most appropriate mechanized tunnelling method, but rather that they could provide a document which:

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.

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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 hydro-geological 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:

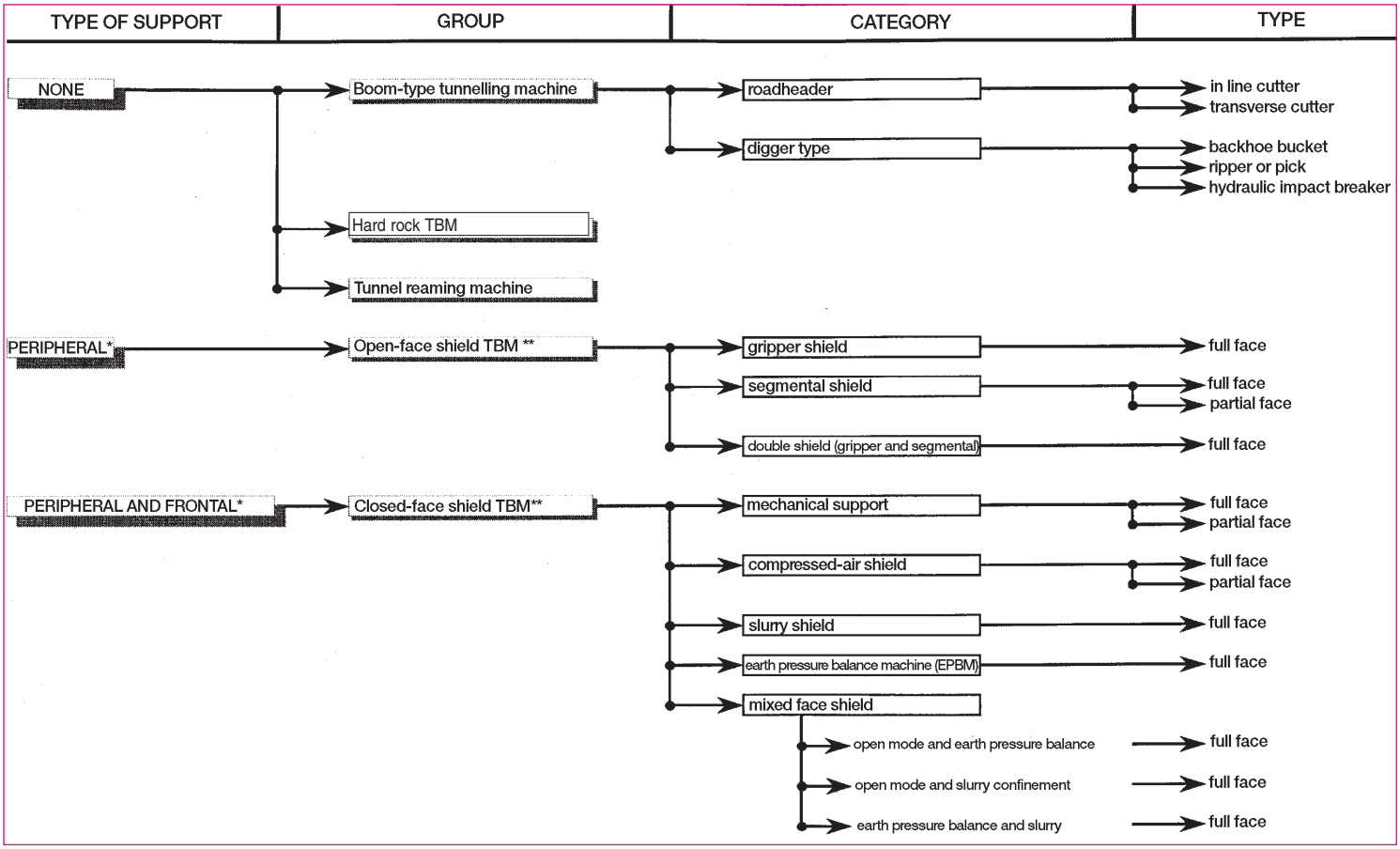
- Backhoe, ripper, or hydraulic impact breaker
- In-line cutterhead (roadheader)
- Transverse cutterhead (roadheader)

AFTES data sheets: No. 8 – 14

4.1.3 - Hard rock TBM

A Hard rock TBM has a cutterhead that excavates the full tunnel face in a single pass.

The thrust on the cutterhead is reacted by



*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

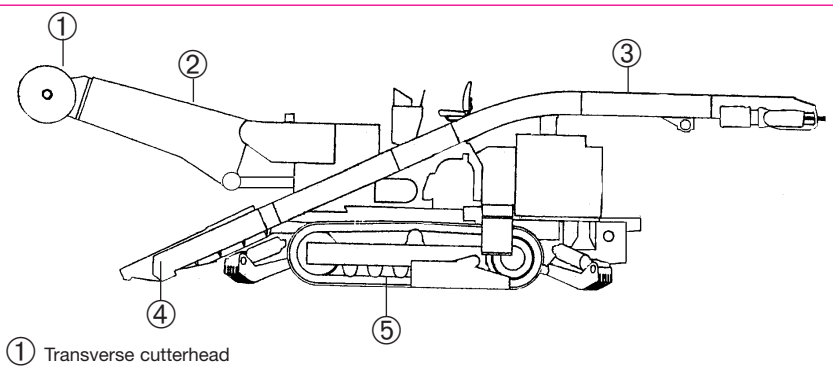


Schéma 4.1.2



Photo 4.1.2 - Roadheader

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

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

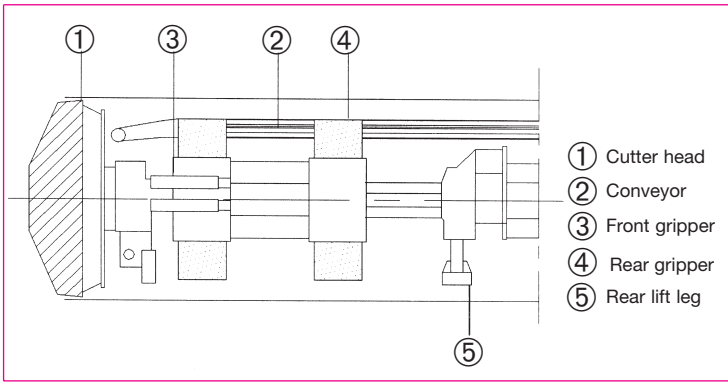
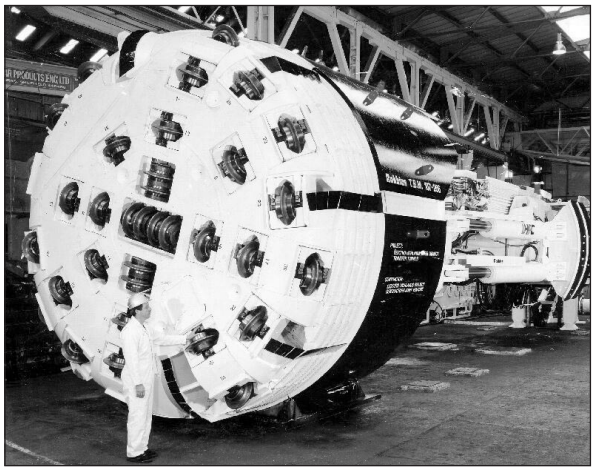


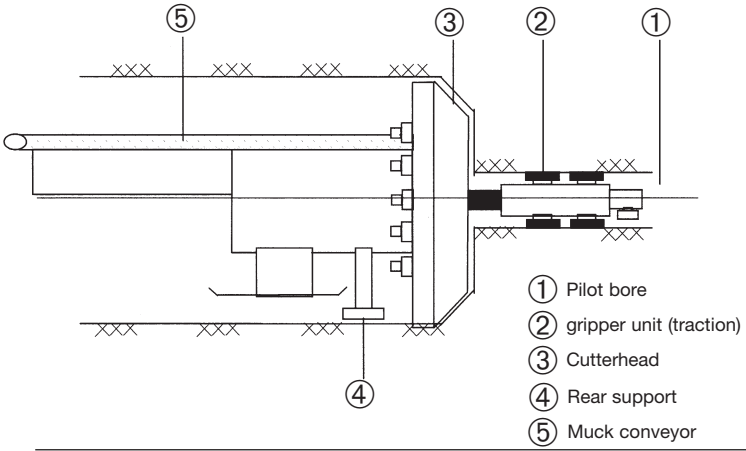
Photo 4.1.3 - Lesotho Highlands Water Project



4.1.4 - Tunnel reaming machine

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

(Schéma and photo 4.1.4).



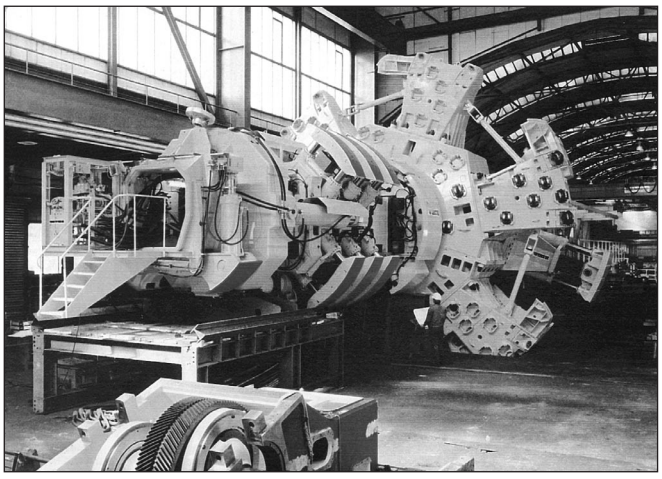


Photo 4.1.4 - Sauges tunnel (Switzerland)

4.2 - MACHINES PROVIDING IMMEDIATE PERIPHERAL 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.

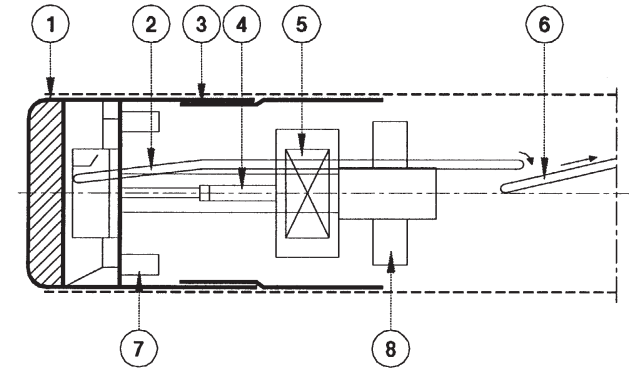
The different configurations for peripheral-support TBMs are detailed below.

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

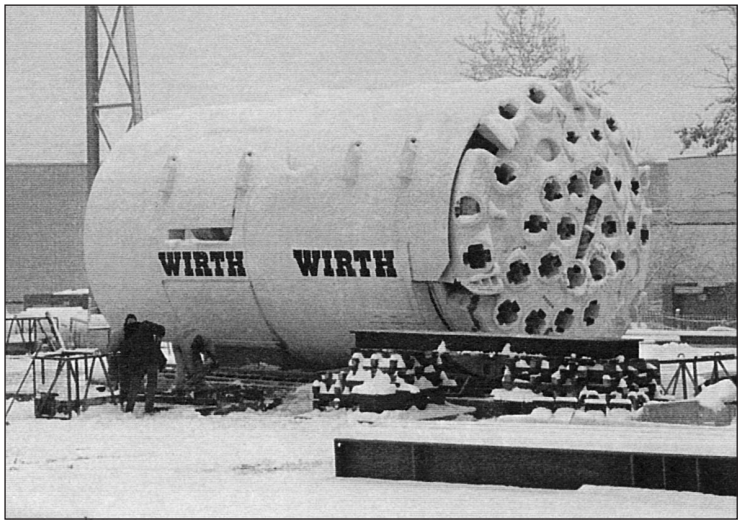
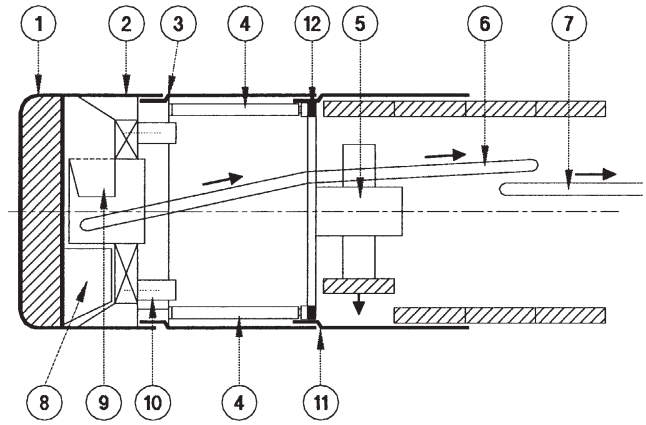


Photo 4.2.2 - Main CERN tunnel

4.2.3 - Open-face shield TBM

An open-face 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



① Cutterhead
② Shield
③ Articulation (option)
④ Thrust ram
⑤ Segment erector
⑥ Muck extraction conveyor
⑦ Muck transfer conveyor
⑧ Gathering arm
⑨ Muck hopper
⑩ Motor
⑪ Tailskin articulation (option)
⑫ Thrust ring

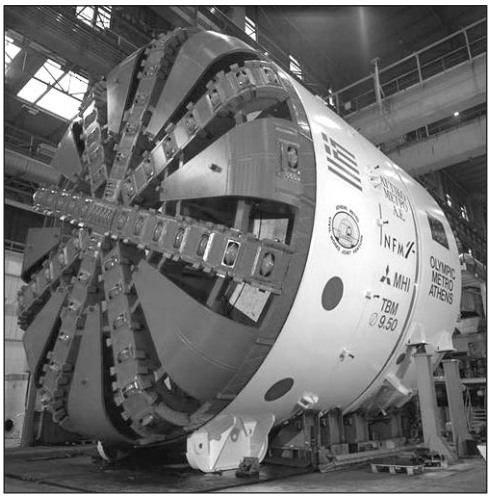


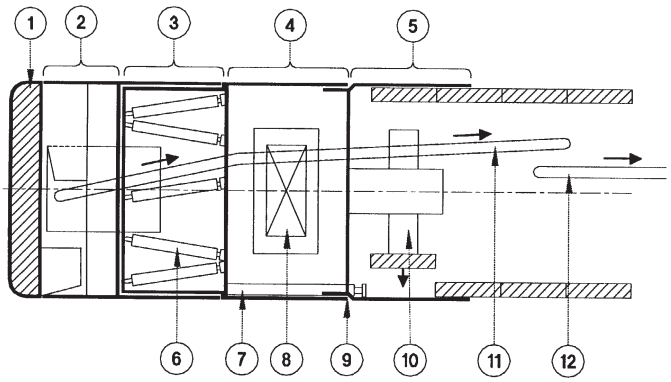
Photo 4.2.3
Athens metro

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



① Cutterhead
② Front unit
③ Telescopic section
④ Gripper unit
⑤ Tailskin
⑥ Main thrust rams
⑦ Longitudinal thrust rams
⑧ Grippers
⑨ Tailskin articulation
⑩ Segment erector
⑪ Muck extraction conveyor
⑫ Muck transfer conveyor

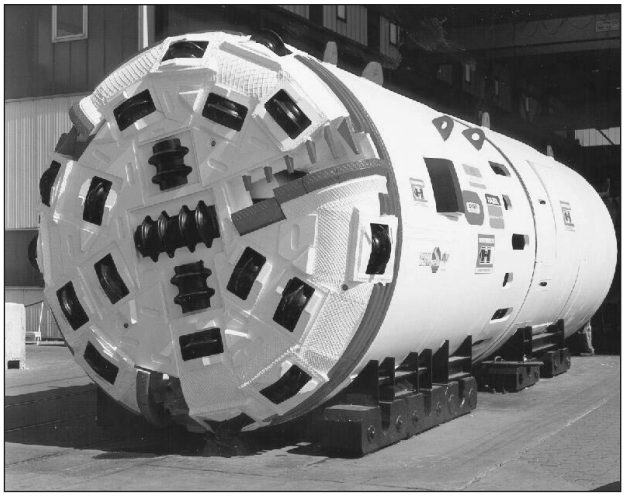


Photo 4.2.4 - Salazie water transfer project (Reunion Island)

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.

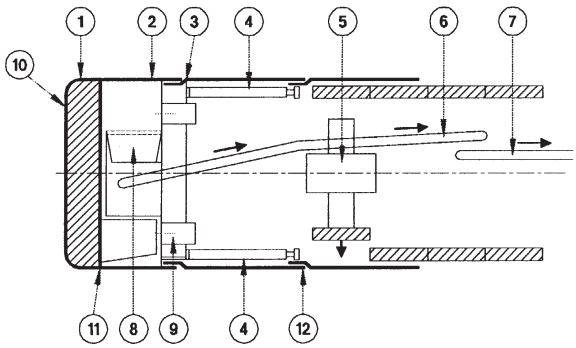
The TBM is jacked forward by rams pushing off the segmental lining erected inside the TBM tailskin, using an erector integrated into the machine.

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



① Cutterhead
② Shield
③ Articulation (option)
④ Thrust ram
⑤ Segment erector
⑥ Muck extraction conveyor
⑦ Muck transfer conveyor
⑧ Muck hopper (with optional gate)
⑨ Cutterhead drive motor
⑨ Gated cutterhead openings
⑪ Peripheral seal between cutterhead and shield
⑫ Tailskin articulation (option)



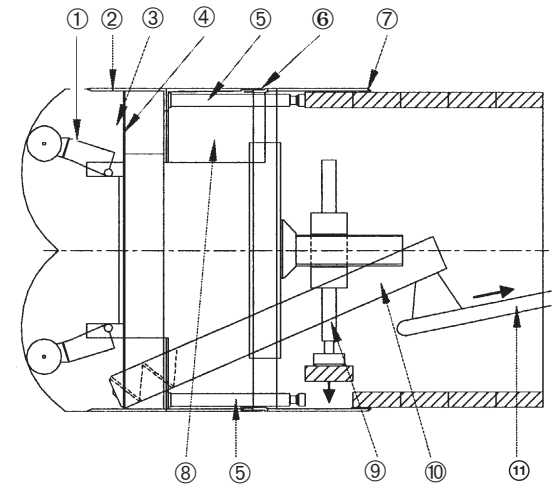
Photo 4.3.2 RER Line D (Paris)

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



① Excavating arm
② Shield
③ Cutting chamber
④ Airtight bulkhead
⑤ Thrust ram
⑥ Articulation (option)
⑦ Tailskin seal
⑧ Airlock to cutting chamber
⑨ Segment erector
⑩ Screw conveyor (or conveyor and gate)
⑪ Muck transfer conveyor

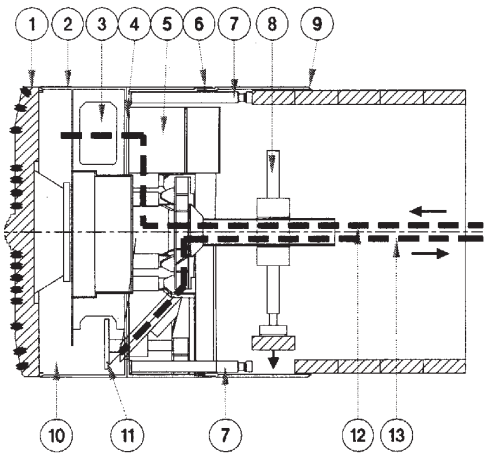


Photo 4.3.3 - Compressed air TBM - Boom type

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



① Cutterhead
② Shield
③ Air bubble
④ Watertight bulkhead
⑤ Airlock to cutterhead chamber
⑥ Tailskin articulation (option)
⑦ Thrust ram
⑧ Segment erector
⑨ Tailskin seal
⑩ Cutterhead chamber
⑪ Agitator (option)
⑫ Slurry supply line
⑬ Slurry return line

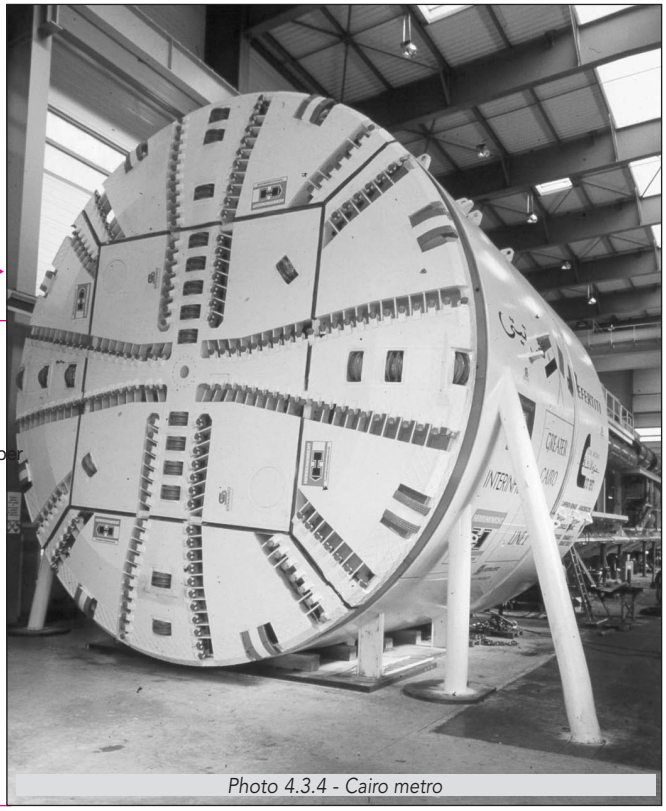


Photo 4.3.4 - Cairo metro

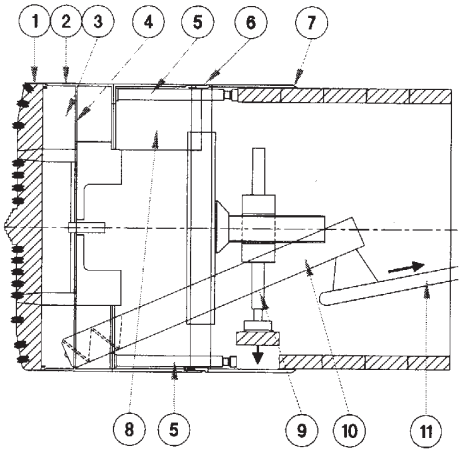
4.3.5 - Earth pressure balance machine

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



① Cutterhead
② Shield
③ Cutterhead chamber
④ Airtight
⑤ Thrust ram
⑥ Articulation (option)
⑦ Tailskin seal
⑧ Airlock to cutterheau chamber
⑨ Segment erector
⑩ Screw conveyor
⑪ Muck transfer conveyor

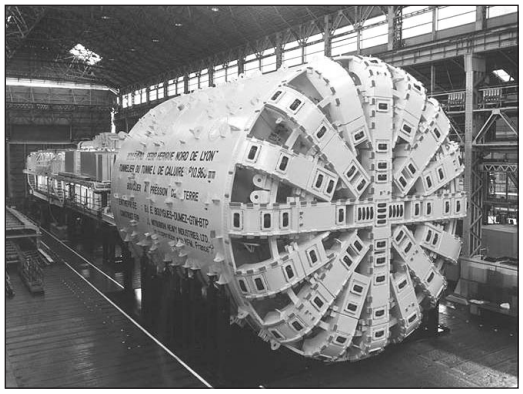


Photo 4.3.5 - CaluireTunnel, Lyons (France)

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)

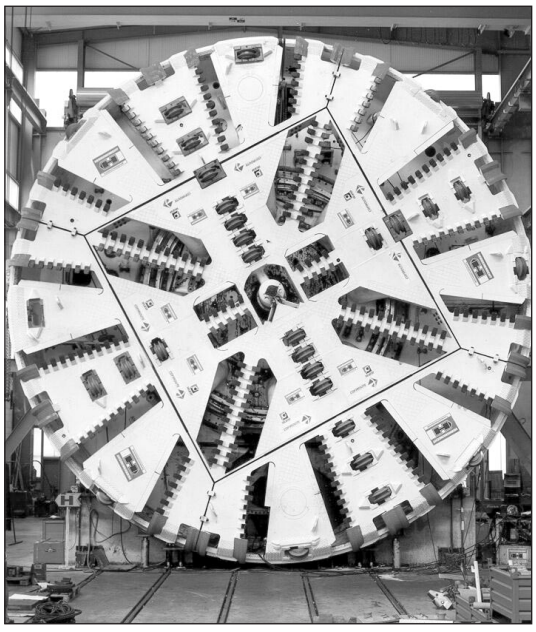


Photo 4.3.6a
A86 Oues tunnel (Socatop)

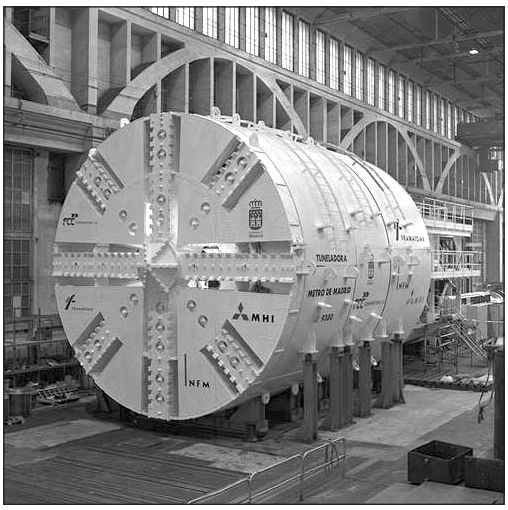


Photo 4.3.6b - A86 Ouest tunnel (Socatop)
Madrid metro

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 OF THE EFFECT OF ELEMENTARY SELECTION PARAMETERS ON MECHANIZED TUNNELLING SOLUTIONS

Solution / Elementary parameters	Machines not providing immediate support		Machines providing immediate support			Machines providing immediate peripheral and frontal support simultaneously				
	Boom-type tunnelling machine	Tunnel reaming and side support machines	Radial support shield tunnel boring machine	Longitudinal support shield tunnel boring machine		Mechanical support shield TBM	Compressed-air shield TBM		Slurry shield TBM	Earth pressure balance shield TBM
				Full face tunnelling machine	Boom-type		Full face tunnelling machine	Boom-type		
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 Hard rock 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 Hard rock 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) (Hard rock 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 (Hard rock TBM).

d) Mucking out

See Chapter 6.1.2.§ d) (Hard rock 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 Hard rock 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) (Hard rock 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) (Hard rock TBM).

6.2.2 - Specific features of open-face 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 ≥ 5 x 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 - Hard rock TBMs

Hard rock 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 facilitate 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.

Hard rock 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 shield TBMs

An open-face 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 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 IMPROVEMENT

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, xanthan 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 studied in parallel with the mechanical parameters (strength in particular).

6 - PROJECT CHARACTERISTICS

No comment.

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 Hard rock 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 Hard rock 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 tailskin, 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, Hard rock 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 4

Mechanized tunnelling data sheets (up to 31/12/99).

N° fiche	Project	*Project type (AITES)	TOS issue**	Date	Bored length (m)	Bore diameter (m)	Geology
1	Echaillon	D	68	1972-1973	4362	5.80	Gneiss, flysch, limestone
2	La Coche	D	77	1972-1973	5287	3.00	Limestone, sandstone, breccia
3	CERN SPS	H	64	1973-1974	6551	4.80	Molasse
4	RER Châtelet-Gare de Lyon	C	64	1973-1975	5100	7.00	Limestone
5	Belledonne	D	64	1974-1978	9998	5.88	Schist, sedimentary granite
6	Bramefarine	D	67	1975-1977	3700	8.10	Limestone, schist
7	Lyons metro - Crémaillère	C	64	1976	220	3.08	Gneiss, granite
8	Galerie du Bourget	C	67	1976-1978	4845	6 m2	Limestone, molasse
9	Monaco - Service tunnel	H	64	1977	913	3.30	Limestone, marne
10	Grand Maison - Eau Dolle	D	64	1978	839	3.60	Gneiss, schist, dolomite
11	Western Oslofjord	G	77	1978-1984	10500	3.00	Slate, limestone, igneous rock
12	Brevon	D	66	1979-1981	4150	3.00	Limestone, dolomite, other calcareous rock (malm)
13	Grand Maison (penstocks and service shaft)	D	75	1979-1982	5466	3.60	Gneiss, schist
14	Marignan aqueduct	F	66	1979-1980	480	5.52 m2	Limestone
15	Super Bissorte	D	73	1980-1981	2975	3.60	Schist, sandstone
16	Pouget	D	66	1980-1981	3999	5.05	Gneiss
17	Grand Maison - Vaujany	D	75	1981-1983	5400	7.70	Liptinite, gneiss, amphibolite
18	Vieux Pré	D	68	1981-1982	1257	2.90	Sandstone, conglomeratee
19	Haute Romanche Tunnel	D	73	1981-1982	2860	3.60	Limestone, schist, crystalline sandstone
20	Cilaos	F	80	1982-1984	5701	3.00	Basalt, tuff
21	Monaco - tunnel No. 6	A	66	1982	183	5.05	Limestone, dolomite
22	Ferrières	D	79	1982-1985	4313	5.90	Schist, gneiss
23	Durolle	D	79	1983-1984	2139	3.40	Granite, quartz, microgranite
24	Montfermy	D	80	1983-1985	5040	3.55	Gneiss, anatexite, granite
25	CERN LEP (machines 1 and 2)	H	82	1985-1986	14680	4.50	Molasse
26	CERN LEP (machine 3)	H	82	1985-1987	4706	4.50	Molasse
27	Val d'Isère funicular	B	97	1986	1689	4.20	Limestone, dolomite, cargneule (cellular dolomite)
28	Calavon and Luberon	F	97	1987-1988	2787	3.40	Limestone
29	Takamaka II	D	101	1985-1987	4803	3.20	Basalt, tuff, agglomerates
30	Oued Lakhdar	D	101	1986-1987	6394	4.56 and 4.80	Limestone, sandstone, marl
31	Paluel nuclear power plant	E	105	1980-1982	2427	5.00	Chalk
32	Penly nuclear power plant	E	105	1986-1988	2510	5.15	Clay
33	Lyons river crossing - metro line D	C	106	1984-1987	2 x 1230	6.50	Recent alluvium and granitic sand
34	Lille metro, line 1b - Package 8	C	106	1986-1987	1000	7.65	White chalk and flint
35	Lille metro, Line 1b - Package 3	C	106	1986-1988	3259	7.70	Clayey sand and silt
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
38	Caracas metro: package PS 01	C	107	1986-1987	2 x 1564	5.70	Silty-sandy alluvium, gravel, and clay
39	Caracas metro: package CP 03	C	107	1987	2 x 2131	5.70	Weathered micaschist and silty sand
40	Caracas metro: package CP 04	C	107	1987-1988	2 x 714	5.70	Micaschist
41	Singapore metro: package 106	C	107	1985-1986	2600	5.89	Sandstone, marl and clay
42	Bordeaux: "boulevards" main sewers Ø3800	G	113	1989-1990	1461	4.36	Karstic limestone and alluvium
43	Bordeaux: Avenue de la Libération Ø2200	G	113	1988-1989	918	2.95	Karstic limestone and alluvium
44	St Maur-Créteil, section 2	G	113	1988-1990	1530	3.35	Old alluvium and boulders
45	Crosne-Villeneuve St Georges	G	113	1988-1990	911	2.58	Weathered marl and indurated limestone
46	Channel Tunnel T1	B	114	1988-1990	15618	5.77	Blue chalk
47	Channel Tunnel T2-T3	B	114	1988-1991	20009 + 18860	8.78	Blue chalk
48	Channel Tunnel T4	B	114	1988-1989	3162	5.61	Grey and white chalk
49	Channel Tunnel T5-T6	B	114	1988 - 1990	2 x 3265	8.64	Grey and white chalk
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
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
52	Créteil - Vitry	G	124	1990 - 1991	2065	3.35	Alluvium and made ground

(APPENDIX 4)

N° fiche	Project	*Project type (AITES)	TOS issue**	Date	Bored length (m)	Bore diameter (m)	Geology
53	Orly Val: Package 2	C	124	1989 - 1990	1160	7.64	Marl with beds of gypsum
54	Bordeaux Caudéran - Naujac Rue de la Liberté	G	126	1991	150	3.84	Karstic limestone
55	Bordeaux Amont Taudin	G	126	1991	500	2.88	Alluvium and karstic limestone
56	Rouen "Métrobus"	C	126	1993	800	8.33	Black clay, middle Albian sand and Gault clay
57	Toulouse metro: Package 3	C	131	1989 - 1991	3150	7.65	Clayey-sandy molasse and beds of sandstone
58	Toulouse metro: Packages 4 and 5	C	131	1990 - 1991	1587 + 1487	5.6	Molasse
59	Lille metro: Line 2 Package 1	C	132	1992 - 1994	5043	7.65	Flanders clay
60	Lille metro: Line 2 Section b	C	132	1992 - 1993	1473	7.65	Chalk, clay, and sandy chalk
61	St Maur: VL3c main sewer	G	133	1992 - 1994	1350	3.5	Very heterogenous plastic clay, sand, coarse limestone, and upper Landenian clay (fausses glaises)
62	Lyons metro: Line D Vaise - Gorge de Loup	C	133	1993 - 1995	2 x 875	6.27	Sand, gravel, and clayey silt
63	METEOR Line 14	C	142	1993 - 1995	4500	8.61	Sand, limestone, marl,upper Lutetian marl/limestone (caillasses)
64	RER Line D Chatelet / Gare de Lyon	C	142	1993 - 1994	2 x 1600	7.08	Coarse limestone
65	Cleuson Dixence Package D Inclined shaft	D	142	1994 - 1996	2300	4.77	Limestone, quartzites, schist, sandstone
66	Cleuson Dixence Inclined shaft	D	142	1994 - 1996	400	4.4	Limestone, schist, sandstone
67	Cleuson Dixence Package B Headrace tunnel	D	153	1994 - 1996	7400	5.6	Schist and gneiss
68	Cleuson Dixence Package C Headrace tunnel	D	152	1994 - 1996	7400	5.8	Schist, micachist, gneiss, and quartzite
69	EOLE	B	146	1993 - 1996	2 x 1700	7.4	Sands, marl and 'caillasse' marl/limestone, sandstone and limestone
70	South-east plateau outfall sewer (EPSE)	G	146	1994 - 1997	3925	4.42	Molasse sand, moraine, alluvium
71	Cadiz: Galerie Guadiaro Majaceite	F	148	1995 - 1997	12200	4.88	Limestone, consolidated clay
72	Lille metro Line 2 Package 2	C	148	1995 - 1997	3962	7.68	Flanders clay
73	North Lyons bypass, Caluire tunnel, North tube	A	150	1994 - 1996	3252	11.02	Gneiss, molasse, sands and conglomerate
74	North Lyons bypass, Caluire tunnel, South tube	A	150	1997 - 1998	3250	11.02	Gneiss, molasse, sand, and conglomerate
75	Storebaelt rail tunnels	B	150	1990 - 1995	14824	8.78	Clay and marl
76	Strasbourg tram line	C	150	1992 - 1993	1198	8.3	Sands and graviers
77	Thiais main sewer Package 1	G	154	1987 - 1989	4404	2.84	Marl and clay
78	Antony urban area main sewer	G	154	1989	1483	2.84	Alluvium, limestone, marl
79	Fresnes transit	G	154	1991	280	2.84	Marl and alluvium
80	Main sewer beneath CD 67 road in Antony	G	154	1991	670	2.84	Marl
81	Duplication of main sewer, Rue de la Barre in Enghien	G	154	1992 - 1993	807	2.84	Sand, marly limestone, marl
82	Bièvre interceptor	G	154	1993	1000	2.84	Marl and alluvium
83	Duplication of main sewer, Ru des Espérances - 8th tranche	G	156	1993 - 1994	1387	2.54	Limestone, sand
84	Duplication of main sewer, Ru des Espérances - 9th tranche	G	156	1995 - 1996	1200	2.54	Coarse limestone, marly limestone
85	Duplication of main sewer, Ru des Espérances - 10th tranche	G	156	1996 - 1997	469	2.54	Marly limestone

*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 -

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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
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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
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29	Takamaka II	D	101	1985-1987	4803	3.20	Basalt, tuff, agglomerates	Bouygues
30	Oued Lakhdar	D	101	1986-1987	6394	4.56 and 4.80	Limestone, sandstone, marl	Wirth
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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
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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
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
52	Créteil - Vitry	G	124	1990 - 1991	2065	3.35	Alluvium and made ground	FCB

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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, and upper Landenian clay (fausses glaises)	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
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