A.F.T.E.S.

WORKING GROUP N° 7
TEMPORARY AND PERMANENT SUPPORT

Recommendations on choice of tunnel support

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1. — PURPOSE OF RECOMMENDATIONS

The most appropriate type of support for an underground opening is an extremely complex question by reason of the large number of criteria governing the final choice and the difficulty of quantifying most of them.

These recommendations review the main criteria to be considered and attempt to help the designer make the final choice in the light of each particular one.

Although, in most cases, any one of these criteria can, alone, eliminate certain types of support, the final choice is usually arrived at by finding a balanced support design that best suits each factor.

Thus, each point is analysed separately, but where necessary, reference is made to the possibilty of certain features being cumulative in the positive or negative sense, with respect to any given type of support.

If, at the outcome of the analysis, several types of support are still feasible, the final choice must be made on the basis of cost and the effect on site organisation.

Detailed design of the support system is not discussed in these recommendations. It is rarely based on purely theoretical considerations, it usually refers to semi-empirical formulations specific to each type. The article « Thoughts on the Usual Methods of Tunnel Lining Design », which refers more specifically to permanent support systems, can also be usefully consulted in connection with temporary support design. The recommendation, published by AFTES on the use of steel ribs, and rock bolts, and the method of tunnel construction based on immediate shotcrete and rock bolt support, available elsewhere, contain practical information on the implementation of these types of support.

2. — CLASSIFICATION OF TEMPORARY SUPPORT SYSTEM METHODS

Temporary support is defined as any system designed and installed to support the perimeter of an underground opening between the time it is first excavated up to the time that the permanent lining is in place. With this definition, one can distinguish four main classes of temporary support, from their interaction with the surrounding ground :

— Support acting by applying a confining pressure to the surrounding ground, chiefly :

- shotcrete,
- shotcrete and lightweight steel ribs.

— Support applying both a confining pressure and acting as reinforcement of the surrounding ground, i.e. various

types of rock bolt with or without shotcrete and/or lightweight steel ribs :

- ungrouted mechanically or chemically anchored rocks bolts,
- grouted (resin or mortar) rock bolts,
- driven anchor bars.

— Systems providing plain "brute strength" support :

- heavy steel ribs,
- lightweight steel ribs,
- steel linings,
- concrete voussoir segments,
- driven tubes (umbrella arch),
- shields.

— System which consolidate the ground to amend its geotechnical and/or hydrological properties :

- consolidation grouting,
- compressed air,
- freezing.

The systems providing plain support are differentiated from those applying a confining pressure by the much greater strength of the components which opposes deformation of the ground and the support system, so that safety relies more on the strength of the support system than on the inherent properties of the surrounding ground.

Where a confining pressure is used to control ground movements on the other hand, the strength of the support system is less important, the rock providing most of the strength. The support system simply applies a (usually small) radial confining pressure which substantially increases rock strength in the tangential direction, so that a "relieving arch" forms above the crown.

The above classification must be considered a theoretical approach reflecting the manner in which each type of support system chiefly operates, although there may be significant variations, depending on the conditions affecting the system. More than one type of support can be used in combination on the same job. For example, shotcrete is often combined with rock bolts and/or lightweight steel ribs, steel linings can be stiffened with lightweight or heavy steel ribs inside, and shields are usually employed only for very short-term support until the steel or concrete segmental lining is installed.

Some methods prevent much of the ground decompression either by supporting it ahead of the working face or by means of a system capable of applying a "recompression" force. What is known as "mechanical presplitting" in which a cut is first made around the tunnel contour outline and filled with concrete so that the ground is supported before the face is excavated, belongs to the first category. It is sometimes possible to install rock bolts from a small pilot tunnel ahead of the face (this is known as pre-bolting). Some types of rigid support (heavy steel ribs or voussoirs) incorporate jacks to recompress the ground to some extent, and thus belong to the second category.

These are all somewhat special applications of some of the support methods listed above.

3. — CRITERIA

The criteria to be considered in support method selection fall into two main categories, relative to (i) the surrounding ground and (ii) the structure and construction method.

3.1. — Ground criteria

The first category refers to the ground inside a volume whose outer boundary is at such a distance from the tunnel that the influence of ground behaviour outside this boundary can be considered as negligible for overall stability. The thickness of this ring of ground will depend on the dimensions of the opening and the ground properties. Unless more detailed data is available, it can be taken as equal to half the excavation width, provided there is no sudden and significant change in ground properties just outside this boundary.

If the ground inside this ring consists of formations with significantly different properties, one usually considers those with the most unfavourable behaviour if they occupy a sufficient volume to have a significant effect on overall behaviour. If there are only slight differences between the formations, it is usually sufficient in the first analysis to take mean values.

The criteria and parameters to be used for ground characterization for tunnelling purposes are those reviewed in the recommendation for a Rock Mass Description System for Tunnel Stability Analysis issued by AFTES Working Group N° 1 in *Tunnels et Ouvrages Souterrains* N° 28, July-Aug. 1978 and T.O.S. (pp. 7 to 16, july 1982).

Those with special relevance to support system selection are (paragraph numbers refer to these recommendations) :

— rock strength (para. 4 b),

— rock discontinuities (para. 3 b, 3 c and Appendix 2),

— weathering potential (para. 4 c and 4 e),

— hydrology (para. 2 a and 2 b),

— natural stresses (para. 5).

The use of these parameters, and modified definitions where the ground is a soil, call for certain amendments to the strength criterion particularly, which will be itemized as each criterion is discussed.

3.2. — Structure and construction method criteria

These criteria are chiefly :

— dimensions and shape of opening;

— method of driving : explosive (with or without smooth blasting or pre-splitting techniques), or mechanical.

3.3. — Environment criteria

These are chiefly :

— environmental sensitivity to settlement ;

— impact of changes to hydrological pattern ;

— impact (if any) of special consolidation techniques (grouting, compressed air, freezing).

Category	Description	Examples	σc (MPa)
R1	Very strong rock	Competent quartzites and basalts	> 200
R2a	Strong rock	Competent granites, porphyries, sandstones and limestones	200 to 120
R2b		Granites, strong or slightly dolitized limestones ans sandstones, marbles, dolomites and compact conglomerates	120 to 60
R3a	Moderately strong rock	Ordinary sandstones, silica shales or shale sandstone, gneiss	60 to 40
R3b		Moderately strong clay shales, sandstones and limestones, compact marls, low-consistency conglomerates	40 to 20
R4	Weak rock	Soft or well-fractured shales or limestones, gypsum, well-fractured or marlaceous sandstone, puddingstone, chalk	20 to 6
R5a	Very weak rock and consolidated cohesive soils	Sandy or clayey marls, marly sands, weathered gypsum and chalk	6 to 0,5
R5b		Normally consolidated clavey sands, gravel alluvium	< 0,5
R6a	Plastic or poorly consolidated soils	Weathered marls, clays, clayey sands, fine silt	
R6b		Poorly consolidated peat, silt and mud, cohesionless fine sand	

I_p = Plastic index = $W_L - W_p$

I_c = Consistency index = $\frac{W_L - W}{I_p}$

W_L et W_p are Atterberg limits

W = Natural moisture content

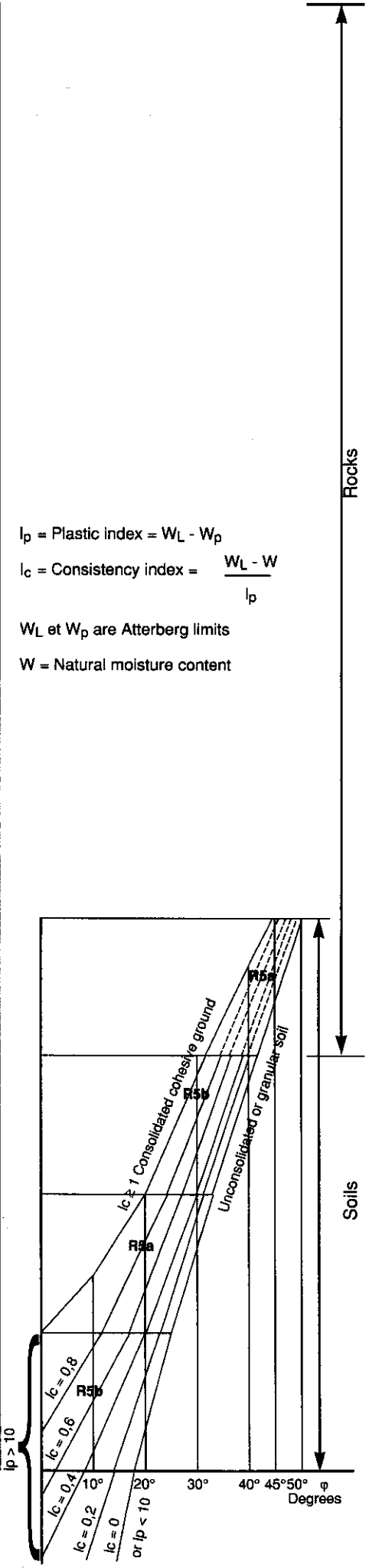


Table 0

4. — SUPPORT SYSTEM SELECTION

The following tables list the suitability of each type of support system with reference to the individual criteria. Each type is rated on the basis of the value of the parameter used to evaluate each criterion :

☑ recommended (Good),

☐ feasible if other criteria are rated Good (Fair),

☒ unsuitable although may be feasible (Poor),

☒ unfeasible in principle (Very Poor).

The ratings for each criterion are then summated to select the most appropriate type of support.

4.1. — Ground mechanical properties
(tables 0 to 1)

The ten categories used to define the mechanical properties of the ground are based on the classification in the Working Group 1 Recommendations mentioned above, and include soils and intermediate materials between soil and rock. The changes made to the original classification consist of subdividing certain rock categories (R2, R3, R5), adding a category R6 (subdivided into R6a and R6b), and refining the definition of the lower strength categories (R5, R6) for soil and intermediate materials, based chiefly on their natural friction angle, plasticity index Ip and consistency index Ic (*).

Table 0 shows the ten ground categories based on mechanical behaviour.

Table 1 relates the various types of support system available to these categories :

— It can be seen that shotcrete and grouted rock bolts are unsuitable where ground strength and cohesion are insufficient to permit arching ensuring stability even when a confining pressure is applied. In any event, such ground usually exhibits insufficient stand-up time for this type of support to be installed.

— Similarly, ungrouted rock bolts are unsuitable in weak ground which would be crushed by the expanding shell or allow the resin anchorage to slip.

— Driven anchors are of course unsuitable if the ground is too hard for driving.

— Shields are unsuitable in rock and in soils containing rock blocks or boulders.

— In poorly cohesive soils, forepoling may be necessary, and the face may even require support if even short-term stability is insufficient.

4.2. — Discontinuities
(table 2)

The criteria considered and the corresponding number of categories defined with respect to discontinuities refer to the number, orientation and spacing of joint sets.

(*) The consitency index is defined as :

$Ic = \frac{W_L - W}{I_p}$ avec W_L = liquid limit, W_p = plastic limit, I_p = plasticity index = $W_L - W_p$

Ic = 0 is the liquid limit
Ic = 1 is the plastic limit

Table 1

Mechanical behavour	Unsupported		Shotcrete	Rock bolts: Ungrouted	Rock bolts: Grouted	Rock bolts: Jacked bars	Steel ribs: Heavy	Steel ribs: Light, yielding	Segments: Steel	Segments: Concrete	Perforated tubes	Shield or jacked pipe	Special: Grouting	Special: Comp. air	Special: Freezing
R1	●			●		☒			☒	☒	☒	☒		☒	☒
R2a	●			●		☒			☒	☒	☒	☒		☒	☒
R2b			●	●	●	☒			☒	☒	☒	☒		☒	☒
R3a			●	●	●	☒		●	☒	☒	☒	☒		☒	
R3b			●		●	☒		●		☒	☒	☒			
R4	☒		●	☒			●	●							
R5a	☒		●	☒			●	●	●						
R5b	☒			☒	☒		●	●	●	●	●	●	●		
R6a	☒		☒	☒	☒	☒	● Enf	Enf	● Enf	● Bcl		●	●		
R6b	☒		☒	☒	☒	☒	● Enf Blf	Enf Blf	● Enf Blf	● Bcl Blf	Blf	● Blf	●		●

Legend Enf : with forepoling Blf : face lined Bcl : shield

Discontinuities (tunnel driven with explosives, with smooth-blasting) **1 — Rock (R1 to R4)**			Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
						Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Number of sets	Orientation	Spacing (1)					(2)										
N1			●					X			X	X	X	X	X	X	X
N2	Or2 or Or3	S1 to S3	●					X			X	X	X	X	X	X	X
N2 N3 or N4	Random	S1				●		X			X	X	X	X	X	X	X
		S2				●	●	X			X	X	X	X	X	X	X
		S3			●	Gr	Gr ●	X				X	X	X		X	X
		S4	X		●	Gr ou Bp	Gr ou Bp	X	Bl ou Bp ●	Bl ou Bp ●			X	X		X	X
		S5	X		●	X	Bp	X	Bl ou Bp ●	Bl ou Bp ●			X	X		X	X
N5			X		●	X	Bp	X	Bl ou Bp ●	Bl ou Bp ●	●		X	X	●	X	X

2 — Soil (R5 and R6)
Not applicable

Table 2

Nota 1 — For densest set
2 — Mortar grout preferred to resin when joints are open

Legend Gr = with continuous mesh Bp = with shotcrete Bl = with timber or steel lagging

Discontinuities (tunnel driven with explosives, without smooth-blasting) **1 — Rock (R1 to R4)**			Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
						Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Number of sets	Orientation	Spacing (1)					(2)										
Random N1 to N4	Random	S1				●	●	X		●	X	X	X	X	X	X	X
		S2				Gr	Gr ●	X		●	X	X	X	X	X	X	X
		S3	X		●	Gr	Gr ●	X	Bl ●	Bl ●		X	X	X		X	X
		S4 or S5	X		●	X	Bp	X	Bl ou Bp ●	Bl ou Bp ●				X		X	X
N5			X		●	X	Bp	X	Bl ou Bp ●	Bl ou Bp ●	●			X		X	X

2 — Soil (R5 and R6)
Not applicable

Table 2 a

Nota 1 — For densest set
2 — Mortar grout preferred to resin when joints are open

Legend Gr = with continuous mesh Bp = with shotcrete Bl = with timber or steel lagging

4.2.1. — Number of district joint sets

— N1 No (or very few) joints
— N2 One main set
— N3 Two main sets
— N4 More than two main sets
— N5 Abundant joints, no discernible pattern.

4.2.2. — Joint set orientation with respect to tunnel direction

— OR1 Subhorizontal joints
— OR2 Tunnel perpendicular to strike
— OR3 Intermediate
— OR4 Tunnel parallel to strike.

4.2.3. — Joint spacing

This classification can be based either on the mean spacing of the joints is each set, or failing this, from the RQD index, although the two approaches do not of course coincide.

— S1 Very wide spacing :
S > 200 cm or RQD > 90 %

— S2 Wide spacing :
60 cm < S < 200 cm or 75 % < RQD < 90 %

— S3 Moderate spacing :
20 cm < S < 60 cm or 50 % < RQD < 75 %

— S4 Close spacing :
6 cm < S < 20 cm or 25 % < RQD < 50%

Discontinuities (machine-driven tunnel) **1 —Rock (R1 to R4)**			Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
						Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Number of sets	Orientation	Spacing (1)					(2)										
N1			•					X					X	X	X	X	X
N2	Or2 or Or3	S1 to S3															
N2		S1 S2				•		X					X	X	X	X	X
N3		S3				•	•	X		•			X	X		X	X
or		S4			•	• Gr ou Bp	• Gr ou Bp	X		•				X		X	X
N4		S5	X		•	• Gr ou Bp	• Gr ou Bp	X	• Bl ou Bp	• Bl ou Bp	•						
N5			X		•	X	• Gr ou Bp	X	• Bl ou Bp	• Bl ou Bp	•						

2 — Soil (R5 and R6)
Not applicable

Table 2 b

Nota 1 — For densest set
2 — Mortar grout preferred to resin when joints are open

Legend Gr = with continuous mesh Bp = with shotcrete Bl = with timber or steel lagging

Weathering potential & swelling	Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
				Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Exfoliation potential	X		•	Gr ou Bp	Gr ou Bp	Bl ou Bp	Bl ou Bp	• Bl ou Bp	•	•					
Dissolution potential (1)	X		•	X	X	X	• Bl	• Bl	•	•					•
Swelling potential	X		• (2)	X	Bp	Bp	Bl ou Bp	Bl ou Bp		•					
Others															

Table 3

Nota 1 — If risk effectively exists (flowing water)
2 — Concrete only recommended if there is no flowing water in ground

Legend Gr = with continuous mesh Bp = with shotcrete Bl = with timber or steel lagging

— S5 Very close spacing :
S < 6 cm or RQD < 25 %

Open faults more than a few centimetres wide and karsts are not included since they are isolated features and the support must be selected on the basis of the poorest material.

Table 2 shows the most appropriate support with reference to rock jointing, for tunnels driven with explosives using pre-splitting or smooth blasting techniques. Other excavation methods are covered by tables 2a and 2b and discussed in section 4.7 below.

4.2.4.

Ungrouted rocks bolts are not suitable in finely fractured rock because of the danger of slippage of the anchor shell (pull-out tests are required in doubtful cases). If resin is used, it may escape if joints are open.

Driven anchor bars or shield are in principle unsuitable in rock. Because these joint ratings refer only to rock and this criterion is meaningless in soils, it is ignored.

4.3. — Weathering potential and swelling (table 3)

4.3.1. — The categories under this heading are as follows

— Ground subject to exfoliation through the mechanical effects of joints opening when the stress field changes, or through thermal changes (freezing or differential deformations of mineral inclusions) ;

Hydrology				Unsupported		Shotcrete	Rock bolts: Ungrouted	Rock bolts: Grouted	Rock bolts: Jacked bars	Steel ribs: Heavy	Steel ribs: Light, yielding	Segments: Steel	Segments: Concrete	Perforated tubes	Shield or jacked pipe	Special: Grouting	Special: Comp. air	Special: Freezing
								(1)									(2)	
Dry																		
Rocks R1 to R4	Charge H1		Permeability K1 K2 or K3			Dr	•	•	X	•	•					X		
			K4			X	•		X	•	•					•		
	Charge H2 or H3		K1 or K2			Dr	•	•	X	•						X		
			K3 or K4			X			X	•						•		
Soils R5 and R6	H1 H2 or H3		K1 or K2	X		Dr X	X			•	•	•	•			X		
			K3	X		X	X	X	X	Enf	Enf	Enf •	Bcl •		•	•	•	•
			K4	X		X	X	X	X	Enf Blf	Enf Blf	Enf Blf	Bcl • Blf	Blf	• Blf	•		•

Table 4

Nota 1 — Mortar grout, or special wet-curing resins
2 — Or bentonite (preferable with very high permeabilities)

Legend Dr = with drainage Enf= with forepoling Blf = with face lined Bcl = with shield

— Ground subject to dissolution or chemical alteration from the water or other fluids in contact with it ;

— Ground subject to swelling by taking up water or through stress changes ;

— Other types of ground.

4.3.2.

Ungrouted rocks bolts, and to a lesser degree, other types of bolt are unsuitable in grounds subject to solution action by water. Broadly speaking, all types of ground subject to weathering or alteration require the complete covering of the whole rock face with mesh, shotcrete, timber lagging or steel lining in exfoliating ground, and full lining in swelling ground.

In the latter case, shotcrete is only suitable if the cause of the swelling is dampness in the air, and not seepage. A covering of shotcrete will thus protect the rock and stop the swelling. The lining must cover the whole tunnel perimeter, including the invert. If swelling is caused by seepage however, shotcrete may be both unreliable (when applied to the wet rock) and inefficient (since there is a danger of it failing under what may well be high swelling pressures) ; with seepage-induced rock swelling, shotcrete is unfeasible.

Whatever the causes of the weathering or swelling, and whatever type of temporary support is used, it is usually important to install the permanent lining as early as possible ; the design analyses must include for the extra loads caused by swelling (rock pressure rise) or localised dissolution (loss of bearing area).

Swelling ground often gives rise to special problems and field trials are often needed before deciding on the most appropriate temporary and permanent support methods. Specialists are usually called in to specify the testing methods to be used and interpret results.

4.4. — Hydrology
(table 4)

4.4.1. — Hydrological criteria are basically water pressure and permeability. The following categories are used :

— Water load

H1	< 10 m	Low
H2	10 m - 100 m	Moderate
H3	> 100 m	High

— Mass permeability

K1	< 10^{-8} m/s	Very low to low
K2	10^{-8} to 10^{-6}	Low to moderate
K3	10^{-6} to 10^{-4}	Moderate to high
K4	> 10^{-4} m/s	High to very high

A distinction must be made between rock and soil because of their very different responses to water.

4.4.2. — Rock (Categories R1 to R4)

The most serious risk of inflow into the excavation usually comes from faults and karsts where water pressures or flow rates are high (localised high permeability). If such risks exist, it is strongly recommended to drill exploratory boreholes ahead of the face to locate the faults

Rock/ Soil cover		Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
					Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
																
Rocks R1 to R4	Cover < D	X			X	X	X	●	●				X		X	
	CN1	●					X						X			
	CN2	X					X						X			
	CN3	X		X	●Sf	●Sf	X	X	Sf	Sf	Sf	Sf	X			
Soils R5 and R6	Cover < 1,5 D	X		X	X	X	X	●	●	●	●	●	●	●		
	σ^o moderate	X			X											
	σ^o > 10 MPa	X		X	X	Sf	Sf	Sf	Sf	Sf	●	Sf	●Sf	●		

Table 5

Legend Sf = face support if necessary

or karsts. If they are small, the water may be drained off ; otherwise, they are usually grouted up.

The most appropriate type of support where heavy seepage cannot be avoided is the convential arrangement of ribs and lagging (or steel lining).

There may also be a more diffuse pattern of water in the rock, caused by low mass permeability and low to moderate pressure. In this case, most types of rock support are feasible, except that shotcrete must be combined with drain holes in the rock to prevent any build-up of pressure behind, and rock bolts should be held in place by mortar or expanding shell anchorages rather than resin, because resin curing is unreliable in contact with water.

4.4.3. — Soils (Categories R5, R6)

Soil permeability is a very important factor, since it usually governs seepage currents liable to lead to soil entrainment.

If soil permeability is consistently low, seepage rates and velocities will be low, and feasible support systems are ribs and lagging, or even shotcrete and drains, if other conditions are suitable, or lastly, shield and voussoirs. Grouting is costly and difficult because of the impermeability of the ground.

If soil permeability is moderate, or the soil is very heterogeneous (as in sedimentary formations in which pervious and impervious beds alternate), there is a danger of the hydraulic gradient producing concentrated seepage in the more pervious materials, with boils in the looser soil zones.

Under favourable conditions, ribs and lagging, accompanied by forepoling, are suitable. In many cases, the more pervious soil zones must be consolidated by grouting ahead of the face. Ground freezing, compressed air, bentonite mud and pressurized water techniques are also applicable, but must be kept for extreme situations or very large jobs, because of the cost and complications to the work.

Lastly, if permeability is unformly high (gravel alluvium), one must resort to pattern grouting ahead of the face, a bentonite or compressed air shield, or freezing. The final lining must be installed as quickly as possible. The working face usually has to be supported.

4.5. — Ground cover and natural stresses
(table 5)

This criterion relates to the ground itself, and its history, as regards the natural effective stresses within it, and to the geometry of the design as regards the position of the tunnel within the ground mass, especially its depth below surface.

4.5.1. — The limiting factor is the minimum cover necessary for arching to develop over the roof, whereby some stability is provided by the ground itself. This minimum cover value can be estimated at between one and two tunnels widths, depending on whether it is driven by blasting or tunnelling machine in rock, or in soil. At shallower depths, any support system based on confining pressure and reinforcement (rock bolts and shotcrete) might be dangerous because of the risk of brittle fracture ; a loadbearing type of support (ribs) is nearly always necessary. In soils, consolidation by grouting or freezing may also be necessary at shallow depths.

Tunnel size	Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
				Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
															
D < 2,50 m			×	×	×	×		●	●			●			
2,5 m < D < 10 m												(1)			
D > 10 m			Bo ●	●	●		×	Bo+Rev				× (1)			

Table 6

Nota 1 — Pipe jacking usually unsuitable for D greater than 4 m

Legend Bo = bolting always necessary

Rev = permanent lining follows close behind

Beyond this limit, rocks and soils are considered separately.

4.5.2. — Rock

The need for support in rock depends on the ratio between the material's uniaxial compressive strength σ_c and the geostatic major stress σ_o at the tunnel site. The categories are :

CN1 $\sigma_c / \sigma_o > 4$

CN2 $2 < \sigma_c / \sigma_o < 4$

CN3 $\sigma_c / \sigma_o < 2$

In the first case, no support is needed in theory, except perhaps some protective lining (nailed mesh). In the second case, support is usually required, the method being chosen with reference to the other criteria.

The third category indicates that the rock material is much too weak, regardless of jointing. The tunnel walls may be overloaded, usually leading to spalling as the original stresses are relaxed. Spalling may occur immediately on excavation, or after a few days or weeks. The appropriate remedy is usually bolting, which has the advantage over all other types of support of being capable of accommodating the large deformations which very often accompany rock stress relaxation, while still applying a near-constant confining pressure. Bolting is often combined with a protective mesh or even some non-continuous concreting if deformations are moderate.

Rigid support systems like ribs or shotcrete usually fail before there has been sufficient convergence for rock stresses to relax to a sufficient degree.

Instability and failure conditions may even reach the working face, in which case, heading and benching methods must be used to reduce the exposed surface area, or the face must be supported in the same way as the crown, with rock bolts and shotcrete.

4.5.3. — Soils

The tunnel depth effect is not so marked in soils as in rock, because the failure criteria are usually exceeded near the tunnel walls, even with low initial geostatic stresses, meaning that support is nearly always necessary, and that the most appropriate type will usually depend on other criteria. However, at very great depths (e.g. $\sigma_o > 10$ MPa) at which stability can only be obtained with very high confining pressures or very large deformations, there is a danger of uncontrollable soil creep. It may be necessary to consider systematic consolidation by fan grouting as driving proceeds, immediately followed by the permanent lining, which must be very stiff (prefabricated concrete segments). Care must also be taken to support the working face at all times, and provide extra support when work is interrupted over week-ends, etc.

4.6. — Cavity dimensions

(table 6)

4.6.1. — Cavity size is a direct factor in stand-up time (roughly inversely proportional to span) and the dimensions of the support system components (rock bolt diameter and length, steel rib modulus, voussoirs thickness, etc). But within certain limits, cavity size may also affect the choice of support, usually from technical considerations regarding actual working conditions on site, e.g. some type of support may be possible to install if the cavity is too small or too large.

Environment	Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
				Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
															
Sensitivity to settlement (nearby buildings)			Ci or Pm	Bp	Bp	Bp	Act		Enf	Bcl		Inj			

Table 7

Legend
Ci = with ribs (and bolts if necessary) for R4a, R4b, R4c rocks
Bp = with shotcrete
Act= active ribs (with jacks) (and if necessary expanding chocks)
Inj = gaps grouted immediately, or expanding rings
Bcl= shield
Enf= with forepoling
Pm= mechanical pre-splitting (for R2b to R5a ground)

For example, in small tunnels (less than 2.50 m wide), the lack of space makes it extremely difficult and even impossible to drill rock bolt holes or spray concrete. The most appropriate methods are either pipe jacking or steel lining in soil, or steel ribs in rock.

At the opposite end of the scale, the use of heavy, high-modulus steel ribs even, in very large tunnels more than 10 m wide, may be quite ineffective if convergence is large. The most appropriate system is rock bolting and/or shotcrete whenever possible. Otherwise, multi-stage heading and benching immediately followed by installation of the permanent lining is often inevitable.

4.6.2. — Cavity size is a factor in evaluating the influence of rock discontinuities because joints are only a problem if they are closely spaced as compared with tunnel size (less than half the tunnel width). For example, a joint set may be extremely deleterious to the stability of a large tunnel, but insignificant for a smaller tunnel.

4.6.3. — Lastly, cavity shape must sometimes be chosen to suit ground conditions and support requirements. For example, a circular or near-circular shape is best in swelling ground and in very high natural stress fields.

4.7. — Excavation procedure
(tables 2a, 2b)

4.7.1. — The tunnelling procedure may have a significant impact on support system selection in that it affects the residual properties of the ground around the perimeter of the opening, since full-face and other tunnelling machines will produce less disturbance in the material than explosives (with or without pre-splitting or smooth blasting).

4.7.2. — Without these special blasting techniques, the rock left in place around the tunnel perimeter is much more severely fractured, with all the attendant consequences already described in connection with the use of mechanically or resin-anchored rock bolts in jointed rock, and the need for mesh or continuous lining. It must also be remembered that shotcreting is much more difficult on an irregular surface. If steel ribs are used, wedging and packing them will require much more time and material if the wall is not smooth, and the end result will not be so reliable. To take account of these considerations, table 2a should be substituted for table 2 in classifying discontinuities if no particular precautions are taken as regards smooth blasting or pre-splitting.

4.7.3. — In machine-driven tunnels where no explosives are used, the rock left in place is hardly disturbed at all and its natural properties are retained, up to the exposed face. This is favourable factor for stability, usually requiring less support, and in some cases, a support system can be chosen that is less disruptive to work organisation and progress.

Table 2b should therefore be substituted for table 2 in connection with the jointing criterion, for machine-driven tunnels.

4.8. — Environment
(table 7)

Apart from the temporary effects to tunnelling operations (noise, ground tremors, etc), the long-term consequences of tunnel construction on the environment are movements at ground level, changes in the sub-surface

Example n° 1 12 m diameter tunnel in jointed shale, deep rock cover (σ_o/σ_o < 2) no groundwater			Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated	Shield or jacked pipe	Special		
						Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Criteria	**Categories**																
1 Mecha. behaviour	**R3a**				●	●	●			●							
2 Discontinuities	**N3**	**S4**			●	Gr ou Bp	● Gr ou Bp		● Bl ou Bp	● Bl ou Bp							
3 Weathering	Exfoliation				●	Gr ou Bp	Gr ou Bp	Gr ou Bp	Bl ou Bp	● Bl ou Bp	●	●					
4 Hydrology	Dry																
5 Cover	**CN3**					●	●										
6 Size	**D > 10**				Bo ●	●	●			Bo ou Rev							
Synthesis						● Gr ou Bp	● Gr ou Bp			Bo ● Bp ou Rev			Bif				

Table 8

Conclusion Grouted or ungrouted rock bolts with mesh or shotcrete or ditto bolts and yielding arches

hydrological pattern, and various types of nuisance arising from some ground consolidation method.

The importance of these environmental effects will depend to a great extent on the type of support selected. The choice must therefore consider environmental aspects and the degree of environmental sensitivity to the effects of construction. It is in fact usually a matter of adapting the selected support system to minimize environmental effects, rather than selecting a different system.

4.8.1.

With shallow tunnels in urban areas or near existing structures, settlement must be controlled and monitored. Other factors in addition to the support system must be considered.

If shotcrete is to be used, mechanical pre-splitting as used in moderately strong rock and cohesive soils (R2b to R5a) is one suitable technique. In other cases, lightweight steel ribs and, perhaps, rock bolts will be needed in addition to the shotcrete. Large tunnels must be driven by heading and benching, the shotcrete being sprayed immediately as each section is excavated (including the temporary arched invert), and it may also be necessary to apply shotcrete to the working face to control rock decompression at this location. Lastly, systematic, careful and frequent convergence monitoring is required.

Except where used only to control small fault openings rock bolts cannot be used alone where the minimum cover does not exist (section 4.5.1 above), since they accompany ground deformations without reducing them, and so they must usually be combined with a more rigid type of lining, like shotcrete.

Steel ribs may be suitable if they incorporate effective devices for controlling decompression, which will occur if they are not packed tightly to the surrounding ground. Jacks under the upringhts or at the crown actively apply pressure to the ground, hydraulic or mechanical props can be used in small tunnels, and expanding chocks (inflatable packers) can be set between the rib and the ground.

Prefabricated concrete or steel segments, usually installed inside a shield, can also control movement, even in poorly-cohesive ground, provided that the annular space behind the shield is filled with grout and the working face is supported if necessary by means of jacked panels, if excavation is manual, or by the tunnelling machine cutterhead (full-face tunnelling machines must be design to prevent "overbreak"). There are various types of expanding segment linings with hydraulic jacks, which can partially offset the effect of the annular space behind the lining, and reduce the amount of grouting needed.

Lastly, other less conventional sytstems such as forepoling by means of lengths of speel pipe in holes drilled forward of the face, around the tunnel perimeter (to form a continuous or discrete umbrella) may also be used effectively to control settlement when other methods are unsuitable.

As a general rule, support efficiency is improved and settlement reduced if explosives are not used, and the tunnel is driven accurately to leave a smooth wall.

Example n° 2 6 m diameter tunnel in gypsous clay under 10 m cover, 8 m below water table, in built-up area		Unsupported		Shotcrete	Rock bolts			Steel ribs		Segments		Perforated tubes	Shield or jacked pipe	Special		
					Ungrouted	Grouted	Jacked bars	Heavy	Light, yielding	Steel	Concrete			Grouting	Comp. air	Freezing
Criteria	**Categories**															
1 Mechan. behaviour	**R5a**	X		●	X			●	●	●						
3 Weathering	Dissolution	X		●	X	X	X	● Bl	● Bl	●	●					
4 Hydrology	**H1** **K2**	X		X Df	X			●	●	●	●		●	X		
5 Cover	σ^{o} moderate	X			X											
7 Environment	Sensitive			Ci	X	X	X	Act	X		Bcl		Inj			
Synthesis		X		X	X	X	X	● Act + Bl	X	● Enf	● Bcl		● Inj	X		

Table 9

Conclusion

— Either heavy active ribs and lining
— Or steel lining and forepoling
— Or prefabricated voussoir segments installed in shield

4.8.2.

Disturbance to the original hydrological pattern may be caused by a lowering of the water table for example, either purposely through well points sunk from the surface or drainage holes ahead of the face to allow excavation to proceed in the dry, or through the tunnel itself acting as a drain.

A lowered water table may reduce pore pressures and increase settlement in compressible ground, and cause even remote springs to dry up as seepage flow is diverted away. If such risks exist, with potentially deleterious consequences, some sort of ground consolidation (grouting, compressed air or freezing) must be substituted for groundwater lowering.

4.8.3.

Some consolidation techniques may also be harmful in environmentally sensitive areas. If chemical grouting is being considered, it must be ascertained that there is no danger of contaminating underground water supplied. It may be necessary to limit grout flow and pressure to prevent its emergence at ground level and surface heave in populated areas.

Compressed air may be very harmfull if it is liable to escape at ground level or oxydise coal measures, etc., and such effects are not easily prevented or controlled.

In doubtful cases, a specific study must be untertaken to assess the importance of the consequences of the method being considered.

Lastly, ground freezing must be used with circumspection in urban areas, because the soil swells and may rupture buried service pipe-work and other disorders.

5. — SYNTHESIS AND CONCLUSION

Tables 8 and 9 are two examples illustrating the use of the support selection system described. The first is a large, deep, dry tunnel in jointed silica shale susceptible to exfoliation. The second example concerns a moderate size of tunnel below the water table in moderately consolidated, low-permeability clay with some gypsous inclusions, and a settlement-sensitive environment.

The tables are filled in with the relevant code symbols for the eight criteria examined. The columns are added up in the following way :

— If a column has one or more Poor or Very Poor evaluations, the bottom-line synthesis is Unsuitable or Unfeasible, regardless of the assessments, in the rest of the column.

— The most unfavourable subscript notes in the boxes are also added to the bottom line.

— The final choice among the good evaluations is made on the basis of the number and relative importance of favourable criteria, with reference to cost and general site organisation factors.

The second example shows that there may still be a wide choice after considering all the engineering criteria, so that the decise factor will be one of cost, which itself will depend chiefly on the size of the job, construction schedule and plant availability.