ITAtech Guideline for use of Rock Classification Systems for Ground Support on TBM Tunnels

ITAtech Activity Group Excavation

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1 >> Background

Rock support is arguably one of the most important aspects of any tunneling operation. Historically, the decision about which rock support to use was made by tunnellers on a case-by-case basis. Over the last 50 years, however, various rock classification systems have been developed to assist in selecting rock support type and quantity based on empirical data. When these systems are applied to rock support in mechanized tunneling it becomes a problem that the empirical data is obtained almost exclusively from the drill and blast tunneling method. This approach has two major shortcomings when applied to the requirements of bored tunnels:

- The rock support methodology is not optimized for efficient TBM operation, which involves installing rock support while boring.
- The rock support schemes needed for a relatively smooth cylindrical TBM tunnel require less rock support as there is no blasting damage to the rock mass.

This guidelinesuggests a modified rock support selection methodology adapted to bored tunnels using both the Q (Barton, Lien, & Lunde, 1974) and/or RMR (Bieniawski, 1989) rock classification systems. The methodology is based on published literature from the developers of the rock classification systems. This suggested methodology is suitable for use in design, cost estimating, and other rock support considerations.

The proposed rock support schemes are limited to work within the L1 and L2 areas and are not intended to be a guide to the requirements for the final lining. The final lining is likely to be determined before excavating the tunnel; however, the design of the final lining obviously must take into full consideration the final use of the tunnel.

The support areas on the TBM are defined as follows (see Figure 1 below):

- The area right behind the cutterhead is defined as L1
- The rest of the TBM, less L1, is defined as L2
- The back-up system and all of the tunnel behind the back-up system is defined as L3.

This guideline primarily addresses excavation with an open-type TBM using conventional support measures such as rock bolts, wire mesh, ring beams and shotcrete, and briefly discusses the use of tunnel lining and the use of shielded machine types in more challenging geological formations.

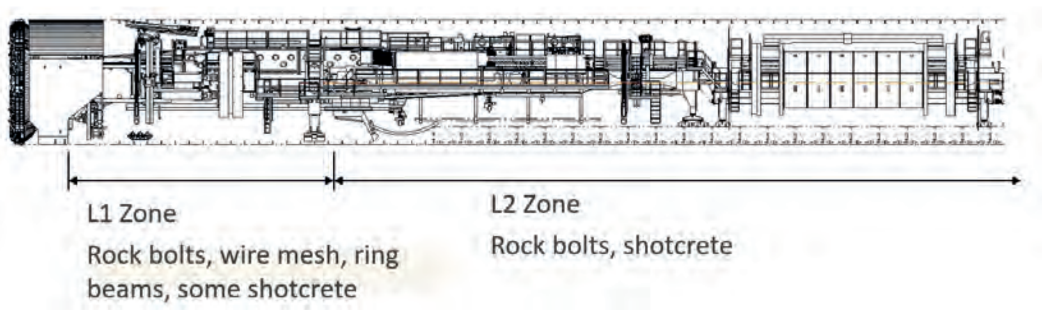

Figure 1: Diagram of TBM showing L1 and L2 areas.

The methodology of developing the rock support diagrams given in this guideline is based on adaptions of the Q-system and RMR system. The adaptions are based on published literature and aligned with the authors' experience.

In addition to the modified rock support scheme presented in this guideline, special considerations are presented for projects where there is risk of rock-stress-related problems such as squeezing and rock bursting, as well as challenges related to high pressure water ingress.

TUNNEL TYPE	ESR VALUE
All support of temporary nature	2-5
Pilot tunnels	1.6-2.0
Water/sewage tunnels	1.6-2.0
Traffic tunnels	0.5 to 0.8[2)]

Table 1 Suggested ESR values for TBM support/liner selection (Barton & Grimstad, Tunnel and cavern support selection in Norway, based on rock mass classification with the Q-system, 2014)).

[1)] ESR varies between 2 and 5 based on the needed stand-up time and requirement of the project. In this report a relatively high ESR is used to compensate for the long stand-up time experienced for TBM tunnels.
[2)] ESR may be reduced to 0.5 for long, high speed rail or long motorway tunnels. This of course is very conservative.

Note: *Q-value correction (x 2 to 5) is needed in the "central threshold" areas for the relevant tunnel diameters. Use 2Q for large diameter tunnels and 5Q for small diameter tunnels to account for the greater stability of TBM tunnels in this region of the Q-system support chart.*

THE Q-METHOD – EXCAVATION SUPPORT RATIO (ESR) AND THE 'CENTRAL THRESHOLD'

This rock support recommendation presented in this guideline is based on adaptions of the Q and RMR classification systems to mechanically driven tunnels.

The suggested rock support methodology and support types are based on stability and safety requirements for different scenarios with the Q-method as a basis. For this guideline the scenarios are:

1. Temporary support in all types of tunnels.
2. Possible final support for tunnels with moderate long term lining requirements such as water tunnels for hydropower, some water supply tunnels, exploration[1)] tunnels, access tunnels, etc.

To address these different scenarios the Excavation Support Ratio (ESR) used in the Q-method is utilized. The ESR values used in the rock support diagrams in this report generally have a correlation with Barton's suggested ESR values for TBM tunnels, which is given in Table 1.

In general, the literature and the experience of the authors from unlined TBM tunnels indicate a significant reduction in installed rock support compared to drill-and-blast.

Through detailed mapping and analyses it was identified by Grimstad and Barton (Barton N. , TBM tunnelling in jointed and faulted rock, 2000) that this reduction in required rock support is especially relevant in the region referred to by Grimstad and Barton as 'the central threshold'. In the Q support diagram developed/updated by Grimstad this is mostly in the section referred to as rock support class 3 (see Figure 2).
The identification of the central threshold is based on deviations in mapped Q-values in TBM and D&B tunnels in this class, when the Q-values identified in the preinvestigations are the same. This means that if the rock support is based on Q values identified in the preinvestigations, the Q value in this central threshold should be increased by a factor of 2 for large diameters (D>5m) and multiplied by 5 for small diameters (D<5m) in the Q-chart.

The Q-values above and below the central threshold are, according to Barton, indicating similar mapping after excavation based on the same original Q-Value. This suggests that the areas with higher Q values generally have very low levels of rock support needed, while the ones with lower Q-values generally have the same need for heavy rock support for both methods.

This identification is well aligned with the experience from numerous tunneling projects worldwide and shows that the system is a valid approach, based on the empirical data available.

In the specific 'central threshold' part of the Q-diagram, Barton suggests multiplying the Q value by a factor of 2 for large diameter (Diameter >5m) TBM tunnels and a factor of 5 for small diameters (Diameter <5m). For the rock support diagrams presented later in this guideline, the Q values in the 'central threshold' area are already adjusted as suggested by Barton, to make the diagrams easier to use.

Correlation between the Q and RMR system

To be able to present a support methodology for both the Q and RMR systems in the same rock support diagrams, a correlation factor needs to be identified.

The Q and RMR systems are fairly strongly correlated in central rock qualities. Correlation factors between these two systems that are commonly used are given by ((Bieniawski, 1989) and (Barton N. , 1995)

(Bieniawski, 1989)

$$RMR = 9 \ln Q + 44$$

(Barton N. , The influence of joint properties in modelling jointed rock masses, 1995)

$$RMR = 15 \log Q + 50$$

The two correlations are given in Figure 3.

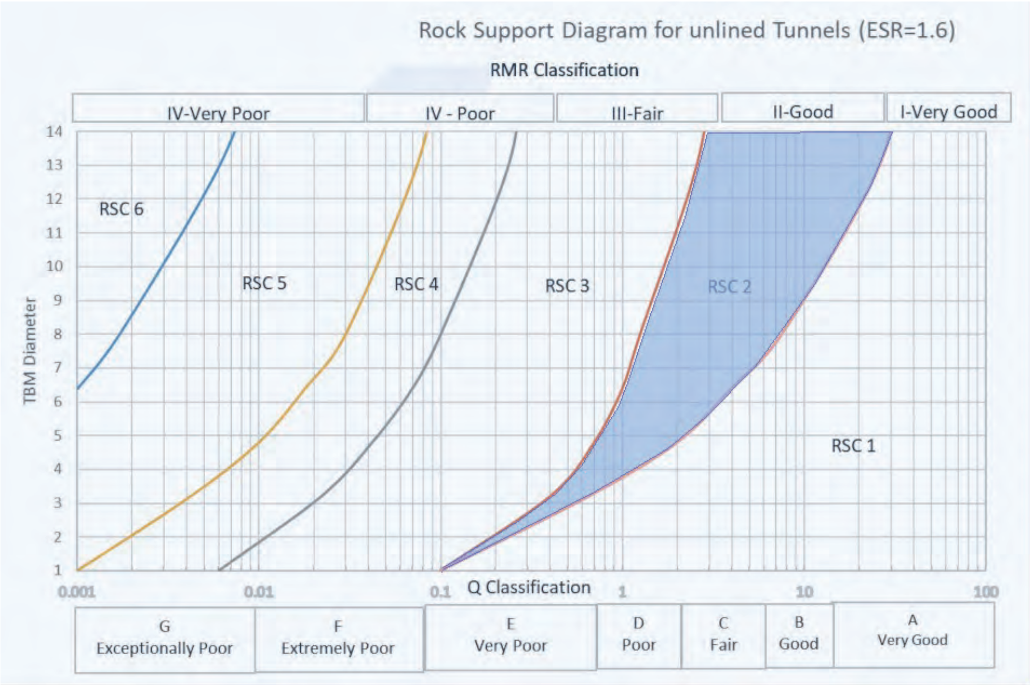

Figure 2: Rock Support Diagram for Unlined Tunnels, with the central threshold highlighted in blue.

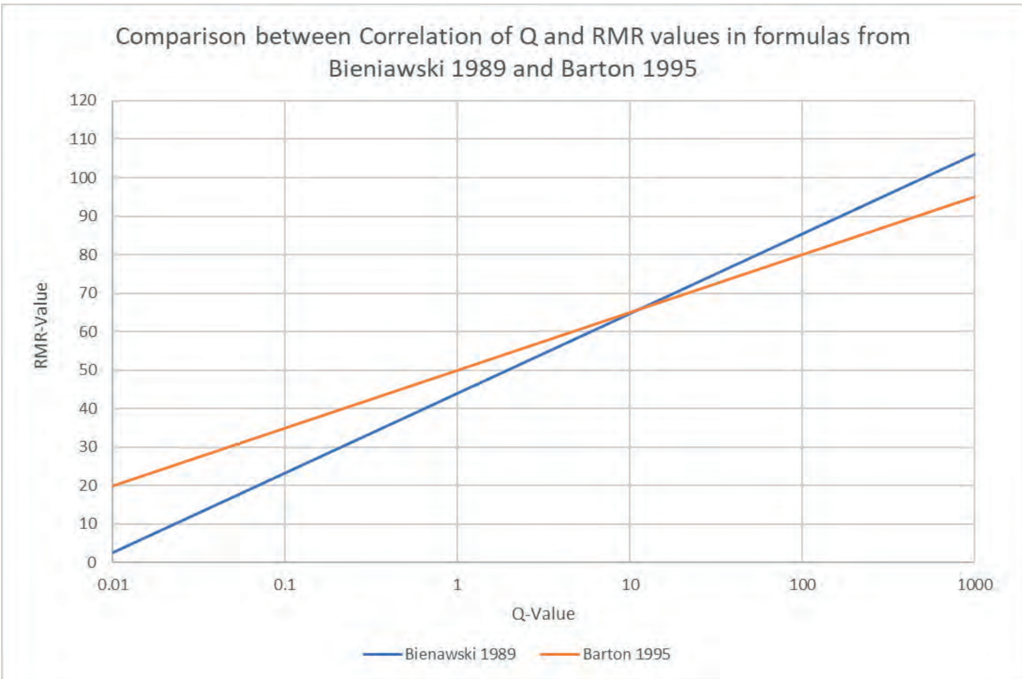

Figure 3: The red line, based on Barton (1995), is used for the remainder of this guideline. Note that it avoids a zero or even negative value of RMR prediction when Q value is exceptionally low Q < 0.01.

3 >> Rock Support Diagrams

There are two different rock support diagrams presented in this guideline.

1. The first diagram is for temporary rock support
2. The second is for tunnels with a moderate long term use requirement, where no secondary lining is installed.

For temporary support it is suggested to use relatively high excavation support ratios due to the high standup time of a mechanized excavated tunnel. The general recommendation for ESR of temporary support is between ESR = 2.5 and ESR=5 by Barton. For unlined tunnels an ESR= 1.6 is used.

The classifications of the rock mass classifications given in the rock support diagrams are given in tables 2 and 3.

The diagrams given on the next two pages (Figures 4 and 5) are a direct adaption of the Q-diagrams and the suggested adjustments given in table 1. (Barton & Grimstad, 2014).

In contrast to the original Q-diagram, the TBM diagrams do not have a logarithmic Y-axis and the diagrams are made with a set excavation support ratio per diagram. This change was made so that the curves can be read directly based on the TBM diameter.

The diagrams below show the support classes for the following situations:

1. Temporary rock support for tunnels where additional support can be installed behind the TBM and backup (ESR =4)
2. Final or long-term rock support for tunnels where non secondary lining is foreseen (ESR=1.6)

RMR CLASS	RMR	ROCK QUALITY
I	80-100	Very good
II	60-80	Good
III	40-60	Fair
IV	20-40	Poor
V	0-20	Very poor

Table 2 Rock classification systems for RMR

Q-CLASS	Q-VALUE	ROCK QUALITY
A	Q > 40	Very good
B	10 < Q < 40	Good
C	4 < Q < 40	Fair
D	1 < Q < 4	Poor
E	0.1 < Q < 1	Very poor
F	0.01 < Q < 0.1	Extremely poor
G	Q < 0.01	Exceptionnaly poor

Table 3 Rock classification systems for the Q method

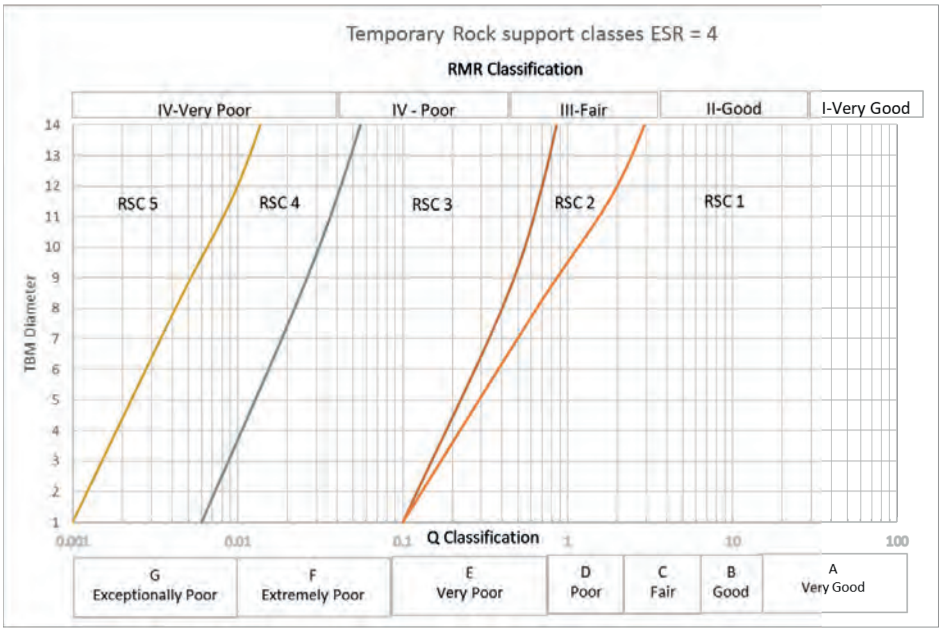

Figure 4: Rock Support Diagram for temporary support (ESR = 4).

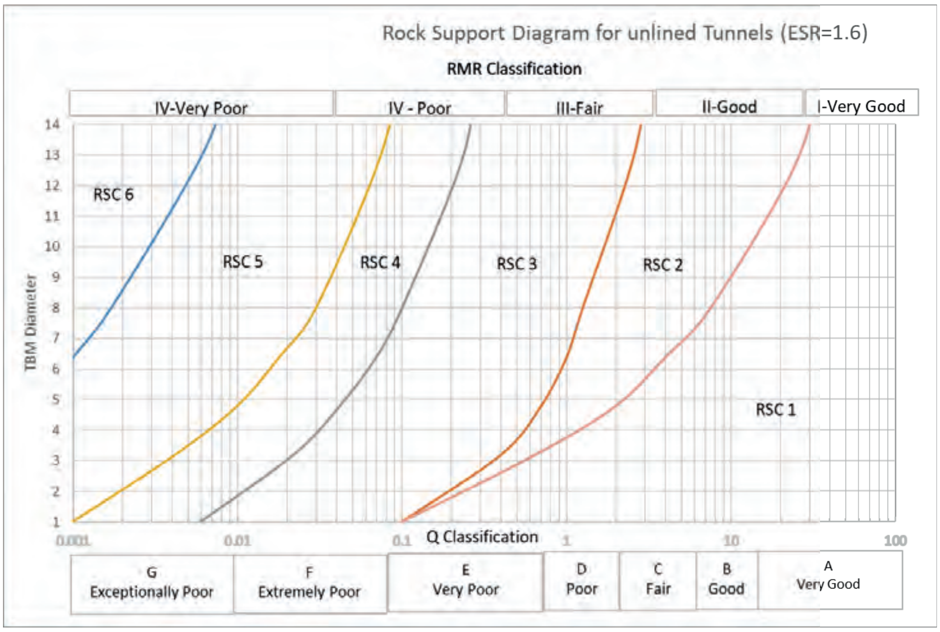

Figure 5: Rock Support Diagram for unlined tunnels over an extended period of time (ESR=1.6).

ROCK SUPPORT CLASSES (RSC)

Rock Support Class 1

Rock Support Class 1 is in a very competent rock mass that requires no or very limited rock support. If needed, rock support measures are spot bolting if there is any local occurrence of fractures that intersect with the tunnel.

Rock Support Class 2

Rock Support Class 2 applies where the rock masses are competent. The rock mass in Rock Support Class 2 has some fissures, joints and fractures that gives a need for local rock support on a limited amount of the tunnel circumference. The rock support consists of some spot bolting, McNally slats and/or wire mesh or similar when needed locally.

Rock Support Class 3

Rock Support Class 3 applies in a fairly competent rock mass where there is a need for systematic rock support. The rock support used is systematic bolting with varying patterns, McNally slats, wire mesh and/or reinforced shotcrete when needed.

Rock Support Class 4

Rock Support Class 4 applies in a less competent rock mass with a need for continuous rock support.

The rock support methodology typically consists of systematic bolting, McNally slats, wire mesh and/or shotcrete with fiber or ring beams.

Rock Support Class 5

Rock Support Class 5 applies in weaker rock masses where there is a continuous need for heavy rock support. In such conditions the support methodology should be carefully evaluated and determined on a case-to-case basis.

Typical rock support is systematic bolting, McNally slats with or without heavy steel ribs, ring beams, wire mesh and fiber reinforced shotcrete.

If longer stretches of Rock Support Class 5 are expected, special capabilities on the TBM should be considered:

A) The TBM should have the capability to operate in closed mode, which usually means installing precast concrete segmental lining concurrent to advance. Considerations for a fully equipped Crossover-type TBM should be evaluated.

B) The TBM should have sufficient torque to rotate the cutterhead with a full load of loose material against the excavation face.

C) Alternatively, special features should be implemented to efficiently pretreat the ground prior to excavation.

Rock Support Class 6

Rock Support Class 6 applies in severe conditions where special considerations and evaluations need to be made with regard to rock support on a case-to-case basis. Typically, these conditions are running and collapsing ground, high water ingress, etc. Typical support measures include installation of precast concrete segments or other continuous lining like steel lining. In some conditions, pre-treatment of the ground such as grouting, forepoling, etc., should be considered even though precast concrete segments are being installed.

If longer stretches of Class 6 are expected, special capabilities on the TBM are strongly recommended such as:

1. The TBM should be fully shielded with the capability to operate in closed mode. Considerations for a fully equipped Crossover-type TBM should be evaluated to facilitate advancing while holding water pressure.
2. The TBM should have sufficient torque to rotate the cutterhead with full pressure of material against the excavation face.

Alternatively, special customization of the TBM should be implemented to efficiently detect and pre-treat the ground prior to excavation, through probe drilling and pre-excavation grouting.

It is strongly recommended that special features for control of difficult ground be built into the TBM design.

EXAMPLE OF ROCK SUPPORT QUANTITIES

The recommended rock support quantities must be considered and decided for each specific project, subject to each project's needs. However, it is considered valuable to provide an example of rock support schemes to better understand how to use the guideline.

The chosen example is modified from the Austrian TBM rock support scheme (Scolari, 1995) and (Barton N. , 2000)) for a 6 m diameter TBM, and is given below in Tables 4 and 5. The permanent rock support scheme for unlined tunnels is used (ESR=1.6).

	APPROX. Q VALUES	APPROX. RMR VALUES
RSC 1	> 4	> 59
RSC 2	1-4	50-59
RSC 3	0.06-1	30-50
RSC 4	0.01-0.06	17-30
RSC 5	0.001-0.01	5-17
RSC 6	< 0.001	< 5

Table 4: Example Q and RMR values for 6 m TBM.

The following rock support quantities are suggested in the different rock support classes by Barton and Scolari:

	TYPE OF SUPPORT	QUANTITY PER LINEAR METER
RSC 1	Local support, rock bolts (L=2 m) support, rock bolts (L=2 m)	Up to 1 bolt/m
RSC 2	Local Support including rock bolts (L=2 m), wire mesh and shotc rete	1 – 3 bolts/m 1-1.5 m² mesh /m 0.1-0.5m³ shotcrete/m
RSC 3	Rock bolts (L=2.5 m) wire mesh Shotcrete Ring beams/Ribs	3-7 bolts/m 5-15 m² Mesh /m 0.5-1.5m³ Shotcrete/m 40-150 kg Steel
RSC 4	Rock Bolts (L = 3) Wire mesh Shotcrete Ring beams/Ribs	6-10 bolts/m 15-27 m² Mesh /m 1.5-3.0m³ Shotcrete/m 120-300 kg Steel
RSC 5	Rock Bolts Wire mesh Shotcrete Ring beams/Ribs Cast in-situ concrete through the RSC5 sections	Quantities are highly dependent on the conditions encountered and need to be evaluated case by case
RSC 6	Special measures according to conditions. Can include forepo-ling, pre-grouting, jet grouting, cast concrete, etc.	Quantities are highly dependent on the conditions encountered and need to be evaluated case by case

Table 5: Example rock support quantities for 6 m TBM.

There are some geological challenges that cannot be properly addressed through the rock classes given in this guideline.

ROCK STRESSES

Some of the most critical geological challenges in a tunnel excavation include rock bursting, squeezing and other rock-stress-related phenomena. In this regard there are some situations that need to be treated with great attention. These are identified as:

A. Weakness zones, which can have an influence on the (local) rock stress situation in the rock mass.

B. Several weakness zones with clay or chemically altered rock mass of very low quality in the tunnel alignment.

C. Potential of high rock stresses in competent rock that could cause spalling or rock bursting. This is especially important if: [2, 3, 4]

$$\sigma_c / \sigma_1 < 5$$

$$\sigma_\theta / \sigma_c > 0{,}5$$

D. Potential for squeezing. This is especially critical if:

$$\sigma_\theta / \sigma_c > 5$$

E. Chemical swelling potential.

If there is a potential for stress-related problems as noted above, measures for handling the rock stress challenges should be carefully considered during TBM design and when deciding on rock support measures installed on the TBM.

When challenges related to rock stress are expected the following measures are recommended by ITA Working Group 17 (ITA-AITES-WG17, 2017) and this guideline supports these recommendations (see Table 6a-6b).

[2] σ_c - Is the Unaxial compressive strength of an intact rock.

[3] σ_1 - Major principal stress in the rock mass (highest).

[4] σ_θ - Tangential stress around an opening in the rock.

PHENOMENA HAZARDS	LEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
				(grey)	**Not concerned**
				✓	Easy to implement on site, to be previously considered in the design
				⚠	Medium difficulty of implementation
				◆!	Very difficult to implement, (could have an impact on the requirements)
Brittle behaviour: Rockburst, spalling					
1- Spalling	(grey)	(grey)	✓		1.1) Selection of the appropriate type of the telescope in order to limit the material accumulation, and so prevent its blockage
	(grey)	(grey)	⚠		1.2) Operation of the double shield TBM as a single shield TBM. (The prediction of spalling is difficult, so these changes of mode will probably require cleaning of the telescopic section before)
		⚠	⚠		1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tailskin or segments)
	✓	(grey)	(grey)		1.4) Installation of radial bolting (friction anchors) in combination with wire mesh and eventually ribs
	✓	✓	✓		1.5) Appropriate torque reserve high torque low speed gear)
2- Rock-burst	✓	✓	✓		2.1) Execution of subhorizontal destructive drilling eventually combined with blasting around the perimeter of the TBM (in order to release the in-situ stresses)
	✓	⚠	(grey)		2.2) Drilling of large diameter holes (approximately 100 mm), as close as possible to the cutterhead (in order to release the in-situ stresses)
	✓	✓	✓		2.3) Avoid front loading cutterhead; change cutter tools from inside (back-loading cutterhead)
	◆!	◆!	◆!		2.4) Avoid face inspections and work in front of the cutterhead in risk zone.
	✓	✓	✓		2.5) Install face inspection cameras and wear cutters tools
	✓	(grey)	(grey)		2.6) Depending on the level and the location of risk, the presence of workers in the machine zone (0- 2 diameters) should be analysed (statistics, geological, stress monitoring) Over high risk stretches, avoid the presence of workers **close to exposed rock surfaces** during the first hours lapsing after excavation

Table 6a: TBM Tunnelling Related Hazards & Mitigations Measures.

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
				■	**Not concerned**
				✓	Easy to implement on site, to be previously considered in the design
				⚠	Medium difficulty of implementation
				◆!	Very difficult to implement, (could have an impact on the requirements)
Brittle behaviour: Rockburst, spalling					
2- Rock-burst	✓	■	■		2.7) Passive protection[7] : • Finger shield, that allows bolting in between • Mesh and bolts with or without ribs; in all cases, these added protection should be done under the protection of a finger shield • Create safe and protected walkways
	✓	■	■		2.8) Installation of radial bolting (friction anchors or other energy adsorbing bolts, e.g. D-bolts) combined with wire mesh and ribs, and shotcrete in the machine zone
	■	■	✓		*1.1) Selection of the appropriate type of the telescope in order to limit the material accumulation, and so prevent its blockage*
	■	■	⚠		*1.2) Operation of the double shield TBM as a single shield TBM. (The prediction of spalling is difficult, so these changes of mode will probably require cleaning of the telescopic section before)*
	■	⚠	⚠		*1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tailskin or segments)*
	✓	✓	✓		1.4) Appropriate torque reserve (high torque low speed gear)
Highly deformable behaviour					
3- Squeezing and buckling	✓	✓	✓		3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey
	✓	✓	✓		3.2) Non-stop operations (requiring modification of the shift system)
	✓	⚠	⚠		3.3) Increase the radial over-cutting (and consequently the annular gap around the shield) The difficulty to implement the measure increases with the increase of the amount of overcutting (easier up to 5 cm on radius, more difficult requiring stop of the machine for more than 10 cm on the radius)
	■	✓	✓		3.4) Appropriate **shield geometry** (conical shape, reduction of the shield length) The choice of this geometry is a compromise of different constraints and a key point of the design The use of Double shield TBM is not recommended for small tunnel diameter for which the ratio between diameter and shield length is unfavourable in respect to jamming
	✓	✓	✓		3.5) Lubrication of the shield extrados
	✓	✓	✓		3.6) Installation of a high thrust force – with sufficiently high factor of safety (overdesign). The high (axial) thrust force has to be considered in the design of the lining
	✓	✓	✓		*1.4) Appropriate torque reserve (high torque low speed gear)*
	■	⚠	⚠		3.7) Increase of steel ratio in the pre-cast concrete, use high strength concrete, identify different type of rings
	■	⚠	⚠		3.8) Double lining concept (cf. [4]); this concept allows a reduction of the load acting on the final lining
	⚠	■	■		3.9) Installation of a yielding support (e.g. sliding ribs, openings in the shotcrete, closed or not closed with compressive elements)
	■	⚠	⚠		*1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tail skin or segments)*
	■	◆!	◆!		3.10) Deformable annular filling in extreme squeezing conditions (the low stiffness of the embedment has to be considered in the design of the lining)

Table 6b: TBM Tunnelling Related Hazards & Mitigations Measures (cont'd).

[7] *See also the MacNally patented system [16].*

WATER INFLOW

Water inflow can cause severe conditions in any underground excavation. The factors that are especially challenging are:

1. Extremely high-volume water inflow
2. High pressure water ingress
3. Combination of the above

Water handling itself can in some cases be very challenging to control; however, it is often the case that water is combined with other geological challenges, such as weakness zones, swelling clays, etc., the combination of which can cause highly adverse geological challenges.

Experience from tunneling and other underground works has proven that water is most efficiently handled if the water ingress is treated prior to excavation (pre-grouting), rather than after excavation (post-grouting). To efficiently pre-treat the ground, detection of the water is important. Currently the most efficient way of detecting water is through probe drilling. If water ingress is expected or possible, the TBM should be set up with a good capability to efficiently probe drill and pre-grout. This includes:

- Probing equipment that is suitable for efficient boring.
- Several drilling positions equally distributed over the tunnel circumference.
- Minimization of the angle between the tunnel direction and drilling direction (should not exceed 12 degrees) and allowance for variety in angles of the holes.
- Reduction in drilling deviations as much as possible, with Down The Hole (DTH) hammers or guiding rods while drilling. This will also allow longer holes to be drilled.
- Measurement While Drilling system (MWD).
- Grouting systems with sufficient capacity.
- All drilling and grouting equipment mounted on the TBM when possible and grouting material readily available.

If there is a potential for sudden water inrush into the tunnel, the TBM should be designed with the possibility to seal against water in a static or dynamic situation. Once the TBM has been sealed, the crew can then grout though blowout preventers until an acceptable leakage rate is achieved.

It is also important to mention that if the lining is designed for the theoretical water pressure on the project, the only area that the tunnel is vulnerable to water ingress is the area between the cutterhead and the continuous lining installation, which typically is between 5 to 15 m. If the TBM is designed with the ability to seal against water ingress and drill and grout through blow-out preventers, this risk of future water leakage into the tunnel is reduced to an absolute minimum. It should not be necessary to have a totally sealed tunnel from pre-grouting only if the lining being installed behind the TBM is sealed concrete segments for example, with proper segment annulus grouting which lining system is designed to hold the full water pressure.

In addition, there are some aspects of the TBM excavation that are advantageous for bored tunnels and directly related to the lining to control water:

- Modern TBMs, when used with segmental lining, essentially form a plug when running ground is encountered that provides time to safely consolidate the ground.
- With modern Crossover-type TBMs it is practical to segmentally line a section of the tunnel and hold water pressure while in other sections excavate with efficient open mode operation.
- With a properly equipped open-type TBM it is possible and practical to place final shotcrete lining while boring at high rates of advance.
- Today's TBMs are specifically designed to excavate through extreme and difficult ground conditions utilizing segmented lining, and are a safer and faster means of excavation than non-TBM methods.

Working Group 17 of the ITA guidelines support the following measures as outlined in Table 7. (ITA-AITES-WG17, 2017).

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
				—	**Not concerned**
				✓	Easy to implement on site, to be previously considered in the design
				⚠	Medium difficulty of implementation
				❗	Very difficult to implement, (could have an impact on the requirements)
Presence of water					
4.1- Extremely high water inflow	✓	✓	✓		*3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey*
	⚠	⚠	⚠		4.1.1) Reduction of the permeability by grouting ahead of the machine It is suitable to grout before the water flows into the tunnel Maybe unsuccessful due to the layout imposed by the TBM equipment or by the quantity of water inflow.
	—	⚠	—		4.1.2) Closed mode operation in the case of using a Single Shield Multimode TBM, and low water table (up to 15 bar)
	✓	✓	✓		4.1.3) Installation of a muck chute closure gate
	⚠	❗	❗		4.1.4) Try to separate the water inflow from the mucking material, in order to manage mucking-out difficulties. Drainage solution could be implemented to collect the water
	❗	❗	❗		4.1.5) Reduction of the permeability by freezing (in advance)
4.2- High water pressure	⚠	❗	❗		*3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey. It is mandatory to do it with preventer in case of high water pressure*
	⚠	❗	❗		4.2.1) Long advance drainage, at least 2 diameter long, in the periphery and /or front the face of the machine to release the pressure
	⚠	❗	❗		4.2.2) Improve the ground characteristic by grouting ahead of / and around the machine
	—	⚠	—		*4.1.2 Closed mode operation in the case of a mix-shield TBM and low water table (up to 15 bar)*
	❗	❗	❗		*4.1.4. Reduction of the permeability by freezing (in advance)*
		❗	❗		4.2.3) Improve the ground characteristic by grouting around the segmental lining
	⚠ (grey)	❗	❗		4.2.4) Drainage boreholes around the lining
		⚠	⚠		4.2.5) Double lining concept

Table 7: Working Group 17 recommendations for water inflows.

CONCLUSIVE REMARKS

In conclusion, this guideline presents a model that uses empirical data and conclusions found in the literature to better suggest the rock support methodology and quantities when excavating with a TBM. This guideline is more accurate when used with TBMs compared to the commonly used rock classification systems designed for D&B tunneling.

The model highlights that mechanically excavated tunnels can reduce the requirements for temporary rock support in given rock mass classes. This is especially important in the classes where the quantity of rock support is limited, and all rock support installation can be done simultaneously with the boring process. Many improvements have been made by the TBM manufacturers and by the industry in general regarding the ability to apply temporary rock support and to make good advance rates, even in very complex and difficult rock mass conditions.

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