TBM Excavation of Long and Deep Tunnels Under Difficult Rock Conditions

ITA Working Group n°17
Long Tunnels at Great Depth

N° ISBN: 978-2-9701122-2-8

ITA REPORT N°19 / MAY 2017

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
AITES
ITA
INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

ITA Report n°19 - **TBM Excavation of Long and Deep Tunnels Under Difficult Rock Conditions**
- N°ISBN: 978-2-9701122-2-8 / MAY 2017
Layout : Longrine – Avignon – France – www.longrine.fr

TBM Excavation of Long and Deep Tunnels Under Difficult Rock Conditions

ITA Working Group n°17
Long Tunnels at Great Depth

>> SUMMARY

>> SUMMARY

MAIN CONTRIBUTORS

Gerard Seingre (Animator), Magali SCHIVRE (Vice-Animator),

Jens Classen, Brad Grothen, Benjamin Lecomte, Andrea Pigorini, Roberto Schuerch.

MEMBERS OF WG17

Altay Ertin, Kim Hong Moon, Myung Sagong, Einar Broch, Minoru Shimokawachi, Isamu Otsuka, Nicola Posse, Anne Kathrine Kalager, Daniel Mortfelt, Bahram Safari, Jakob Likar, Tulin Solak, Ahmet Sirin, Alper Ozdogan, Rafael Garcia Mange, Andy Thompson, Stuart Warren, David Jurich

TUTOR

Jinxiu (Jenny) Yan

PEER REVIEWERS

Lok Home, Jinxiu (Jenny) Yan, Heinz Ehrbar

1 >> Introduction

Nowadays, tunnels often represent the best solution for infrastructure crossing mountainous regions. In the last decades – for example – the need for a more efficient freight transport with reduced environmental impact and the increasing road traffic has led to strong political and economic efforts in the development of new railway networks through the Alps in Europe (e.g. the Lötschberg and Gotthard Base tunnels in Switzerland, the Koralm Base Tunnel in Austria, the Lyon-Torino between France and Italy and finally the Brenner Base tunnel between Austria and Italy) or cross-border projects in Latin America like the Central Bioceanic Corridor. Moreover, like in the Andes and the Himalayas, long tunnels are driven to realize hydropower and irrigation projects (Jinping in China, Olmos in Peru, or Neelum-Jhelum in Pakistan)

The peculiarities of tunnels through mountain ranges are the **high overburden** and the **great length**. For economic reasons, the great length of the tunnels requires the industrialization of the construction method, thus the use of TBMs wherever possible.

The TBM excavation of long and deep tunnels becomes particularly demanding when tunnel portions of very high overburden, bad rock quality or, in the worst case, the combination of both are encountered. Under such circumstances extreme phenomena (like squeezing) may strongly affect the TBM advance. Furthermore, the geological uncertainty (the depth and the length of the tunnel make an exhaustive exploration technically and economically extremely questionable), the low grade of adaptability of TBM excavation (compared to conventional methods), and the almost impossibility of intervention from the surface in case of problems make the TBM excavation of long and deep tunnels a real challenge for engineers and contractors.

To this respect it is worth noting the words of Prof. Bienawski at the ITA Congress WTC 2014, in Brazil, for the MEMORIAL-CLOSING-LECTURE [13] :
"For tunnel boring machines (TBMs), the use of which will be more extensive, the challenges will be to bore tunnels under high rock pressures and high water pressures, both in hard rock and in soft ground conditions; these challenges are simply extraordinary."

The key aspect for a successful TBM excavation (i.e., the minimization of the construction risks) is the preliminary identification of all possible hazard scenarios and the consequent selection and design of an appropriate TBM.

The aim of the present report is to:

- Introduce a **common technical language** and a simplified classification on the main geotechnical hazards that may be encountered during the excavation of long and deep tunnels crossing difficult rock conditions;
- Analyse the **influence and the consequences of these phenomenon regarding the various TBM types**;
- Provide **recommendations for the design, for the selection of the TBM type and for the mitigation measures to be implemented on-site**.

The Appendix of the report is a **worldwide date base collected by the members of the ITA Working Group 17 on the TBM tunnelling experience in difficult rock conditions** gained over the last 20 years.

The present report **focuses on hazard scenarios that are associated – or their magnitude is by far increased – by the high overburden.** However, as for more shallow tunnels, other hazard scenarios may be encountered during the tunnel construction of long and deep tunnels (e.g. rock falls, swelling, packing of fines around the shield, karstic phenomena, gripper bracing problems, environmental aspects as gas, radioactivity or asbestos etc…), and so have to be additionally considered in the design phase of a project.
In the same idea, the following non-geological related hazards are not handled in this report: fatigue of the workforce due to long travel distances, logistic difficulties in long tunnels, excessive wear and replacement needs for equipment and materials due to long construction times, maintenance needs for the already constructed parts of the project, and personnel fluctuation.

2 >> Definition of the hazard scenarios

According to the working group members, the main hazard scenarios and phenomena that may be encountered– or their magnitude is by far increased – by the high overburden are the following:

§2.1 Brittle behaviour :

- Rockburst , Spalling, §2.1.1

§ 2.2 Highly deformable rock mass :

- Buckling, §2.2.1
- Squeezing §2.2.2

§2.3 Presence of water (water inrush) :

- Water inrush with extremely high water inflow, §2.3.1
- Water inflow under high hydrostatic pressure, §2.3.2
- Mud inrush §2.3.3

§2.4 Other Phenomena or consequence :

- Face instability, §2.4.1

§2.5 Environmental conditions :

- High temperature §2.5.1

It is important to remark that these phenomena do not only occur in bad rock conditions: although tunnelling through fault zones or hydrothermally altered zones represent the most difficult conditions because of the possible simultaneous occurrence of more hazard scenarios (e.g. squeezing and face instability), some of these phenomena may affect the excavation in sound rock (e.g. spalling or rock-burst). The next section provides a detailed definition of the main hazard scenarios specifying the rock conditions under which the hazards may occur.

Finally, the report gives an indication on the predictability (spatial and temporal) of each phenomenon. The predictability is rated assuming that a detailed and a good geomechanical /geological base is available before excavation, and that during excavation works systematic advance exploration (probe and/or core drilling, possibly geophysics, ..) as well as systematic analysis of the TBM data, of the collected muck and of the face mapping is carried-out.

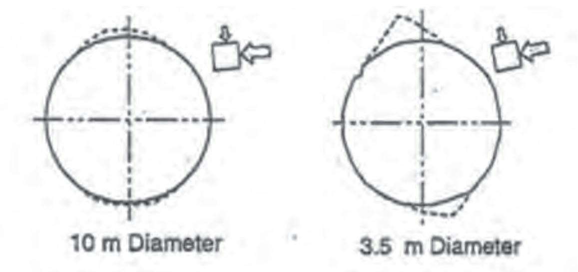
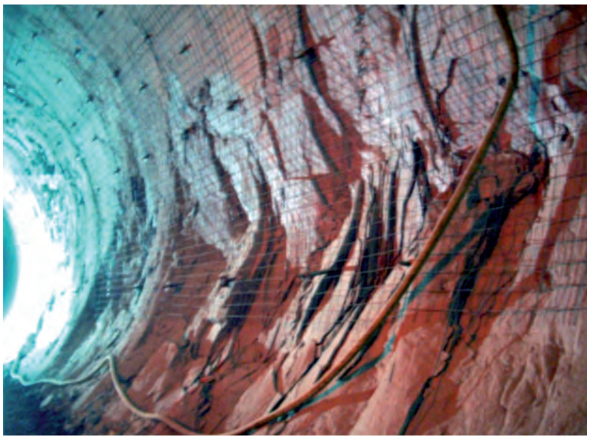
The **predictability** is classified as :

- **VERY DIFFICULT TO PREDICT;**
- **DIFFICULT TO PREDICT;**
- **POSSIBLE TO PREDICT.**

2 >> Definition of the hazard scenarios

2.1. BRITTLE BEHAVIOUR

2.1.1. Rockburst, Spalling

BRITTLE BEHAVIOUR: ROCKBURST, SPALLING	
Definition	Rockburst is a failure of the rockmass with sudden energy release, which happens due to stress concentration. Burst occurs parallel to the direction of the maximum compression stress (Fig . 1).  *Figure 1. Comparison of the failed areas for tunnels of different size and shape and corresponding orientation of the in-plane in-situ principal stresses [3].* This hazard is mainly observed at the tunnel crown or at the side walls (Fig. 2). Rockburst may also happen at the face, leading thus to a blocky face (Fig. 3). Rockburst mostly happens approximately 0 to 2 diameters behind the face, and some hours after the front excavation, and stops when the surrounding rock mass has found a new equilibrium based on the prevailing stress conditions. This phenomena is also known as “strainburst”. Rockburst can also happen unexpectedly at any time, in a greater distance from the tunnel face, due to unpredictable stress redistribution (induced e.g. by surrounding excavations, seismic event, etc…). **Brittle rock behaviour** has different qualification regarding the intensity level: • **Spalling (low intensity).** Failure of the rockmass without projection of materials (so-called onion skin or scaling); • **Rockburst (high intensity).** Failure of the rockmass characterized by a violent and sudden release of energy with shooting/projection of pieces of rock. In the extreme case, the rockburst may lead to a complete collapse of the tunnel. The occurrence of such problems may lead to damage of the machine and/or injure the workers. Moreover, the occurrence of rock-burst may lead to a blocky much which may case difficulties in the mucking-out operations.
Predictability	**VERY DIFFICULT**
Rock conditions	• **High rock strength** • **Massive homogeneous rock mass** • **Brittle rock behaviour (low deformability)** • **High stress level (high overburden and/or anisotropy)**
Phenomena	 *Figure 2. Rock spalling in the Aare granite during the construction of the Lötschberg Base tunnel.*  *Figure 3. Blocky face observed after rock-burst (Gotthard Base tunnel).*

2.2. HIGHLY DEFORMABLE BEHAVIOUR

2.2.1. Buckling

<table>
<tr><th colspan="2">BUCKLING</th></tr>
<tr><td>Definition</td><td>Rupture of the rock along the direction of the foliation or bedding planes leading to bending of the foliation towards the opening (Fig. 4).

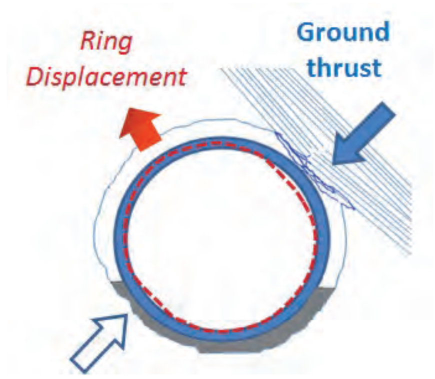
This phenomenon is mainly observed in tunnels excavated parallel to the foliation direction and it occurs in the proximity of the tunnel face. Buckling is particularly intense when the in-situ stress is parallel to the foliation direction.
The consequence of buckling is a highly anisotropic deformation of the excavation profile (convergence perpendicular to the foliation much higher than parallel to it) and consequently a strong asymmetrical load on the support (e.g. ribs, shotcrete, see Fig. 5) and on the final lining (e.g. segmental lining), respectively.


Figure 4. Buckling occouring on the upper right (and bottom left) side wall [8].

The occurrence of buckling may lead to long standstills, particularly when hand-mining works are necessary</td></tr>
<tr><td>Predictability</td><td>DIFFICULT TO PREDICT</td></tr>
<tr><td>Rock conditions</td><td>• High stress level (high overburden)
• Foliated (e.g. cleavage) or jointed rock mass (anisotropy of the rock /rock mass)
• Orientation of the foliation (bedding) parallel to tunnel axis</td></tr>
<tr><td>Phenomena</td><td>

Figure 5a. Consequences of buckling on ribs and shotcrete support (Loetschberg base tunnel).

Figure 5b. Consequences of buckling on ribs and shotcrete support : rexcavation before final lining.</td></tr>
</table>

2.2.2. Squeezing

SQUEEZING	
Definition	Overstress of the rock mass leading to high convergences or – if hindered by a stiff support – to high ground pressures. Differently to buckling, squeezing generally causes a convergence of the entire excavation perimeter (see Fig. 6). A peculiarity of squeezing is that it may take days, weeks or months to fully develop (particularly in water-bearing low permeability rock masses, cf. [7]). In TBM tunnelling, following problems may occur: (i) jamming (or trapping) of the of the shield (Fig. 7); (ii) jamming of the back-up equipment; (iii) jamming of the cutterhead; (iv) inadmissible convergences of the bored profile; (v) damage of the tunnel support. The occurrence of such problems may lead to long standstills, particularly when hand-mining works are necessary (in order to free a jammed TBM).
Predictability	DIFFICULT TO PREDICT
Rock conditions	**• High stress level (high overburden)** **• Low strength rock mass (compared to the in-situ stresses)** **• High deformability of the rock mass**
Phenomena	(see Figures 6 and 7 below)

Figure 6. Tunnel convergence due to highly intense squeezing – Gotthard tunnel conventional drive (Sedrun) [15].

Figure 7. Single shielded TBM jammed in squeezing ground (Uluabat Tunnel; Figure courtesy of Werner Burger, Herrenknecht AG).

2.3. PRESENCE OF WATER INRUSH

2.3.1. Water inrush with extremely high inflow (clear water)

<table>
<tr><th colspan="2">EXTREMELY HIGH WATER INRUSH (CLEAR WATER)</th></tr>
<tr><td>Definition</td><td>
Water inrush through discontinuities in the rock mass (such as joints, shear planes or intra-formational shears, or karstic zone) or fault zones (Fig. 8). Water inrush may occur during excavation or during the execution of exploratory borings.

In deep tunnels, water inflows may be of great volume (Fig. 9, 10) and in extreme cases may cause the flooding of the tunnel. Water inflows may cause mucking-out problems particularly in combination with soft or highly sheared rock mass (the muck resembles a watery mud that may be difficult to extract by belt conveyor), and logistics problem.

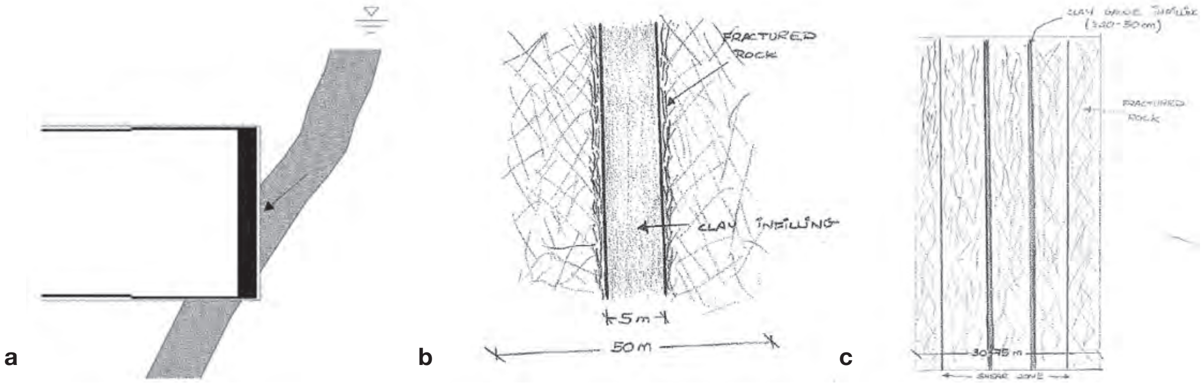


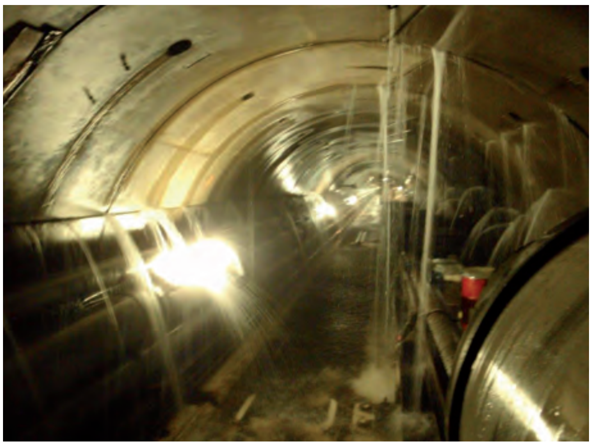
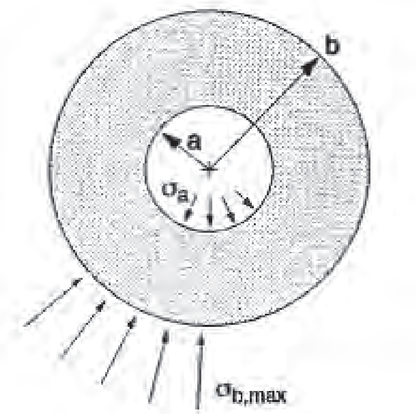
Figure 8. (a) Water and fines inrush and trapped water in (b) open dykes or (c) clay layers.
</td></tr>
<tr><td>Predictability</td><td>POSSIBLE TO PREDICT to DIFFICULT TO PREDICT (e.g. in karstic rock)</td></tr>
<tr><td>Rock conditions</td><td>
• Water bearing rock mass
• High permeability rock mass
• (High recharge potential)
</td></tr>
<tr><td>Phenomena</td><td>


Figure 9. Water inflow observed during the construction of Salazie Aval (Figure courtesy of JV RAZEL-BEC).

Figure 10. Water inflow observed during the construction of the Lake Mead Intake No. 3 tunnel (Figure courtesy of JV Impregilo-Salini-Healy, USA).
</td></tr>
</table>

2.3.2. Water inflow under high hydrostatic pressure

HIGH WATER PRESSURE	
Definition	High water pressure at the tunnel elevation. The high pressure increases the probability of occurrence of other geotechnical hazards like face instability, squeezing and water inrush with washing-out of fines. A high hydrostatic pressure could require the improvement of the rock mass mechanical properties by means of grouting in order to reduce the pressure acting on the TBM, support or lining (fig. 11). In some cases this may not be sufficient and drainage of the rockmass (by means of advance drainage during TBM excavation or by installing a pervious lining[1]) should be implemented to reduce the hydrostatic pressure.
Predictability	**POSSIBLE TO PREDICT the location with survey boreholes and to characterize the intensity**
Rock conditions	**• Water bearing rock mass** **• High water table**
Phenomena	 *Figure 11. Water pressure acting on the grouted rock mass [10].*

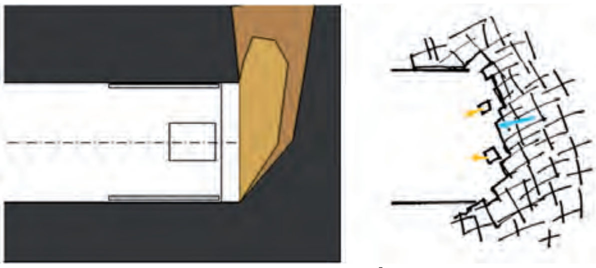
[1] *A similar issue is related to the lining of the tunnel: in deep tunnels the pervious lining concept is usually applied because of the impossibility for the lining to withstand the water pressure. In this case the drainage details should be properly designed*

2.3.3. Mud inrush

MUD INRUSH	
Definition	Water inflows may wash out fines from discontinuities (such as joints, shear planes or intra-formational shears, or karstic zone or fault zones) causing thus loosening of the ground and uncontrolled mud inrush. Mud inrush may occur during excavation or during the execution of exploratory borings. Mud inflows may cause mucking-out problems, particularly in combination with soft or highly sheared rock mass (the muck resembles a watery mud that may be difficult to extract by belt conveyor). Mud inrush with flow of material may also occur behind the shield thus endangering the safety of workers.
Predictability	**POSSIBLE TO PREDICT to DIFFICULT TO PREDICT (e.g. in karstic rock)**
Rock conditions	**• Water bearing rock mass** **• High permeability rock mass** **• (High recharge potential)**

2.4. OTHER PHENOMENA OR CONSEQUENCES

2.4.1. Face instability

FACE INSTABILITY	
Definition	Instability of the rock mass at the tunnel face (Fig. 12a). The tunnel face instability may be induced by the singular or simultaneous occurrence of poor rock quality, high stress level, high water pressure and unfavourable orientation of the discontinuities: • Poor rock quality. Low strength rock masses are typically faults or hydrothermally altered zones (e.g. sandy fault zones, clayey fault zones, blocky rock mass, …). The tunnel face may become unstable because of an insufficient bearing capacity of the ground. • High water pressure. Deep tunnels located below the water table are often characterized by high water pressure (and so high destabilizing seepage forces) that may induce face instability (even of cemented rock mass). The high water pressure increases also the intensity of local instabilities: rock pieces may be projected from the tunnel face, thus making even face inspections dangerous (cf. Fig. 12b). Finally, water pressure may cause punching type failures, when acting on low permeability rock layers. • Rockburst. Sudden and explosive failure of the face, causing damage to the cutterhead and cutters; can lead to sudden blockage of the cutterhead. • Squeezing. Intense squeezing phenomenon leads to large plastic extrusion of the tunnel face, and in extreme cases to a face collapse. • Unfavourable discontinuity orientation. The TBM advance in rock mass characterized by closely spaced discontinuity planes running perpendicular/sub-perpendicular to the tunnel axis is unfavorable because of the formation of a blocky muck (i.e. no chips); the cutting action of the discs produces the formation of unstable wedges that slide from the tunnel face. This may cause the damage of the cutterhead, cutters, buckets and belt conveyor. In TBM tunnelling, the occurrence of major face instability causes blocking and possibly damaging of the cutterhead (Fig. 13).  a b *Figure 12. (a) Major tunnel face instability and (b) local face intability under high water pressure ("pop-rock").*
Predictability	DIFFICULT TO PREDICT
Rock conditions	**• Low strength ground or blocky rock mass (typically fault or hydrothermally altered zones)** **• (High water gradients)** **• (for face instability induced by rockburst see §2.1.1)**
Phenomena	 *Figure 13a. Blocky face due to high stress level (Lotschberg Base tunnel).*  *Figure 13b.TBM blocked due to a major face instability (Gotthard Base tunnel [1]).*

2.5. ENVIRONMENTAL ASPECTS

2.5.1. High temperature

HIGH WATER PRESSURE	
Definition	High rock and water temperatures due to high overburden lead to challenging work conditions, especially when water is flowing from the excavated rock surface. High demand for venting and cooling installations in all working areas including the cutterhead during maintenance. Water needs to be caught early in order to not cover large surfaces, over which heat distribution is favoured (as happened in Fig. 14).
Predictability	**POSSIBLE TO PREDICT with survey boreholes**
Rock conditions	• **High overburden and / or** • **Presence of a high temperature aquifer**
Phenomena	 *Figure 14. High hot water ingress (43°C) at the Gotthard Base Tunnel.*

The timely identification of the geotechnical hazards and the understanding of their consequences are essential in order to minimize the risks during construction (for example, by selecting and designing the most appropriate TBM). The phenomena described in Section 2, if not timely identified, could have dramatic consequences on the tunnelling works (delays of months on the time schedule) because of the less adaptively offered by the mechanized excavation compared to conventional excavation.

This chapter identifies and evaluates the **consequences on the TBM advance** of the main geotechnical hazards described in Section §2 (Section §3.1) and gives recommendations of possible mitigation measures (Section §3.2). The goal of Section 3 is to provide a support to the designers, constructors and owners for the timely identification (from the preliminary phases of a tunnel project) of hazards and for the timely planning of the countermeasures.

The TBM types considered in the present document are those typically used for the excavation of long and deep tunnels:

- Open TBM (Hard Rock TBM with grippers),
- Single Shield TBM (Open mode)
- Double Shield TBM (as reference case, it is assumed that the double shield TBM is operated in double shield mode – i.e. with lining installation during advance).

Usually in deep tunnel, open mode machine are used (i.e. without pressurization of the tunnel face). However, in specific cases, single shield Multimode TBM, which are able to provide a support of the tunnel face (e.g. by means of pressurized slurry) may be required (e.g. : Lake Mead Intake No. 3 Tunnel).

All identified consequences and countermeasures are based upon the experienced shared among the working group members over the last decade.

3.1. HAZARDS AND CONSEQUENCES REGARDING THE TBM TYPE

The possible consequences of the main geotechnical hazards listed in the previous Sections are evaluated thereafter for the different TBM types, with respect to their impact on the tunneling operations and on the safety of the workers. The evaluation is based upon the experience shared by the working group members. No considerations on the probability of occurrence have been done in the present Chapter.

The evaluation is based on the definition given in the ITA guideline of WG2, published in 2004 [11]:

CONSEQUENCE LEVEL	
	Not concerned
1	**Negligible :** No further consideration of the hazard is needed
2	**Unwanted** : mitigation measures shall be identified. The measures shall be implemented as long as the costs of the measures are not disproportionate with the risk reduction obtained
3	**Unacceptable :** The hazard shall be reduced at least to Unwanted, regardless of its mitigation costs

PHENOMENA HAZARDS	CONSEQUENCE LEVEL				IDENTIFICATION OF CONSEQUENCES ON TBM	LOCATION		
	OPEN	SINGLE SHIELD	DOUBLE SHIELD		**Not concerned**	TUNNEL FACE	TBM AREA	BACK-UP AREA
				1	**Negligible :** No further consideration of the hazard is needed			
				2	**Unwanted :** Risk mitigation measures shall be identified. The measures shall be implemented as long as the costs of the measures are not disproportionate with the risk reduction obtained			
				3	**Unacceptable :** The risk shall be reduced at least to Unwanted, regardless of the costs of risk mitigation			
Brittle behaviour: Rockburst, spalling								
Spalling			2		Blocking of the telescopic part of the shield			
	2		2		Gripper bracing difficulties			
		1	1		Cracks in the segmental lining			
	1				Damage of the support			
	2				High cleaning effort in invert (time consuming)			
Rock-burst	3	3	3		Damage of TBM[2]			
	2	2	2		Damage of the cutterhead and/or the cutting tools[3]			
	3	3	3		Injuries of the workers during face inspections			
		2	2		Damage of the segmental lining[4]			
	2				Damage of the support			
	3				Injuries for workers			
	3				Damage of the back-up ; Damage of the belt conveyor			
Highly deformable behaviour								
Squeezing and buckling	2	2	2		Jamming of the cutterhead			
	1	2	3		Jamming and damage of the shield			
	2				Jamming and damage of the back-up			
		3	3		Overstress of the segmental lining			
	2				Overstress of the support			
	3				Inadmissible high tunnel convergences			
Presence of water								
Extremely high water inflow	2	2	2		Reduction of advance rate up to stop			
	3	3	3		Complete Stop of the TBM due to site flooding			
	2	2	2		Mucking-out difficulties			
		2	2		Difficulty in Bedding the segment			
	3	3	3		Hazardous working conditions			
High water pressure	2	2	2		Damage of the support or segmental lining			
	2	2	2		Damage of the drilling equipment			
Mud inrush	3	3	3		Complete Stop of the TBM due to site flooding[5]			
	3	3	3		Hazardous working conditions			
	2	2	2		Mucking-out difficulties			
	2	2	2		Cleaning problem			
Other Phenomena and consequences								
Face instability	2	2	2		Block of the cutterhead			
	2	2	2		Damage of the cutterhead and/or the cutting tools[6]			
	1	3	3		Injury of workers during inspection and maintenance			
	2	2	2		Overstress of the support or the segmental lining (due to stress redistribution)			
	2	2	2		Damage of belt conveyor due to large or sharp edged blocks destroying the belt and/or the transfer chutes			
Environmental aspects								
High temperature	3	3	3		Difficult to unacceptable working conditions			
	1	2	2		Where mortar & shotcrete has to be installed, quick grout hardening could happen			

[2] Due to dynamic load (impact)
[3] Due to unstable blocks rotating with the cutterhead leading to wear
[4] Due to asymmetric loads and dynamic load (impact)
[5] In the case of mud inrush, the duration of the phenomena is assumed to be shorter than in the case of high water inflows
[6] Due to unstable blocks rotating with the cutterhead leading to wear

3.2. MITIGATIONS MEASURES REGARDING THE CONSEQUENCES OF THE HAZARDS DURING TBM OPERATION

This section provides recommendations for the design of the TBM and for the mitigation measures that can be implemented on-site (the latter defining the required TBM equipment needed to be anticipated in the design).

The mitigation measures are evaluated with respect to their difficulty of implementation (economic considerations are neglected because the mitigation costs are usually small compared to the total cost of the project or the intervention cost rising after an accident) :

DIFFICULTY LEVEL TO IMPLEMENT MITIGATION MEASURE ON SITE	
■ (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)

The following general recommendations apply :

- The level of difficulty increases with smaller machines;
- For shielded TBM's the drillings operations have to be considered already in design of the TBM (in order to foresee the required openings, space, equipment…);
- The mitigation measures are classified as "easy to be implement on site" assuming that their implementation was considered in the design of the TBM (including TBM equipment). The design issues of the TBM are not considered in the evaluation, even if the equipment integration leads to complex issues.

■ (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)

PHENOMENA HAZARDS	LEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE: OPEN	SINGLE SHIELD	DOUBLE SHIELD	EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
Brittle behaviour: Rockburst, spalling				
1- Spalling	■	■	✓	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) 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)
	✓	⚠	■	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
	✓	■	■	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

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
	OPEN	SINGLE SHIELD	DOUBLE SHIELD	■	**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)

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

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
	OPEN	SINGLE SHIELD	DOUBLE SHIELD	■	**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
	■ ⚠	❗	❗		4.2.4) Drainage boreholes around the lining
		⚠	⚠		4.2.5) Double lining concept
4.3- Mud inrush + due to presence of water	*In this specific case,* ***all the mitigation measures*** *and level of difficulties identified in section "Extremely high water inflow"* ***4.1.i*** *and "High water pressure"* ***4.1.i could be applied***				
	✓	✓	✓		4.3.1) Treatment of the extracted ground by foams (in order to manage mucking-out difficulties)
	⚠	⚠	⚠		4.3.2) It is mandatory to clean TBM area: • Specific equipment could be required (pumps , excavator, …) in the front zone of the machine; • The difficulty increases with the inclination of the TBM (descending) and when the diameter decreases
Other Phenomena and consequences					
5- Face instability	✓	✓	✓		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
	⚠	⚠	⚠		4.2.2) Improve the ground characteristic by grouting ahead of / and around the machine
	■	⚠	■		4.1.2 Closed mode operation in the case of using a Single Shield Multimode TBM and low water table (up to 15 bar)
	⚠	⚠	⚠		5.1) Advance drainage boreholes in order to release the water pressure

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE				EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
	OPEN	SINGLE SHIELD	DOUBLE SHIELD		**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)
Other Phenomena and consequences					
5- Face instability	✓	✓	✓		5.2 'Moderate driving': Reduction of rotation speed and penetration
	✓	✓	✓		5.3 Appropriate design of cutterhead: wedges to protect discs; high-resistance wear plates; high-resistance disc cutters (19-21"); many small bucket openings; closable man holes[8]
	✓	✓	✓		*1.4) Appropriate torque reserve (high torque low speed gear)*
Environmental aspects					
6- High temperature	✓	✓	✓		6.1 Appropriate design of Ventilation (increase of airflow)
	⚠	⚠	⚠		6.2 Foresee modular increase of cooling capacity (systematic equipment of chilled water pipe system in the tunnel and the TBM)
	⚠	⚠	⚠		6.3 Catch water as soon as possible in order to avoid heat transfer to the air. (Could be done with advance drainage boreholes)
	✓	✓	✓		6.4 Reduce shift time for workers
	✓	✓	✓		6.5 Use of additive / formula to delay the grout hardening

[8] A modification of the cutterhead during the operation on the TBM is still possible but difficult, time consuming and expensive

4 >> Conclusion

The geological uncertainty (the depth and the length of the tunnel make exploration technically and economically extremely demanding), the low grade of adaptability of TBM excavation (compared to conventional methods), and the almost impossibility of intervention from the surface in case of problems make the TBM excavation of long and deep tunnels a real challenge for engineers and contractors.

The key aspect for the successful excavation of long and deep tunnels is the identification of all possible geotechnical hazards already in the preliminary phase of the project (appropriate design of the TBM and the selection of the right TBM equipment).

The present document gives an overview of the geotechnical hazards that may be encountered – or their magnitude is by far increased – when excavating at high overburden, it evaluates the impacts of the hazard on the excavation for the TBM types commonly selected for the excavation of long and deep tunnels, and finally, it provides recommendations for the design (and the selection) of the TBM as well for the countermeasures to be implemented on site.

The report is based upon the experience of the WG17 members on projects excavated at great depth under difficult ground conditions. The reference projects are collected as a worldwide database in the Appendix of the present document, describing the difficulties arisen during excavation and the adopted countermeasures.

5 >> References

[1] Tunnelling the Gotthard, Swiss Tunnelling Society, 2016.

[2] Lieb, R.H., Ehrbar, H. 2011. Gotthard Base Tunnel Risk Management for the World's Longest Railway Tunnel: Lessons Learnt. In Proc. 37th ITA-AITES WTC, Helsinki, Finland

[3] Martin, C.D., Kaiser, P.K., Mc Creath, D.R. 1999. Hoek-Brown parameters for predicting the depth of brittle failure around tunnels. Canadian Geotechnical Journal, Vol. 36, No. 1, 136-151

[4] Mezger, F., Ramoni, M., Anagnostou, G. 2015. Some concepts for segmental linings in squeezing rock. In Proc. RETC Rapid Excavation and Tunnelling Conference, New Orleans, USA, 646-658

[5] Nicola, A., Nickerson, J., Bono, R., Donadoni, N., Anagnostou, G., Schürch, R., Zingg, S. 2014. Lake Mead Intake Tunnel No. 3 – A step beyond the limits. In Proc. Swiss Tunnel Congress, Lucerne, Switzerland, 166-173

[6] Ramoni, M., Anagnostou, G. 2010. Thrust force requirements for TBMs in squeezing ground Tunnelling and Underground Space Technology, Vol. 25, No. 4, 433-455

[7] Ramoni, M., Anagnostou, G. 2011. The effect of consolidation on TBM shield loading in water-bearing squeezing ground. Rock Mechanics and Rock Engineering, Vol. 44, No. 1, 63-83

[8] Semeraro, M., Besson, A., Vinnac, A., Schivre, M., Ramond, P., Bochon, A., Bäppler, K. 2014. Rétroanalyse du creusement au tunnelier dans le massif fortement déformable du tunnel du Fréjus sous forte couverture. In Proc. Congrès AFTES, Lion, France

[9] Grandori, R., Bieniawski, Z.T., Vizzino, D., Lizzardo, L., Romualdi, P., Busillo, A. 2011. Hard rock extreme conditions in the first 10 km of TBM-driven Brenner exploratory tunnel. In Proc. RETC 2011, New Orleans, USA , 667-685

[10] Anagnostou, G., Kovari, K. 1994. Zur Dimensionierung von Injektionskoerpern im Tunnelbau. Weiterbildungskurs, ETH Zürich, Institut für Geotechnik

[11] ITA Guidelines for tunnelling risk management: Working Group No. 2 Research, ITA-AITES, c/o EPFL, Vol_19_3_217-237 ; Søren Degn Eskesen, Per Tengborg, Jørgen Kampmann, Trine Holst Veicherts

[12] AFTES Guidelines «Forward probe TBM» - Working Group GT24, AFTES, TOS242_GT24R2A1

[13] Bieniawski, Z. T. 2014. Quo Vadis Tunnel Engineering? Predicting The Unpredictable, Memorial Closing Lecture , WTC 2014.

[14] Kaiser Peter, Ground support for constructabilityof deep underground excavations – Challenge of managing Highly stresses ground in civil and Mining projects –, Muur Wood Lecture WTC2016

[15] Zbinden P., Schoch Keller S., 2005 , Tunnel de base du Saint-Gothard , Etat de l'avancement des travaux et du projet, TOS n 190 S, Juillet-Aout 2005

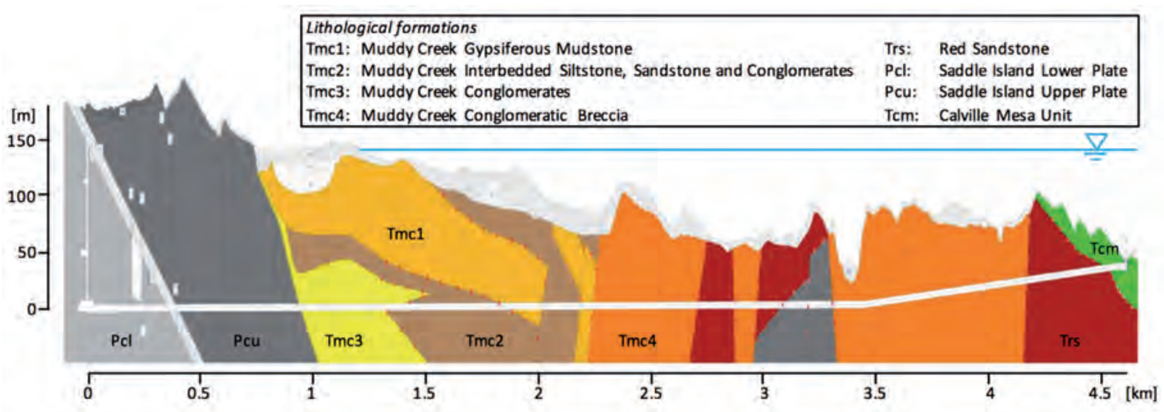
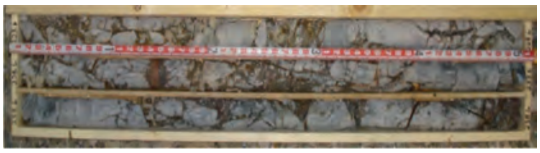
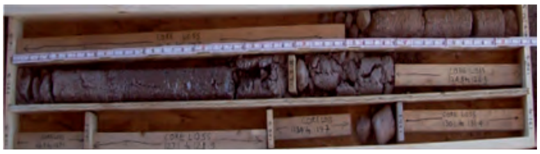
[16] United States Patent McNally et al. (45) Date of Patent: Oct. 22, 2002

Worldwide date base collected by the members of the ITA Working Group 17 on the TBM tunnelling experience in difficult rock conditions gained over the last 20 years

LIST OF PROJECTS					DEFINITION OF THE HAZARD SCENARIOS								
					Brittle behaviour		Highly deformable behaviour		Presence of water				Environmental aspects
Number	Project name	Country	Type of TBM	Diameter [m]	Spalling	Rock-burst	Buckling	Squeezing	Extremely high water inflow (clear water	High water pressure	Mud inrush	Face instability	High temperature
1	Lake Mead	USA	Single shield	7,2				✓	✓	✓	✓	✓	
2	Frejus safety tunnel	France-Italy	Single shield	9,46			✓						
3	Gothard base tunnel - Lot Bodio	Switzerland	Hard Rock TBM with Grippers	8,83								✓	
4	Gothard base tunnel - Lot Faido	Switzerland	Hard Rock TBM with Grippers	9,43	✓			✓	✓	✓		✓	
* 5	Olmos transandino tunnel	Peru	Hard Rock TBM with Grippers	5,35	✓	✓							
6	Loetschberg base tunnel, south section (Steg and Raron drives	Switzerland	Hard Rock TBM with Grippers	9,43	✓	✓	✓			✓		✓	✓
7	Nant de Drance	Switzerland	Hard Rock TBM with Grippers	9,45	✓		✓			✓			✓
* 8	La Maddalena exploratory tunnel	Italy	Hard Rock TBM with Grippers	4,5		✓							✓
* 9	Uma Oya Multipurpose Develepment projetc tailrace tunnel	Sri Lanka	Double shield	4,3								✓	
* 10	Pahang-Selangor Raw Water Transfer Project	Malaysia	Hard Rock TBM with Grippers	5,2	✓	✓			✓				✓
11	Hida tunnel - main tunnel	Japan	Hard Rock TBM with Grippers	12,8		✓			✓	✓		✓	
12	Kargi tunnel	Turkey	Double shield	9,84				✓					
13	Niagara Tunnel Project	USA	Hard Rock TBM with Grippers	14,4	✓								
14	Lesotho Haighlands Water Project	Lesotho	Hard Rock TBM with Grippers	5								✓	

** NB : These datasheet will be fully completed in the next edition*

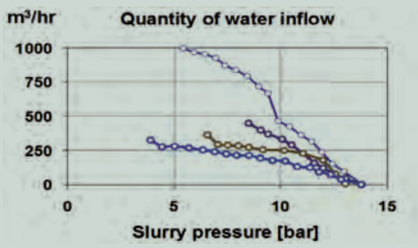
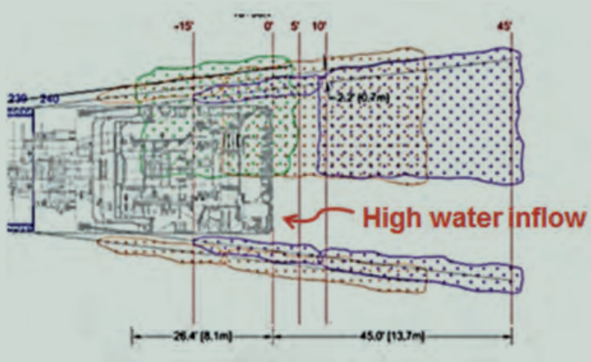
LAKE MEAD PROJECT			
PROJECT CHARACTERISTICS			
Country	USA	**Tunnel Length**	4,7 km
Client	SNWA	**Ø excavated**	7,2 m
Engineers	ARUP (geotech. consultants: ETH Zurich)	**Functionality**	Water supply
Contractors	HEALY-SALINI-IMPREGILO	**TBM Type**	Multimode Single shield

GEOLOGICAL CONDITIONS		
Description	Metamorphic rocks over the first and over the central part of the alignment, and sedimentary rocks in the rest. Two major fault zones of completely sheared rock in the metamorphic rocks at the begin of the TBM drive.	
Main lithologies	• Metamorphic rocks: crystalline rock comprising mostly granite, granite/pegmatite gneiss, chloritic quartz-feldspar gneiss and quartz monzonite. These rocks are variably intruded by Tertiary volcanic rocks consisting mostly of dacite, diorite, andesite, and some monzodiorite, and are typically highly jointed, sheared and faulted. • Sedimentary rocks: conglomerates, sandstone, mudstone and limestone.	
Maximal Overburden	150 m	
Hydrological conditions	See level 140m above the tunnel axis (i.e.,14 bar of hydrostatic pressure)	
Geological Profile		
Representative core samples	 *Sheared metamorphic rock*	 *Less cemented sedimentary rock*
	 *Competent sedimentary rock*	

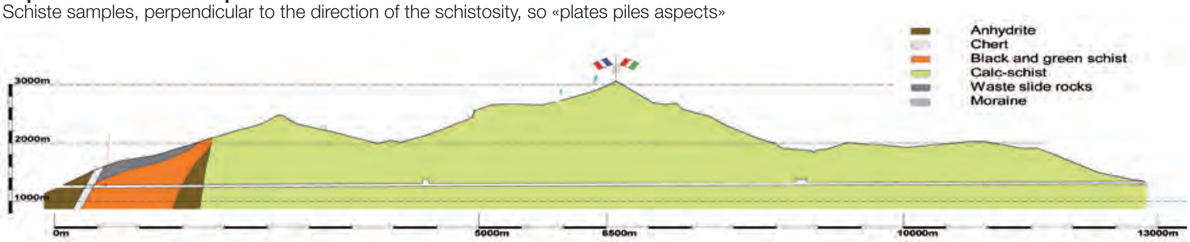
MAIN GEOTECHNICAL HAZARDS			
Definition of the hazard scenarios		**Occurence**	**Comments**
Brittle behaviour	Spalling		
	Rock-burst		
Highly deformable behaviour	Buckling		
	Squeezing	✓	Jamming of the shield caused by the high deformability and the low strength of the rock mass in softer sedimentary rock formations.
Presence of water	Extremely high water inflow (clear water)	✓	Unmeneageable high water inflow mainly caused by fractured rock mass (i.e., a high secondary permeability) and high recharge potential due to the proximity to the lake.
	High water pressure	✓	
	Mud inrush	✓	
Face instability	-	✓	In correspondence of low-strength (or highly fractured) rock mass.
Environmental aspects	High temperature		

>> ANNEX 1 DATA BASE - LAKE MEAD PROJECT 2/3

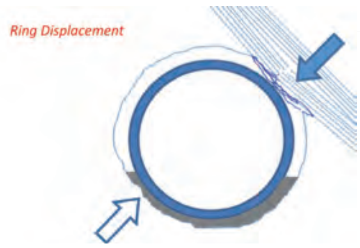
LAKE MEAD PROJECT			
TBM DESIGN DATA			
TBM specific design	• dual-mode TBM able to operate in both open or closed mode (slurry shiled) at high support pressure (up to 17 bar); • possibility of drilling and grouting through both the cutterhead and the rear shield. The auxiliary measures, which were foreseen in order to improve the stability of the tunnel face, included drainage boreholes (3 or 6) and/or grouting (low strength grout in order to reduce the water inflow; high strength grout in order to increase the strength of the ground); • shield conicity; • possibility to increase the boring diameter; • possibility to lubricate the shield extrados.		
Shield Characteristics		**Cutterhead**	
Shield Length	14 m	Nominal cutterhead diameter	7,22 m
Maximal shield diameter	7,18 m	Maximinal cutterhead diameter (overcut on diameter)	7,22 m
Minimal shield diameter	7,15 m	Number (excl. gauge cutters) and Diameter of cutterdisks	40 cutterdisks 17”
Shield conicity on the diameter	30 mm	Total Power	2800 KW
Nominal top void	206,5 mm	Maximal Torque	11,7 MNm
Maximal top void	206 mm	Torque at maximal speed	10,1 MNm
		Breakaway Torque	20,0 MNm
Thrust			
Total Breakaway Thrust	100 in high pressure mode MN	Nb of Grippers	No
Total Service Thrust	70 MN	Grippers Thrust	No
Number of Thrust jacks	12 (reduced to 8 during excavation)	Stress Thrust	No
		Auxiliarry Thrust	No
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	0,75 m	**Precast segments**	
Ribs erector	No	Number of segments	5 + 1
Sprayed Concrete Robots	No	Inner Diameter	6,1 m
Bolts Rigs	31 openings trough the cutterhed, 14 trough the shield (for grouing, and drainage boreholes)	Segment Thickness	40 cm
Other support	No	Ring Length	1,83 m
On the back up		Different type of segments	1 u
Ribs erector	No	Steel ratio reinforcement	85 kg/m³
Sprayed Concrete Robots	No	**Other**	
Bolts Rigs	No	Thickness	None
Other support	No	Steel Reinforcement	None
Observations		**Solutions & consequencies**	
Unstable face conditions were observed in the metamorphic rocks (particularly in correspondence of the major fault zones) when lowering the support pressure (as expected in the design phase). In the less-cemented portion of the sedimentary rock formations and in the transition zones close to the metamorphic rocks, local face instabilities were observed during face inspection.		The adverse ground conditions affected the progress of the tunneling works because they made it necessary to operate the TBM in closed mode at a very high support pressure (15 bar) over a great portion of tunnel. Over the rest of the alignment, the TBM was operated mainly in open mode in combination with 2-3 drainage boreholes.	

LAKE MEAD PROJECT	
CONSTRUCTION EXPERIENCE	
Observations	**Solutions & consequencies**
Unmanageable high water inflows (up to more than 1000 m3/h) in the metamorphic rock units and locally in the harder sedimentary rock units. The quantity of water inflow during closed mode operation was estimated using the TBM as a large scale constant head permeameter.  	Closed mode operation at very high support pressure (required in order to compensate the hydrostatic pressure).
Jamming of the shield. Contrarily to the expectation, no problems related to squeezing (shield jamming) occurred in the sedimentary rocks. The onset of jamming was observed in correspondence of the less competent zones of the metamorphic	Reduction of the support pressure (locally only possible in combination with ground improvement by grouting).
Clogging occurred during closed mode TBM operation in the sedimentary rocks and in the fault zones with a clayey core.	Regular cleaning of the cutterhead openings.
Mucking-out problems occurred in the portion of sedimentary rocks of higher permeability. The combination of higher water inflows and sand-like excavated material caused mucking-out problems during open mode operations (the muck resembled a watery mud that could not be transported by belt conveyor).	Closed mode operation required in the portions of the sedimentary rocks of higher permeability because of mucking-out difficulties (excavated material extracted via slurry lines).
Partially sucesfull groutign operations. The excavation in closed mode at very high support pressure did not allowed a regular maintenance of the cutter-head and of the slurry system under atmospheric conditions. As a consequence, the TBM components affected by the closed mode operation and the cutting tools (particularly in the section where clogging occurred) suffered of major wear. For these reasons exceptionally demanding interventions at the tunnel face were required. These required the excavation of a niche in front of the TBM. In order to reduce the water inflows grouting campaing were carried-out. Although the extensive grouting operation (with stagered grouting procedure) the water inflow could be only partially reduced. The main cause was the sub-optimal layout of the drilling pattern, that did not allowed to grout the central portion ahead of the tunnel face.	
Excessive wear of the gearboxes due to an unfavorable combination of high thrust force (required in order to compensate the tupport presure) and soft ground (low torque).	Modification of the main bearing system (gearboxes reduced from 12 to 8 units).

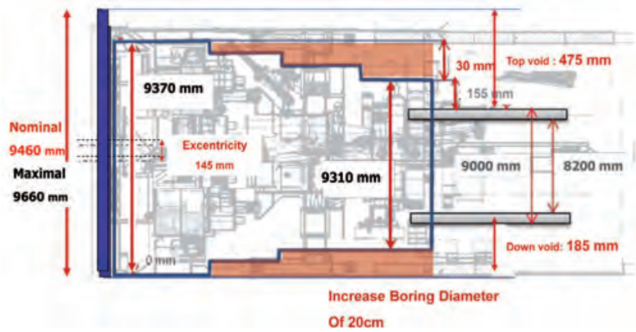
FREJUS SAFETY TUNNEL			
PROJECT CHARACTERISTICS			
Country	France - Italy	**Tunnel Length**	12 km
Client	SFTRF- SITAF	**Ø excavated**	9,46 m
Engineers	SYSTRA (Mandatory) SWS SEA	**Functionality**	Railway
Contractors	RAZEL-BEC (Mandatory) -BILFINGER BERGER	**TBM Type**	Single Shield
GEOLOGICAL CONDITIONS			
Description	Highly deformable schistous rock mass under high rock cover, with anisotropic behaviour resulting in asymmetric convergence		
Main lithologies	Calc-schist (Phyllitic and Carbonate facies)		
Maximal Overburden	1800m		
Hydrological conditions	No presence of water		
Geological Profile	**Representative core samples** Schiste samples, perpendicular to the direction of the schistosity, so «plates piles aspects»		



MAIN GEOTECHNICAL HAZARDS			
Definition of the hazard scenarios		**Occurence**	**Comments**
Brittle behaviour	Spalling		
	Rock-burst		
Highly deformable behaviour	Buckling	✓	Asymmetric convergence phenomenon corresponds to buckling of the schistosity planes; this leads to very localized and asymmetric loads on the tail of the TBM and on the tunnel lining as expected.
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature		



TBM DESIGN DATA	
TBM specific design	In order to reduce the identified hazard the following design specifications were adopted: • a reinforced and short single shield; • a high breakaway thrust; Moreover, in order to allow a certain degree of convergences (and so reduce both the risk of shiled jamming and the pressure acting on the final lining) theTBM was designed with the following peculiarities: • a shield conicity (leading to a very important annular void); • the possibility to increase the boring diameter; • a segmental lining with very strong steel-reinforcement; • the capacity of bolting and drilling.



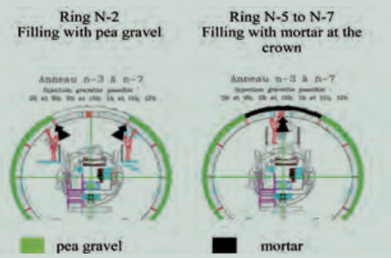
FREJUS SAFETY TUNNEL			
Shield Characteristics		**Cutterhead**	
Shield Length	11,2 m	Nominal cutterhead diameter	9,46 m
Maximal shield diameter	9,7 m	Maximal cutterhead diameter (overcut on diameter)	9,66 m
Minimal shield diameter	9,31 m	Number (excl. gauge cutters) and Diameter of cutterdisks	63 cutterdisks 17”
Shield conicity on the diameter	60 mm	Total Power	4200 KW
Nominal top void	275 mm	Maximal Torque	17.2 (from 0 to 2,2 tr/mn) MNm
Maximal top void	475 mm	Torque at maximal speed	6,3 MNm
		Breakaway Torque	21,3 MNm
Thrust			
Total Breakaway Thrust	106160	Nb of Grippers	No
Total Service Thrust	67200	Grippers Thrust	No
Number of Thrust jacks	2 x 12	Stress Thrust	No
		Auxiliarry Thrust	No
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	xx m	**Precast segments**	
Ribs erector	No	Number of segments	7 + 1
Sprayed Concrete Robots	No	Inner Diameter	8,2 m
Bolts Rigs	12 radial position in the front shield	Segment Thickness	40 cm
Other support	No	Ring Length	1,8 m
On the back up		Different type of segments	3 u
Ribs erector	No	Steel ratio reinforcement	85 , 130, and 285 kg/m³
Sprayed Concrete Robots	No	**Other**	
Bolts Rigs	No	Thickness	None
Other support	No	Steel Reinforcement	None

CONSTRUCTION EXPERIENCE

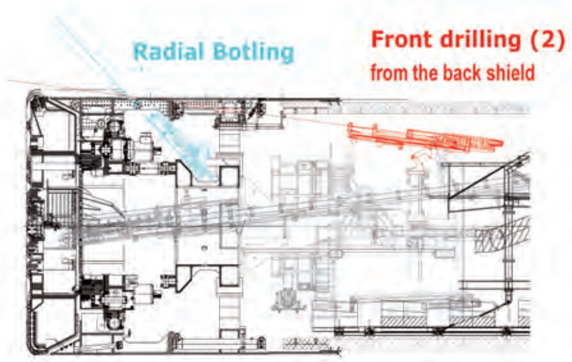
Observations	Solutions & consequencies
The design of the TBM proved to be suitable in order to mitigate the risk of jamming (maximum measured frictional force 50 MN).	Follow up during construction in order to anticipate and to be reactive: • Skilled team • Calibration of threshold values • Iterative procedure (continuous link between design studies and works).

The asymetric load on the lining caused by buckling led to damages on the lining over portion of tunnel of poorest rock quality.

The issue of the ring stabilization was improved by the following modified annular void filling sequence in order to create an abutment and the setting of the ring:
- mortar at the invert immediately during TBM progress;
- pea gravel on the sides since ring N-2;
- mortar at the crown from ring N-5 to ring N-7.



The apparence of cracks was also further reduced by increasing the steel ratio of the segments. This was achieved designing a third type of segments:
- Type 3: C35/45
  285 kg/m3 steel ratio
- 2 x2 SOF-Clips
  with reinforced web.

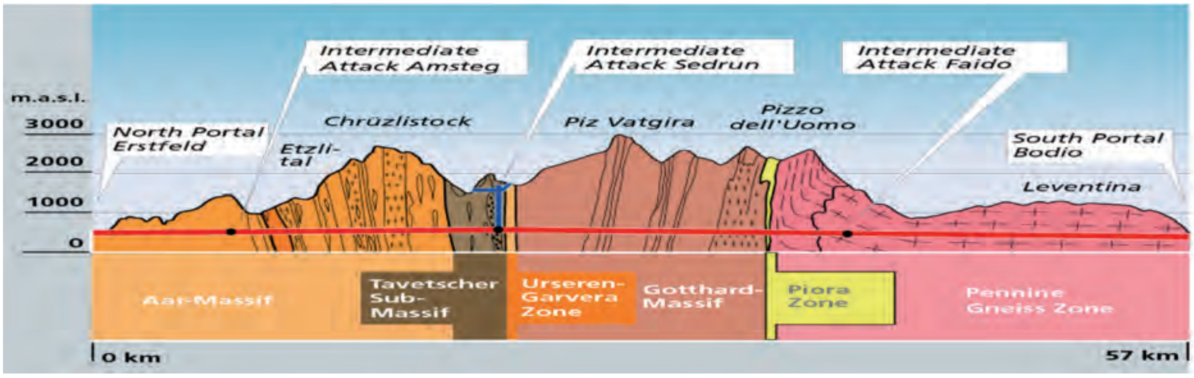
FREJUS SAFETY TUNNEL	
CONSTRUCTION EXPERIENCE	
Observations	Solutions & consequencies
Better manage the buckling phenomena, by efficiently bolting.	The position options of the radial drilling machine are a compromise between efficiency of bolting and the vailable space in the TBM: an optimum position of the bolts (perpendicular to the schistosity) would have involved increased dimensions of the front of the shield. 

GOTTHARD BASE TUNNEL - LOT BODIO

PROJECT CHARACTERISTICS

Country	Switzerland	**Tunnel Length**	12 km
Client	Alptransit Gotthard AG	**Ø excavated**	8,83 m
Engineers	Lombardi SA	**Functionality**	Railway
Contractors	IMPLENIA -HOCHTIEF -ALPINE BAU -IMPREGILO -CSC	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

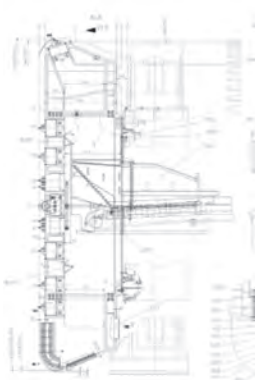
Description	Gneiss layered parallel to the direction of advance; extended fault zones parallel to direction of advance
Main lithologies	Leventina Gneiss
Maximal Overburden	1200 m
Hydrological conditions	Presence of water
Geological Profile	

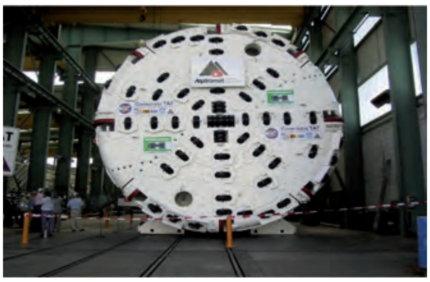
MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling		
	Rock-burst		
Highly deformable behaviour	Buckling		
	Squeezing	✔	Squeezing due to high deformability of the (unexpected) Lucomagno Gneiss; blocking of the complete shield, and subsequent damage to the invert shield segment
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-	✔	Unexpected extended fault zones, partly water-bearing
Environmental aspects	High temperature		

TBM DESIGN DATA

TBM specific design

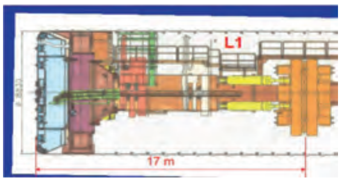




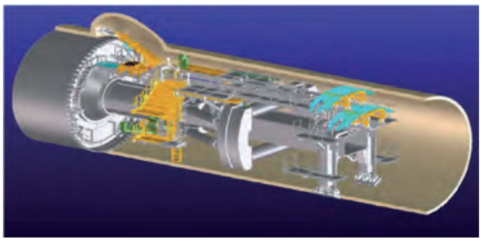
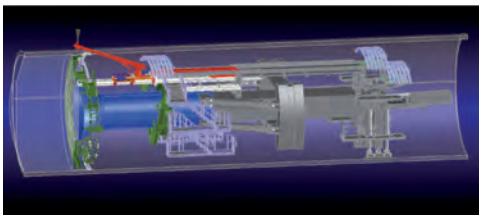
GOTTHARD BASE TUNNEL - LOT BODIO			
TBM DESIGN DATA - TBM specific design			
Shield Characteristics		**Cutterhead**	
Shield Length	4,3 m	Nominal cutterhead diameter	8,83 m
Maximal shield diameter	8,93 m	Maximum Cutterhead Diameter (overcut)	8,93 m
Minimal shield diameter	8,73 m	Number and Diameter of Cutters	58 cutter disks 17”
Shield Extension on the Diameter	20 mm	Total Power	3500 KW
Nominal gap in crown	-	Cutterhead Torque	6 MNm
Maximum gap in crown	-		
Thrust			
Total Installed Thrust	27000 kN	N° of Gripper Shoes	2 No
Total Cutterhead Thrust	14 500 MN	Gripper Thrust	70 000 kN
Number of Thrust Jacks	4 No		
SUPPORT		**FINAL LINING**	
L1 rock support zone (dist. from face)	5,5 m	**Precast segments**	
Ribs erector	Yes	Number of segments	None
Shotcrete Robot	Yes	Inner Diameter	None
Drill Rigs	2 radial drill rigs	Segment Thickness	None
Other rock support	wire mesh	Ring Length	None
In L2 rock support zone		Different type of segments	None
Ribs erector	No	Steel ratio reinforcement	None
Shotcrete Robot	Yes	**Other**	cast-in-situ invert concrete
Drill Rigs	2 radial drill rigs	Thickness	approx. 110 cm
Other rock support	No	Steel Reinforcement	only at cross passages kg/m³

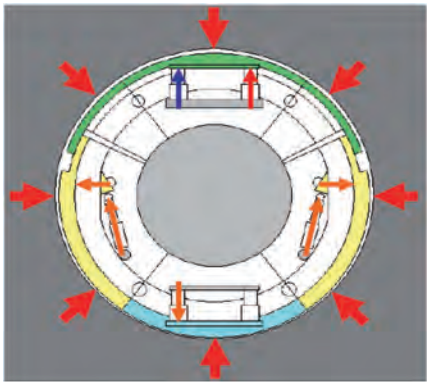
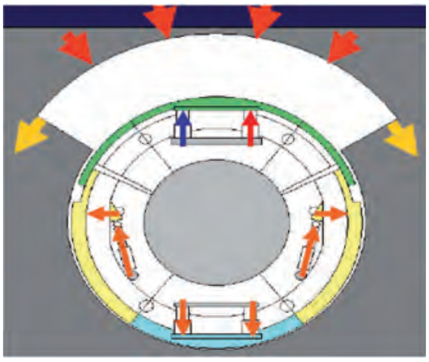
CONSTRUCTION EXPERIENCE

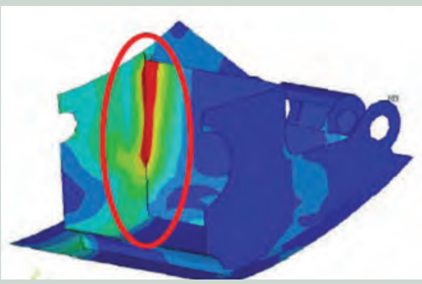
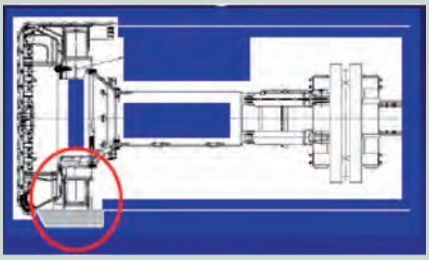
Observations	Solutions & consequencies
Lot Bodio, Both TBM’s: The TBM’s encountered unexpected fault zones which ran parallel to the tunnels for several 100m. The TBM’s were not equipped for installing heavy rock support, equipment in L1 zone comprised 2 drill rigs and a wire mesh erector. Necessary rock support included ring beams and shotcrete in the L1 zone. Due to lack of suitable equipment advance rates were extremely low. Original Layout and Fault Zone Characteristics:	For both TBM’s the L1 zone was re-designed and equipped with a ring beam transport system, a shotcrete robot and new extendable platforms for 360° rock support installation. The installation of the new equipment took 3 weeks. Advance rates improved from 4m/d to 12m/d.





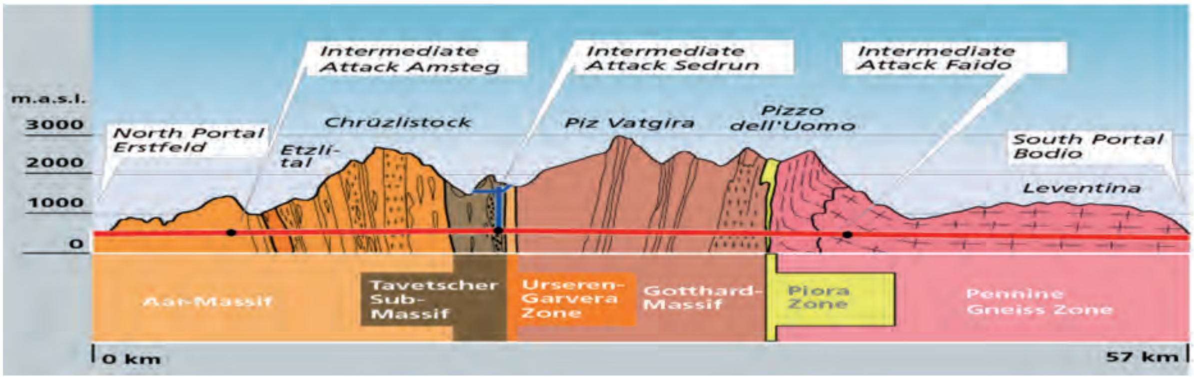




<table>
<tr><th colspan="2">GOTTHARD BASE TUNNEL - LOT BODIO</th></tr>
<tr><th colspan="2">CONSTRUCTION EXPERIENCE</th></tr>
<tr><th>Observations</th><th>Solutions & consequencies</th></tr>
<tr><td>Lot Bodio, Western TBM:
The TBM got stuck after entering into the Lucomagno Gneiss, a formation which had not been expected in the Bodio lot, and which showed increased tendency for squeezing. The Eastern TBM managed to work through the zone with high thrust forces, while the Western TBM got stuck even with applying the maximum available thrust force.

</td><td>The Western TBM was freed by overmining the crown shield, which took 10 days; with the freed crown shield the TBM could be moved; the mined space in the crown was subsequently filled with shotcrete

</td></tr>
<tr><td>Lot Bodio, both TBM's:
The invert shield segments of both TBM's were severely damaged by trying to push the TBM through the squeezing zones.

</td><td>Both TBM's needed in-situ repair of the invert shield segment, which was realized by excavating a small channel in the invert to create space for the welders


Continuous mining was adopted for both TBM's, splitting the 6h maintenance shift into short intervals to keep the TBM moving constantly</td></tr>
</table>

GOTTHARD BASE TUNNEL - LOT FAIDO			
PROJECT CHARACTERISTICS			
Country	Switzerland	**Tunnel Length**	14 km
Client	Alptransit Gotthard AG	**Ø excavated**	9,43 m
Engineers	Lombardi SA	**Functionality**	Railway
Contractors	IMPLENIA -HOCHTIEF -ALPINE BAU -IMPREGILO -CSC	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS	
Description	Fault zone in Gneiss with high overburden
Main lithologies	Streifen (striped) Gneiss of the Gotthard Massive
Maximal Overburden	2400 m
Hydrological conditions	Presence of water
Geological Profile	

MAIN GEOTECHNICAL HAZARDS			
Definition of the hazard scenarios		**Occurence**	**Comments**
Brittle behaviour	Spalling	✓	overbreak mainly at 11:00h and 05:00h positions, scaling necessary, intense cleaning operations in invert
	Rock-burst		
Highly deformable behaviour	Buckling		
	Squeezing	✓	Squeezing; Adaption of TBM to avoid blockage of the shield
Presence of water	Extremely high water inflow (clear water)	✓	Water and sand inflow during excavation of exploratory tunnel; flooding of tunnel
	High water pressure	✓	Water pressure predicted up to 200bar; at base tunnel level presumed marble without water
	Mud inrush		
Face instability	-	✓	Unexpected fault zone; loose ground in front of TBM; high overburden
Environmental aspects	High temperature		

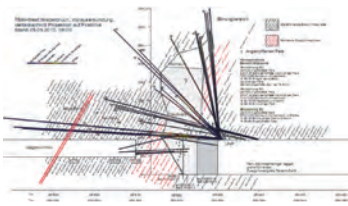
TBM DESIGN DATA

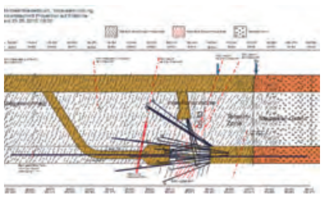
TBM specific design

GOTTHARD BASE TUNNEL - LOT FAIDO			
TBM DESIGN DATA - TBM specific design			
Shield Characteristics		**Cutterhead**	
Shield Length	4,3 m	Nominal cutterhead diameter	9,43 m
Maximal shield diameter	9,63 m	Maximum Cutterhead Diameter (overcut)	9,63 m
Minimal shield diameter	9,33 m	Number and Diameter of Cutters	66 cutter disks 17"
Shield Extension on the Diameter	30 mm	Total Power	3500 KW
Nominal gap in crown	-	Cutterhead Torque	6 MNm
Maximum gap in crown	-		
Thrust			
Total Installed Thrust	27000 kN	N° of Gripper Shoes	2 No
Total Cutterhead Thrust	16 500 MN	Gripper Thrust	70 000 kN
Number of Thrust Jacks	4 No		
SUPPORT		**FINAL LINING**	
L1 rock support zone (dist. from face)	5,5 m	**Precast segments**	
Ribs erector	Yes	Number of segments	None
Shotcrete Robot	Yes	Inner Diameter	None
Drill Rigs	2 radial drill rigs	Segment Thickness	None
Other rock support	wire mesh	Ring Length	None
In L2 rock support zone		Different type of segments	None
Ribs erector	No	Steel ratio reinforcement	None
Shotcrete Robot	Yes	**Other**	cast-in-situ invert concrete
Drill Rigs	2 radial drill rigs	Thickness	approx. 110 cm
Other rock support	No	Steel Reinforcement	only at cross passages ?? kg/m^3
CONSTRUCTION EXPERIENCE			
Observations		**Solutions & consequencies**	

Observations

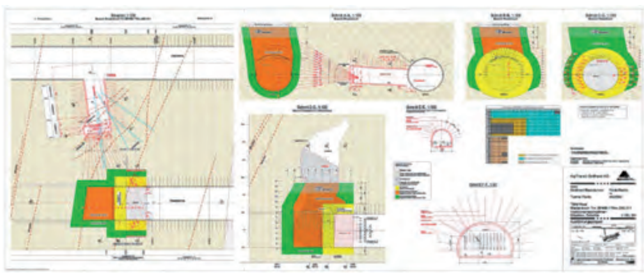
Western TBM:
The TBM encountered a fault zone with loose material. Thrust force was insufficient to push the TBM, but mucking of material was possible. Trials to install umbrella piping were unsuccessful.
Probe drillings were carried out to investigate the extent of the crushed zone:



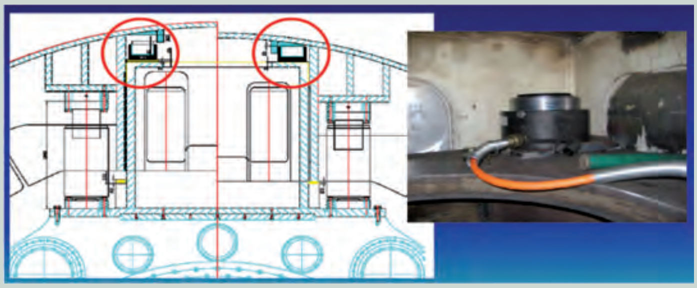
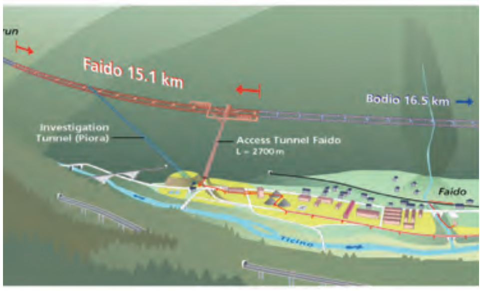
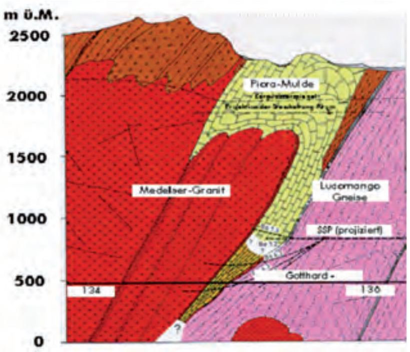
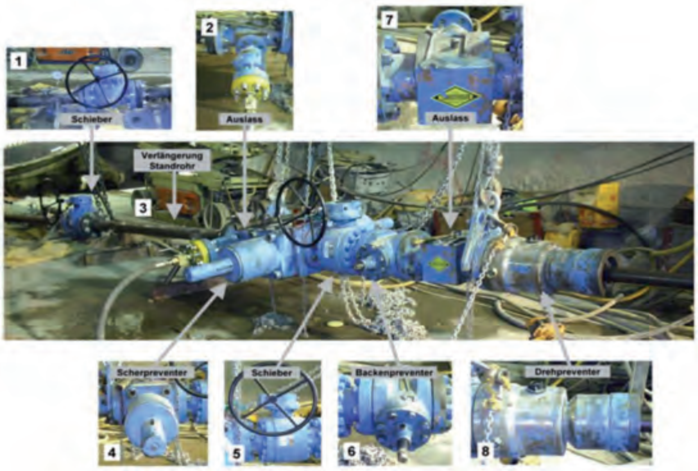
Solutions & consequencies

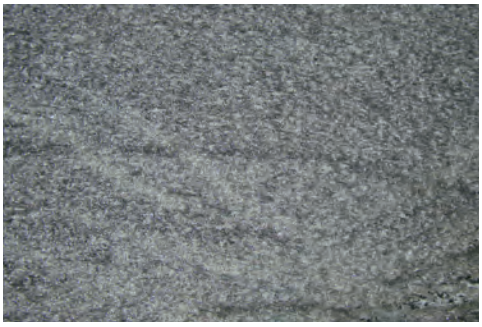
The fault zone was limited in extension, and had to be injected. Injection was executed both from the TBM and an injection cavern from the East tunnel. The TBM was then freed by an access tunnel also from the East tunnel. Duration 4,5months.

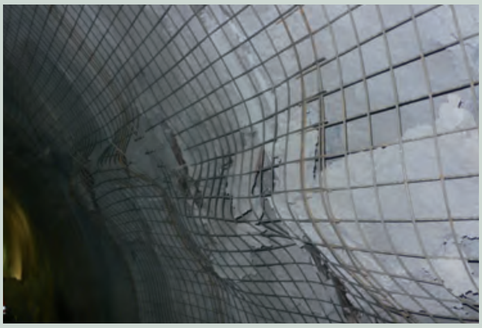
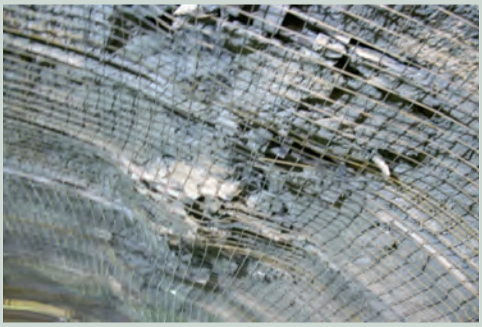


GOTTHARD BASE TUNNEL - LOT FAIDO

CONSTRUCTION EXPERIENCE

Observations	Solutions & consequencies
Lot Faido, both TBM's: For the Faido lot, squeezing conditions were already predicted for the horizontally layered Lucomagno Gneiss. Therefore the project foresaw an enlargement of the boring diameter to 9,33m. In order to further reduce the identified hazard the following design specifications were adopted for the Faido section: • Enlarged boring diameter of 9,43m; • Radial overcut 10cm; • Shield lubrication system; Moreover, in order to allow a certain degree of convergences (and so reduce both the risk of shield jamming and failure of the primary lining) the rock support was designed with the following peculiarities: • Sliding steel ribs TH-type; • Sliding joints in the shotcrete; • Compressive elements in the sliding joints; Finally, continuous mining was adopted whereever possible to guarantee a constant moving of the shield.	The TBM's were modified underground in the multi-functional station of Faido. Main new features were new cutterhead and new shield segments, while the main drive remained the same.   
Lot Faido, both TBM's: The Piora zone, containing sugar dolomite under high water pressure, was explored with an adit tunnel approx. 300m above the base tunnel alignment. High water pressure was encountered. Probe drillings to base tunnel level encountered stable marble without water. Preventer-protected drillings were planned to check the zone which extended for approx. 140m.   	During two years prior to the start, a working group of client/engineer and contractor worked together with specialists to develop core and percussion drill preventers suitable to be used on TBM's. The preventers were designed to withstand a water pressure of 200bar, and were tested in the start caverns of the TBM's prior to departure. The Eastern TBM was first to reach the Piora influence zone, and was stopped 100m short of the presumed rock interface. A 280m long core drilling was executed under preventer protection to explore the rock section containing the Piora zone. The drilling was stopped when it reached the Medelser Granite on the far side of the Piora marble. No water or squeezing phenomena were detected, and the TBM's passed the zone without difficulty. Duration of the campaign: 3 weeks (drilling 10 days) 

<table>
<tr><th colspan="2">GOTTHARD BASE TUNNEL - LOT FAIDO</th></tr>
<tr><th colspan="2">CONSTRUCTION EXPERIENCE</th></tr>
<tr><th>Observations</th><th>Solutions & consequencies</th></tr>
<tr><td>Lot Faido, both TBM's:
Spalling occurred as soon as the TBM's entered the undisturbed Medelser Gneiss, and continued throughout
the granite sections. Spalling was mainly observed at the 11:00h and 05:00h positions, perpendicular to the
main stress distribution.
</td><td>When spalling occurred, the risk for rockburst was rated high, and previously designed rock support was
installed for:
a) low to medium rockburst:
• Yielding Swellex/Super Swellex Anchors, l = 3,9m
• Wire mesh 2 x 5m, 10cm x 10cm mesh width
• Overlap of wire mesh min. 20cm
• Anchors positioned on overlaps of wire mesh
• Head protection U-shaped beams in crown approx. 90°
Measures to be carried out over min. 180°, better 270° to protect personnel working in invert
Advance rates 2m/hour
</td></tr>
<tr><td>A lot of loose material fell to the ground behind the shield
and covered the invert. Cleaning works were improved by
using bobcats as loaders. The secondary belt conveyor was
modified to be lowered during standstills (maintenance shift etc.) so that the rock
material could be loaded directly.

</td><td>b) strong to extensive rockburst:
TH-type flexible ring beams (ring building times less than
30 minutes achievable)
• Wire mesh 2 x 5m, 10cm x 10cm mesh width
• Overlap of wire mesh min. 20cm
• Shotcrete min. 15cm
• Second layer of wire mesh for head protection
If necessary radial pressure relief holes with large diameter
Measures to be carried out over 360°
Advance rates up to 1m/hour

</td></tr>
</table>

OLMOS TRANSANDINO TUNNEL

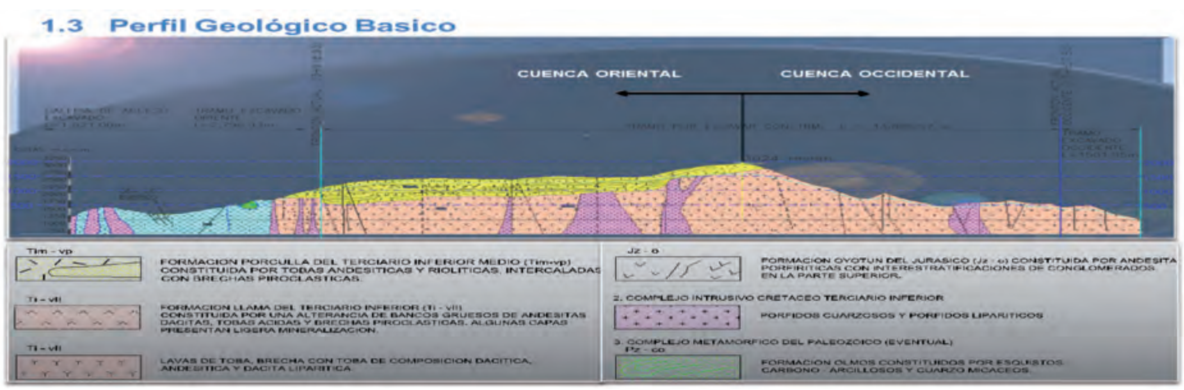
PROJECT CHARACTERISTICS

Country	Peru	**Tunnel Length**	12,5 km
Client	Government of Peru	**Ø excavated**	5,35 m
Engineers		**Functionality**	Water supply
Contractors	Odebrecht	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

Description	Hard to very hard (>250MPa) undisturbed rock horizontal stresses higher than vertical stresses
Main lithologies	Extrusive rock types (andesites/dacites) intrusive rock types (granodiorites/tuffs) metamorphic basement rocks (schists)
Maximal Overburden	2000 m
Hydrological conditions	Minor presence of water
Geological Profile	see figure below

Geological Profile

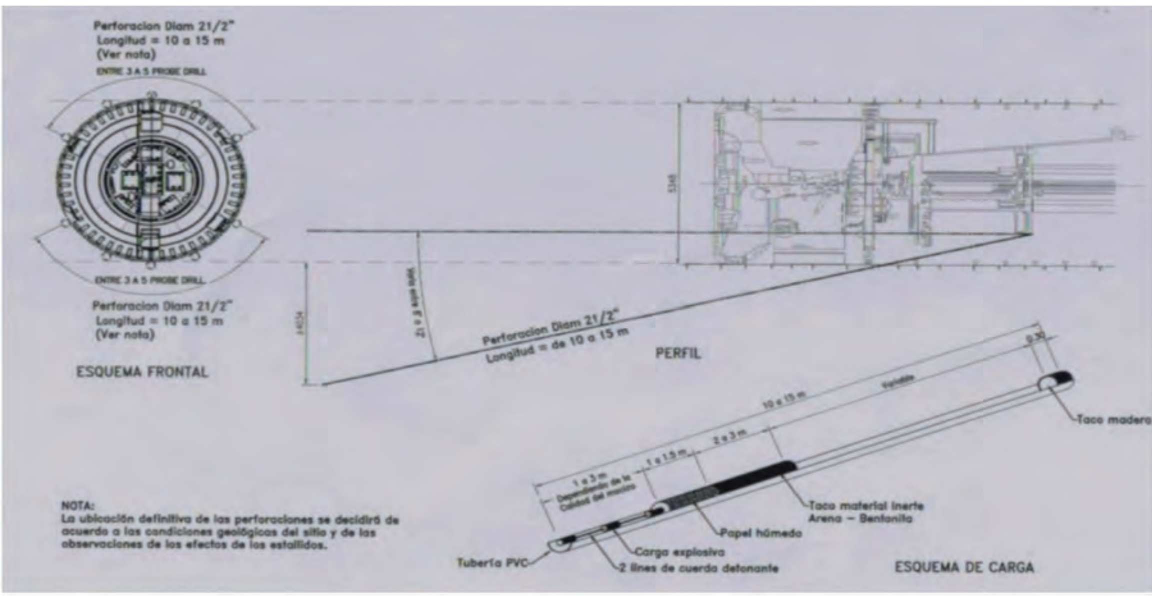


MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling	✓	spalling and popping in the TBM area
	Rock-burst	✓	at the face and along TBM, blocky ground conditions, damage to cutterhead, rock support and TBM installations, large overbreaks
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature		

TBM DESIGN DATA

TBM Specific Design

OLMOS TRANSANDINO TUNNEL			
TBM DESIGN DATA - TBM specific design			
Shield Characteristics		**Cutterhead**	
Shield Length		Nominal cutterhead diameter	5,35 m
Maximal shield diameter		Maximum Cutterhead Diameter (overcut)	
Minimal shield diameter		Number and Diameter of Cutters	35 cutter disks 17"
Shield Extension on the Diameter		Total Power	2205 KW
Nominal gap in crown		Cutterhead Torque	3,5 MNm
Maximum gap in crown			
Thrust			
Total Installed Thrust		N° of Gripper Shoes	2 No
Total Cutterhead Thrust	9345 MN	Gripper Thrust	
Number of Thrust Jacks	4 No		
SUPPORT		**FINAL LINING**	
L1 rock support zone (dist. from face)		**Precast segments**	
Ribs erector	Yes	Number of segments	invert segment only
Shotcrete Robot	No	Inner Diameter	None
Drill Rigs	2 radial drill rigs	Segment Thickness	None
Other rock support	wire mesh	Ring Length	None
In L2 rock support zone		Different type of segments	None
Ribs erector		Steel ratio reinforcement	None
Shotcrete Robot		**Other**	cast-in-situ invert concrete
Drill Rigs		Thickness	
Other rock support		Steel Reinforcement	
CONSTRUCTION EXPERIENCE			
Observations **Solutions & consequencies**			

**To be completed in next edition*

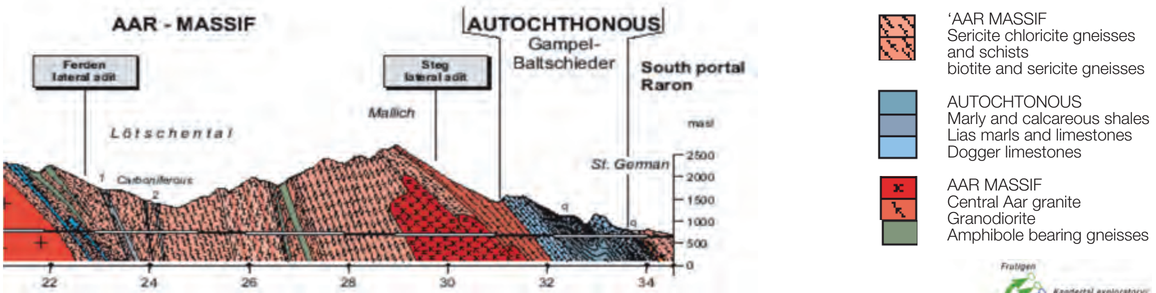
LOETSCHBERG BASE TUNNEL, SOUTH SECTION (STEG AND RARON DRIVES)

PROJECT CHARACTERISTICS

Country	Switzerland	**Tunnel Length**	8,9 and 10,0 km
Client	BLS Alptransit AG	**Ø excavated**	9,43 m
Engineers	IGWS joint venture (BG, SRP, KBM, Stucky, GEOS,…)	**Functionality**	Railway
Contractors	Matrans joint venture: Marti, Walter Gruppe, Porr, Bealfour Beatty	**TBM Type**	Hard Rock TBM with Grippers

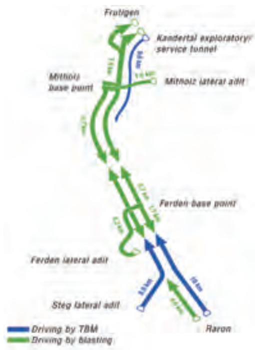
GEOLOGICAL CONDITIONS

Description	Old cristaline gneisses and schists of the Aar massiv basement, Autochtonous of Gampel-Baltschieder (Trias Limestone and Dolomite, Lias and Dogger Limestones), Central Aar massive (Granodiorite, Granite, Gneisses and Schists)
Main lithologies	Sericite chlorite Gneiss of old cristaline (Central Aar massive basement, massive to schistose) (only in the Raron drive) Trias Limestone and Dolomite, (only in the Raron drive) Lias and Dogger Limestones (marly and calcareous shales, marl and limestones, massive limestone) Granodiorite of Baltschieder, Granite of Central Aar massive (very massive), Sericite chlorite gneisses and schists of old cristaline (Central Aar massive basement with some sections of amphibolitic gneisses with asbestos in fractures)
Maximal Overburden	2000 m
Hydrological conditions	Karstic in the Limestones of the Autochtonous; the central Aar massiv was very dry probably due to the very hign overburden
Geological Profile	



Cellular dolomite (Trias of Autochtonous Gampel-Baltschieder)

Disk formation in granitic core (high overburden)



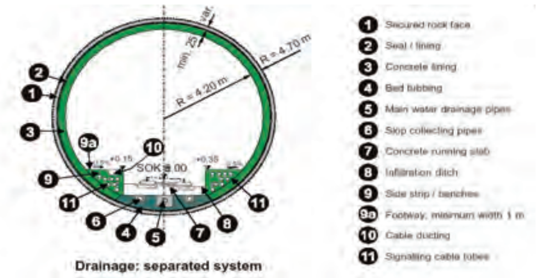
MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling	✓	Severe spalling in the central section in granodiorite, granite and gneiss.
	Rock-burst	✓	Light rock-burst in the central section in granodiorite, granite and gneiss.
Highly deformable behaviour	Buckling	✓	Severe buckling in the lias limestone, that was supposed to be a good rock, due to the unfavourable orientation of the schistosity. The TBM was near to be blocked. The section was reprofiled afterward
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure	✓	Break of one parament due to presence of a karst near the tunnel wall
	Mud inrush		
Face instability	-	✓	Due to the high stress level, frequent and sudden apparition of blocky ground section in good rock. Sometime they were no cutter mark on the face.
Environmental aspects	High temperature	✓	Asbestos in the amphibolitic gneisses

LOETSCHBERG BASE TUNNEL, SOUTH SECTION (STEG AND RARON DRIVES)

TBM DESIGN DATA

TBM specific design	Typical hard rock open TBM with two grippers. One bottom segment to install the rail for the access trains. The trailers were also supported by the rails. TBM length 20m, Total TBM length with trailers 142 m. 80m deep probe drilling equipement (inclination of 7-12% over the TBM-axis) The cutter head was adapted during excavation against blocky ground and high abrasivity (3 stops of several weeks for cutter head reparations for each drive). Installation of a first support consisting of swellex bolts and wire mesh or HEB 180 ribs, 5m behind the face (directly after the shield). Installation of shotcrete approx. 50m behind the cutter head



Drainage: separated system

Shield Characteristics		Cutterhead	
Shield Length	4 m	Nominal cutterhead diameter	9,43 m
Maximal shield diameter		Maximinal cutterhead diameter (overcut on diameter)	9,63 m
Minimal shield diameter		Number (excl. gauge cutters) and Diameter of cutterdisks	(53x1 + 4x 2) disks 17”
Shield conicity on the diameter		Total Power	3500 KW
Nominal top void		Maximal Torque	8885 MNm
Maximal top void		Torque at maximal speed	5570 MNm
		Breakaway Torque	14216 MNm
Thrust			
Total Breakaway Thrust	22 800 MN	Nb of Grippers	2
Total Service Thrust	16 000MN	Grippers Thrust	60 000 kN
Number of Thrust jacks	4	Stress Thrust	3-4 MPa
		Auxiliarry Thrust	No

SUPPORT		FINAL LINING	
Behind the tunnel face (installation distance)	5 m	**Precast segments**	
Ribs erector	1	Number of segments	No segment
Sprayed Concrete Robots	No	Inner Diameter	No segment
Bolts Rigs	2	Segment Thickness	No segment
Other support	wire mesh	Ring Length	No segment
On the back up		Different type of segments	No segment
Ribs erector	No	Steel ratio reinforcement	No segment
Sprayed Concrete Robots	2	**Other**	Cast in situ
Bolts Rigs	2	Thickness	min. 25
Other support	No	Steel Reinforcement	None

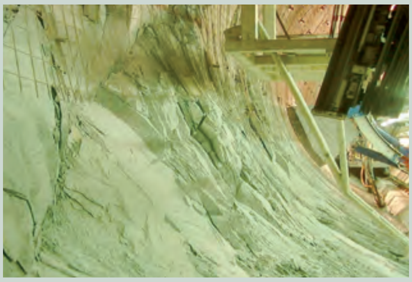
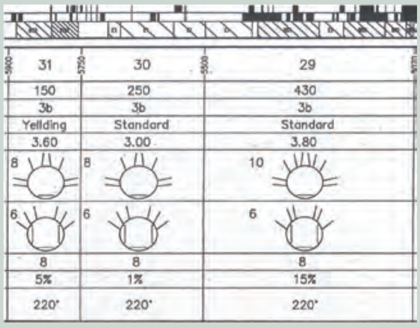
CONSTRUCTION EXPERIENCE

Observations

Buckling in foliated limestone due to unfavourable orientation. In middle orientation the excavation gave no problem, but in direction severe buckling occured and the TBM was near to be blocked. The advance fall to 54m/ per month. The east tunnel (Raron drive) was bored in parallel with a D+B tunnel on 4.5 km. On the other tube (conventional excavation) the management of the buckling was easier.

Solutions & consequencies

The support was performed with HEB 180 steel girder every m’ . Concrete was poured between the stell girder directy after installation. Additional Swellex were intalled to allow the concreting operation. 3 years after the convergence perpendicular to foliation was 60 cm. A 200m section was reexcavated before installation of the permanent concrete lining.

<table>
<tr><th colspan="2">LOETSCHBERG BASE TUNNEL, SOUTH SECTION (STEG AND RARON DRIVES)</th></tr>
<tr><th colspan="2">CONSTRUCTION EXPERIENCE</th></tr>
<tr><th>Observations</th><th>Solutions & consequencies</th></tr>
<tr><td>Vertical stress induced spalling ont walls due to high overburden. In extreme falls no cutters marks were visible on the face.
</td><td>Adaptation of the position of the ancors. Use of yelding swellex. Prediction of risk for the second drive based on the observations done on the first TBM drive

</td></tr>
<tr><td>Frequent and sudden blocky fronts due to high stress. In extreme falls no cutters marks were visible on the face. Frequent tears of the band conveyors. Dammages of the disk cutters. High abrasion.

Tunnel face without any mark of disc cutter</td><td>Adaptations and reinforcement of the cutter head (protection of the disc cutters, new plates against abrasion).
Adaptation of the transitions between band conveyors to avoid blocking due to the blocks and longitudinal tears of the band conveyors.

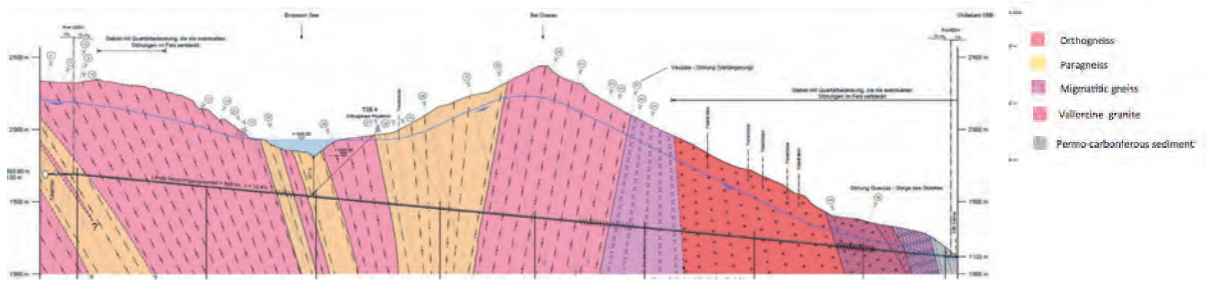
Blocks on band conveyor during boring</td></tr>
</table>

NANT DE DRANCE, PUMPED STORAGE POWER PLANT, MAIN ACCESS TUNNEL

PROJECT CHARACTERISTICS

Country	Switzerland	**Tunnel Length**	5,6 km
Client	Nant de Drance SA (Alpiq, CFF, IWB, FMV)	**Ø excavated**	9.45-9.48 m
Engineers	AF-Consult, Pöyry	**Functionality**	Road
Contractors	GMI joint venture, Marti Implenia	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

Description	The tunnel is located in the Aiguilles Rouges Massif, mainly composed of the following units: Vallorcine granite, orthogneisses and metagraywackes (paragneiss and micaceous schists). Heterogeneous sediments of the Permo-Carboniferous period (gray shale sandstone, sandy shale) for a short section (180 m) near the portal
Main lithologies	Permo-carboniferous sediment: carbonferous schists Vallorcine granite : massive granite, light radioactive Migmatitic gneiss : hornfels, hornfels-gneiss and banded gneiss Orthogneiss: massive granitic gneiss sometime withous any joint Paragneiss: finely banded metagreywacke and dark brown colored micaschists
Maximal Overburden	1050 m
Hydrological conditions	Probably more than 40 bars insitu hydrostatic pressure
Geological Profile	

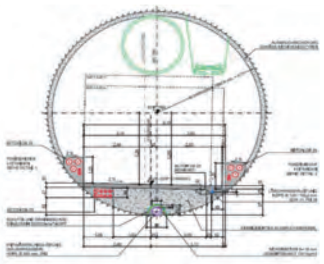
MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling	✓	Indication of light spalling over some sections (distinction between light spalling and light bucling in gneiss not always evident)
	Rock-burst		
Highly deformable behaviour	Buckling	✓	Light buckling on some section. The support on the lower right parament has been reinforced. In one tunnel the support was destroyed after the excavation of a parallel cavern.
	Squeezing		
Presence of water	Extremely high water inflow (clear water)	✓	Due to the proximity of a big arch dam (Emosson) close to the project, water flood control was essential. High water inflow has been prevented by cement grouting ahead the TBM cutter head.
	High water pressure	✓	Max. water pressure 32 bars was observed during excavation phase
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature	✓	Radioactive rock to manage (sytematic measurement to ensure the safety of the workers). Arsenic in rock, mud and water.

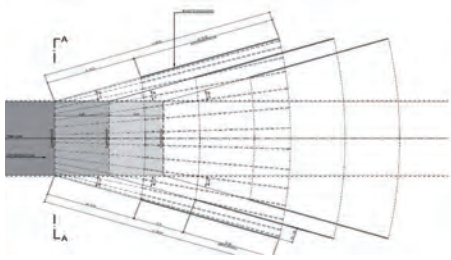
TBM specific design	Reuse of one of the Loetschberg base tunnel TBM. Typical hard rock open TBM with two grippers. The trailers design has been adapted to the tunnel inclination of 12 %. Main change was the suppression of the bottom segment (access by truck insted of acces by rail at the Loetschberg). TBM length 20m, Total TBM length with trailers 142 m. 80m deep probe drilling equipement (inclination of 7-12% over the TBM-axis) 25m deep injection drilling equipement (installation on the TBM on request). Hard rock cutter head adapted for blocky ground and high abrasivity (according to the Loetschberg experience). Installation of a first support consisting of swellex bolts and wire mesh or HEB 160-200 ribs 5m behind the face (directly after the shield). Shotcrete only in fault zone. Installation of the final support consisting of rock bolts and shotcrete approx. 50m behind the cutter head.	

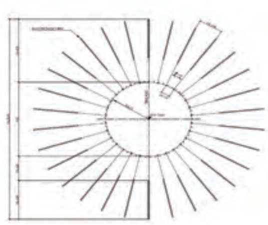
NANT DE DRANCE, PUMPED STORAGE POWER PLANT, MAIN ACCESS TUNNEL			
TBM DESIGN DATA - TBM specific design			
Shield Characteristics		**Cutterhead**	
Shield Length	4 m	Nominal cutterhead diameter	9,45 m
Maximal shield diameter		Maximum Cutterhead Diameter (overcut)	9,48 m
Minimal shield diameter		Number and Diameter of Cutters	(53x1 + 4x 2) disks 17”
Shield Extension on the Diameter		Total Power	3500 KW
Nominal gap in crown		Maximal Torque	8885 MNm
Maximum gap in crown		Torque at maximal speed	5570 MNm
		Breakaway Torque	14216 MNm
Thrust			
Total Breakaway Thrust	22 800 MN	Nb of Grippers	2
Total Service Thrust	16 000 MN	Gripper Thrust	60 000 kN
Number of Thrust Jacks	4	Stress Thrust	3-4 MPa
		Auxiliarry Thrust	None
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	5	**Precast segments**	
Ribs erector	1	Number of segments	None
Sprayed Concrete Robots	1	Inner Diameter	No segment
Bolts Rigs	2	Segment Thickness	No segment
Other support	wire mesh	Ring Length	No segment
On the back up		Different type of segments	No segment
Ribs erector		Steel ratio reinforcement	No segment
Sprayed Concrete Robots	1	**Other**	
Bolts Rigs	2	Thickness	None
Other support		Steel Reinforcement	None
CONSTRUCTION EXPERIENCE			
Observations		**Solutions & consequencies**	
Management of ground water was required in order to limit the settlement of the 180m Emosson arch dam. Systematic destructive probe drillings to detect water in advance. Water with 32 bars was found in in a probe drilling. Decision to stop the TBM and to begin injection.		Systematic grouting injection ahead of the cutter head. Lenght of injection borings was 26 m. Packers were installed at 10 m in the boreholes. After grouting of one section, the advancement step was 6 m. A section of 300m with 3 faults of 10-20 m with high water pressure was succefully injected and crossed in 9 months.	

Nant de Drance access tunnel cross section. Due to low trafic during service, the support is used as final lining.

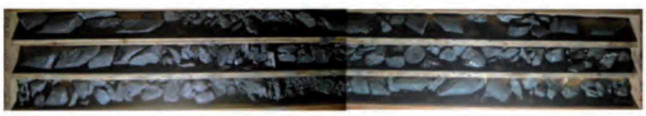


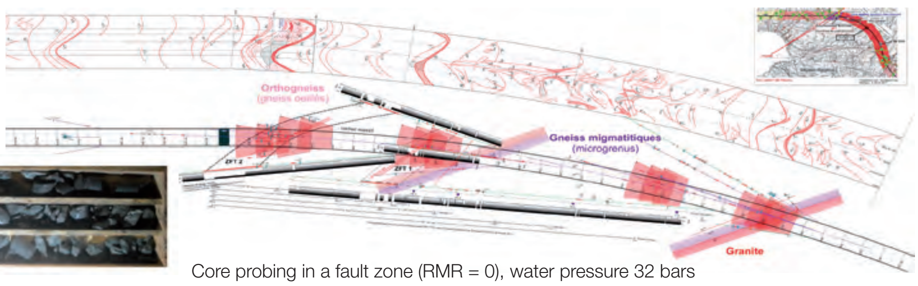
Injection pattern : only 12 hole were bored and grouted during the first step. The decision of grouting the other holes was done after analysis of the results.





Details of the injection of the veudale fault zone:
23 probe drilling (max 200m)
13 injection vaults
10’800 m injection drilling, 70 to cement
Limitation of groundwater flow 20-30 l/s
Stabilisation of hydrostatic water pressure
Total duration : 9 months





Core probing in a fault zone (RMR = 0), water pressure 32 bars

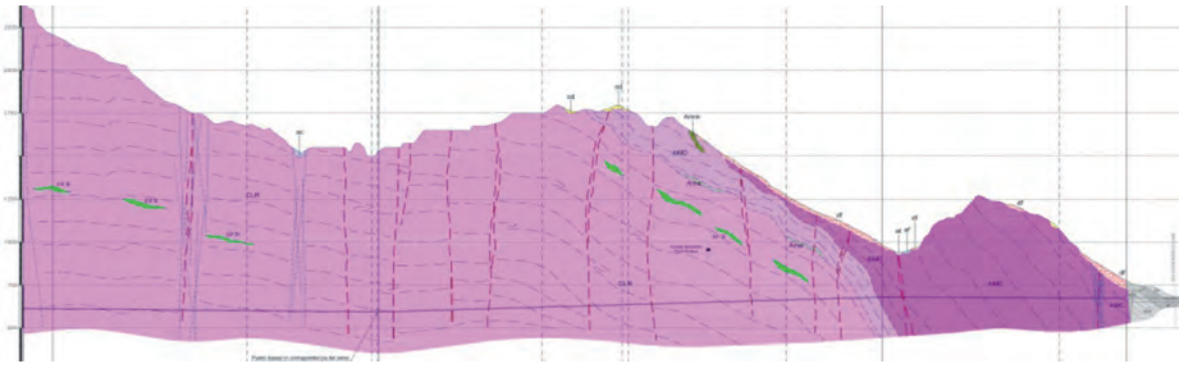
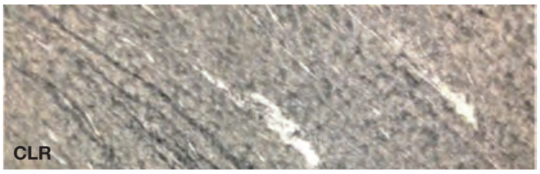
>> ANNEX 1 DATA BASE - LA MADDALENA EXPLORATORY TUNNEL 1/2

LA MADDALENA EXPLORATORY TUNNEL

PROJECT CHARACTERISTICS

Country	Italy - France	**Tunnel Length**	7597 km
Client	TELT	**Ø excavated**	4,5 m
Engineers	GEODATA (leading company) - SOTECNI	**Functionality**	Other
Contractors	CMC (leading company) - STRABAG - COGEIS - GEOTECNA	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

Description	Complex geology in the Ambin Massif of the western Alps mainly composed of micaschists and gneisses, with high overburdens of up to 2000 m and temperatures approaching 50 °C.
Main lithologies	Aplitic gneiss (AMC) - Alternation of albitic gneiss and quartz micaschist (AMD) - Micaschists (CLR)
Maximal Overburden	2012 m
Hydrological conditions	Maximum amount of water inflow 30 l/s
Geological Profile	
Representative core samples	 CLR  AMD  AMC

MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling		
	Rock-burst	✓	
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature	✓	

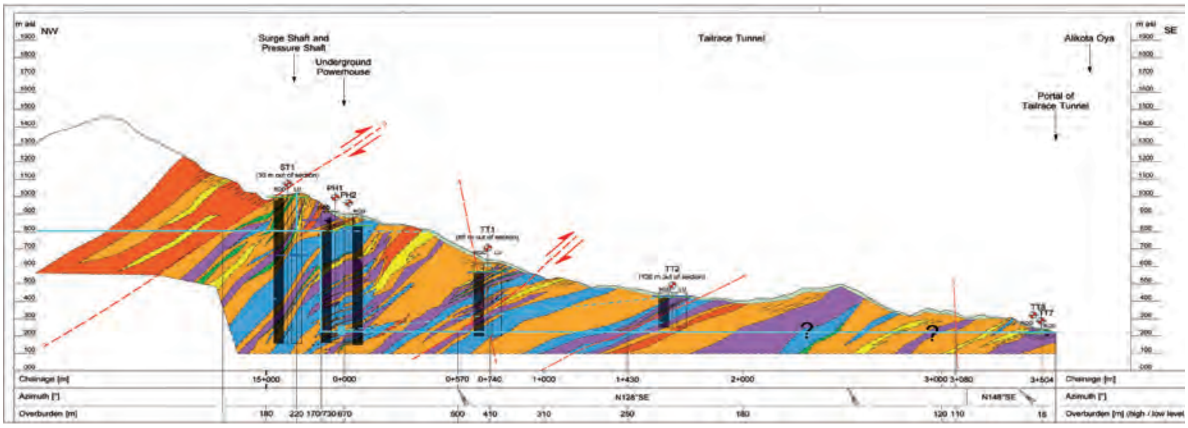
LA MADDALENA EXPLORATORY TUNNEL			
TBM DESIGN DATA			
TBM specific design	Open type TBM The peculiarities of the machine allow: • high feed rates in the presence of hard rock, thanks to the high installed power • operate forward probing of medium length, ahead of TBM • install bolts a short distance from the front • ensure the immediate support of the roof in presence of poor soils with installation of panels • launch medium-long boreholes which will be detecte and investigate geological structures 		
Shield Characteristics		**Cutterhead**	
Shield Length		Nominal cutterhead diameter	6,3 m
Maximal shield diameter		Maximinal cutterhead diameter (overcut on diameter)	6,5 m
Minimal shield diameter		Number (excl. gauge cutters) and Diameter of cutterdisks	41 cutterdisks 17”
Shield conicity on the diameter		Total Power	
Nominal top void		Maximal Torque	2082,888 MNm
Maximal top void		Torque at maximal speed	2083 MNm
		Breakaway Torque	
Thrust			
Total Breakaway Thrust	13 667 MN	Nb of Grippers	2
Total Service Thrust	12 757 MN	Grippers Thrust	1800
Number of Thrust jacks	4	Stress Thrust	
		Auxiliarry Thrust	
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	5 m	**Precast segments**	
Ribs erector		Number of segments	
Sprayed Concrete Robots		Inner Diameter	
Bolts Rigs		Segment Thickness	
Other support		Ring Length	
On the back up		Different type of segments	
Ribs erector		Steel ratio reinforcement	
Sprayed Concrete Robots		**Other**	
Bolts Rigs		Thickness	
Other support		Steel Reinforcement	
CONSTRUCTION EXPERIENCE			
Observations		**Solutions & consequencies**	
Unstable face and roof condition: detachment of block located near the tunnel face due to the high axial stress and the intersection of many joint systems parallel and perpendicular at the tunnel axis.		**MCNALLY Support System:** in order to contain the fractured rock and provided a continuous support during the excavation, the MCNALLY - system is been adopted. The system is installed in the roof and in the later section recovering an arch around 120°; it consists of steel slats anchored to the roof of the tunnel by steel straps and rock bolts, effectively containing loose and unstable rock. These steel slats form an umbrella that allows to work in a safe condition and install the section support (bolts, ribs and mesh).	

UMA OYA MULTIPURPOSE DEVELOPMENT PROJECT TAILRACE TUNNEL

PROJECT CHARACTERISTICS			
Country	Sri Lanka	**Tunnel Length**	3500 km
Client	Ministry of Power and Energy (Gov. Sri Lanka)	**Ø excavated**	4,305 m
Engineers	Pöyry / Mahab Ghodss	**Functionality**	Water supply
Contractors	0	**TBM Type**	Double Shield

GEOLOGICAL CONDITIONS	
Description	Quick change of undifferentiated charnockitic gneisses and garnet-quartz-feldspar gneisses, interlayered with marbles, calc-silicate gneisses, quartz-rich gneisses, biotite hornblende gneisses. Close to the portal of the tailrace tunnel, frequent zones of highly weathered rock mass and shear zones
Main lithologies	Charnockitic and garnet-quartz-felspar gneisses and marbles
Maximal Overburden	670 m
Hydrological conditions	High water ingress possible at shear- and fracture zones due to high secondary permeability

Geological Profile



Representative core samples

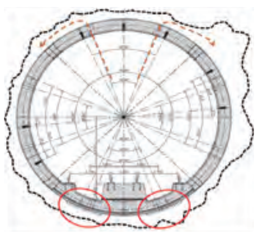
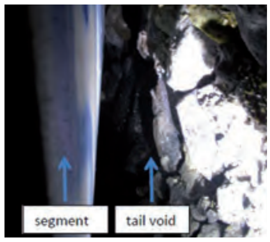
Bedrock group 1: Marbles and Calc-Silicate Gneisses

Bedrock group 2 (2.1): Biotite-Hornblende Gneiss

Bedrock group 2 (2.2): Garnet Gneisses

Bedrock group 2 (2.4): Charnockitic Gneisses

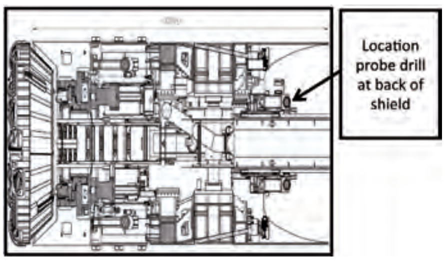
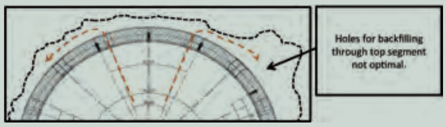
Bedrock group 3: Quartz-rich Gneisses to pure Quartzites

UMA OYA MULTIPURPOSE DEVELOPMENT PROJECT TAILRACE TUNNEL			
MAIN GEOTECHNICAL HAZARDS			
Definition of the hazard scenarios		**Occurence**	**Comments**
Brittle behaviour	Spalling		 
	Rock-burst		
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-	✓	Highly weatered rock mass (nearly residual soil) at shear- and fracture zones cause relatively large overcutting and difficulties with backfilling. At passages of highly weathered/sheared zones, gripper could not be used, forcing single mode operation. Due to difficult backfilling conditions segments show large deformations after advancing in single mode (jack forces on segments but no lateral support of segments).
Environmental aspects	High temperature		

TBM DESIGN DATA	
TBM specific design	**Double shield TBM :** Cutter head of the TBM with 27 disc cutters. TBM has two Grippers, with which the machine can be braced on to the (freshly bored) surrounding rock mass. The cutter head can be pushed into the rockface during boring by use of the Main Thrust Cylinders. This allows simultaneous building of the lining at the rear of the TBM (dual mode). If the rock mass is not strong enough to use the grippers, than the TBM is able to gradually push itself forward by generating a thrust force on the concrete lining with its Auxiliary Thrust Cylinders, in which case simultaneous excavation and ring building is not possible (single mode).

Shield Characteristics		**Cutterhead**	
Shield Length	13,018 m	Nominal cutterhead diameter	4,195 m
Maximal shield diameter	4,24 m	Maximinal cutterhead diameter (overcut on diameter)	4,275 m
Minimal shield diameter	4,18 m	Number (excl. gauge cutters) and Diameter of cutterdisks	(19x1 + 4x 2) 27 disks 17”
Shield conicity on the diameter	-	Total Power	1250 KW
Nominal top void	130 mm	Maximal Torque	2559 MNm
Maximal top void	200 mm	Torque at maximal speed	1706 MNm
		Breakaway Torque	-
Thrust			
Total Breakaway Thrust	21 287 MN	Nb of Grippers	2
Total Service Thrust		Grippers Thrust	
Number of Thrust jacks	8 main / 8 auxiliary	Stress Thrust	
		Auxiliarry Thrust	

SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	-	**Precast segments**	
Ribs erector	-	Number of segments	4
Sprayed Concrete Robots	-	Inner Diameter	3,6 m
Bolts Rigs	-	Segment Thickness	25 cm
Other support	-	Ring Length	1,2 m
On the back up		Different type of segments	3 u
Ribs erector		Steel ratio reinforcement	No
Sprayed Concrete Robots	-	**Other**	Cast in situ
Bolts Rigs	-	Thickness	0,25 cm
Other support	-	Steel Reinforcement	70-100 kg/m^3

UMA OYA MULTIPURPOSE DEVELOPMENT PROJECT TAILRACE TUNNEL	
CONSTRUCTION EXPERIENCE	
Observations	**Solutions & consequencies**
Drilling / Bolting / Injection Capacity: Probe drilling was necessary frequently. However due to the position of the probe drill installation on the erector at the back of the shield, probe drilling could not be performed efficiently. Apart from required time for installing equipment and preparing for the probe drills a relatively large distance had to be drilled before reaching the rock mass in front of the TBM. No bolting	
Annular void filling: Especially in zones where rock mass is highly fractured and/or weathered of large overcut/overbreak during excavation occurred. Backfilling up to the back of the machine up to ring N-2 proved problematic even with pea gravel. Furthermore, placement of backfilling holes in the segment was not optimal (no hole at center of top segment). Insufficient back filling caused relatively large deformations of the lining, while advancing in single mode (high pressures in auxiliary thrusters).	

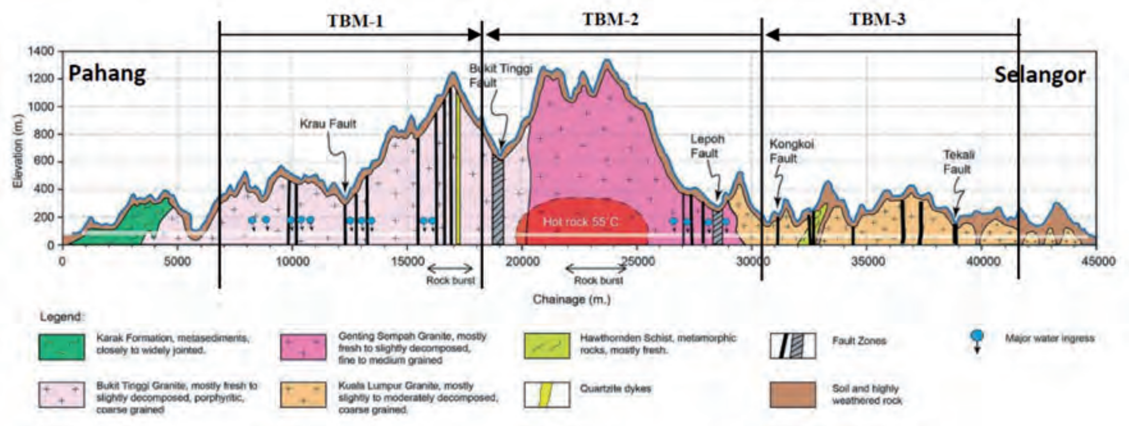
***To be completed in next edition**

PAHANG SELANGOR RAW WATER TRANSFER PROJECT

PROJECT CHARACTERISTICS

Country	Malaysia	**Tunnel Length**	44,6 km
Client	Ministry of Green Technology Malaysia	**Ø excavated**	5,2 m
Engineers	TEPSCO, SMEC, SMHB	**Functionality**	Water supply
Contractors	Shimizu-Nishimatsu-UEM-IJM JV	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

Description	Main Range Granite (Trassic period); and Karak Formation (Silurian-Devonian Period), however, all TBM section was within the Granite.
Main lithologies	Mainly strong to very strong, massive to widely jointed, fresh to moderately decomposed Granite, ranging from fine grained to coarse porphyritic Granite; locally at fault zone and quartz dykes intrusion area, rock was weak to very weak, blocky, filled with thick clay and/or completely decomposed
Maximal Overburden	1246 m
Hydrological conditions	Increase of water inflow within short period of time were anticipated at major fault zone area.
Geological Profile	

MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling	✓	
	Rock-burst	✓	
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)	✓	
	High water pressure		
	Mud inrush	✓	
Face instability	-		
Environmental aspects	High temperature	✓	

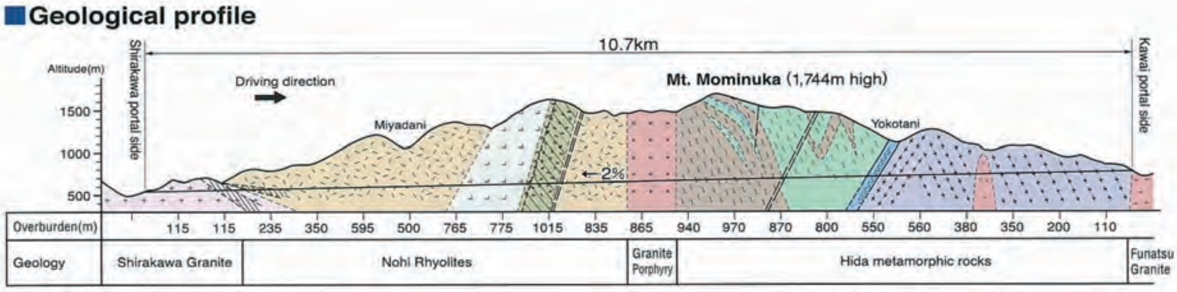
TBM DESIGN DATA

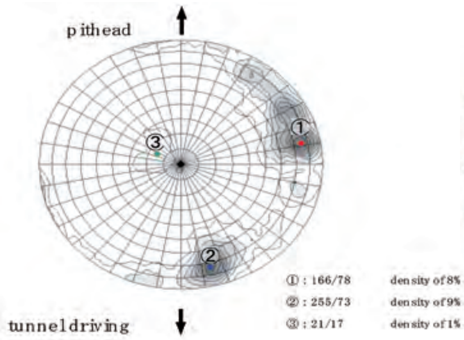
TBM specific design	• TBM shall be open-type or shield-type having a 5.2m diameter cutterhead with a complete backup system designed for intergrated operation with minimum maintenance periods for excavating more than 10km long tunneling distance through massive, hard, and abrasive rock conditions. • Numer of cutterdisks shall be more than 40nos for 17» cutterdisk.

PAHANG SELANGOR RAW WATER TRANSFER PROJECT			
TBM DESIGN DATA - TBM specific design			
Shield Characteristics		**Cutterhead**	
Shield Length	-	Nominal cutterhead diameter	5,2 m
Maximal shield diameter	-	Maximinal cutterhead diameter (overcut on diameter)	5,23 m
Minimal shield diameter	-	Number (excl. gauge cutters) and Diameter of cutterdisks	Double cutter: 17”(8nos) Single cutter: 19”(19nos)
Shield conicity on the diameter	-	Total Power	2310 KW
Nominal top void	-	Maximal Torque	4,1 MNm
Maximal top void	-	Torque at maximal speed	1,8 MNm
		Breakaway Torque	5,3 MNm
Thrust			
Total Breakaway Thrust	-	Nb of Grippers	2 nos
Total Service Thrust	14 000 MN	Grippers Thrust	18 150 kN
Number of Thrust jacks	2	Stress Thrust	No
		Auxiliarry Thrust	Invert thrust cylinder
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	5 m	**Precast segments**	
Ribs erector	1 nos	Number of segments	-
Sprayed Concrete Robots	1 nos	Inner Diameter	-
Bolts Rigs	1 nos	Segment Thickness	-
Other support		Ring Length	-
On the back up		Different type of segments	-
Ribs erector	-	Steel ratio reinforcement	-
Sprayed Concrete Robots	-	**Other**	
Bolts Rigs	-	Thickness	Depending on rock class, none to 25 cm
Other support	-	Steel Reinforcement	35 kg/m^3
CONSTRUCTION EXPERIENCE			
Observations		**Solutions & consequencies**	
Collapsing ground at major fault zone		Tunnel seismic prediction and probe drilling were carried out to detect the actual fault/weak area boundary. Control excavation and early application of fiber mortar (7m behind tunnel face), steel rib, and/or injection of forepoling were carried out.	
Excavation through constant massive groundwater inflows (max 24.6m^3/min)		Increased the drainage capacity (max 31.5m^3/min at tunnel, max 40m^3/min at TBM base) and installed back-up generator to ensure continuous operation in order to prevent TBM inundation. Seriously impacted the construction programme due to the mucking out of sediment materials which flowed with ingress water.	
Excavating through high rock temperature (Max 55°C)		Installed water-cooled air-conditioner to the TBM locomotives, passenger car, rest room and increased water-cooled air cooling system in the TBM working area. These adverse physical condition drastically decreased the TBM and workers productivity.	
Rock burst		Applied fiber mortar and wire-mesh to avoid «flying rock» from hitting the worker ; on the other hand, all personnel were prohibited to enter the cutterhead immediately after cessation of TBM excavation to allow rock-bursting inducing stresses to equilibrate.	

**To be completed in next edition*

HIDATUNNEL - MAIN TUNNEL			
PROJECT CHARACTERISTICS			
Country	Japan	**Tunnel Length**	10.7 km (TBM section 4.3)
Client	Japan Highway Public Corporation	**Ø excavated**	12,84 m
Engineers		**Functionality**	Road
Contractors	Taisei-Nishimatsu-Sato JV	**TBM Type**	Hard Rock TBM with Grippers
GEOLOGICAL CONDITIONS			
Description	very hard but includes many discontinuities		
Main lithologies			
Maximal Overburden	about 1000 m		
Hydrological conditions	Large amount of inflow from Nohi Rhyolites Maximum hydraulic pressure is 6MPa behind clay layer.		
Geological Profile			





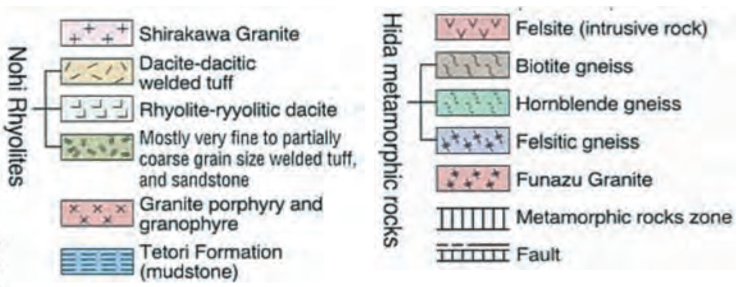
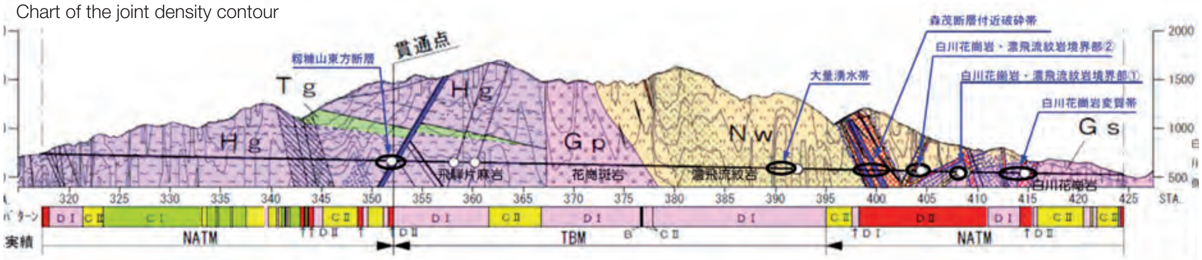
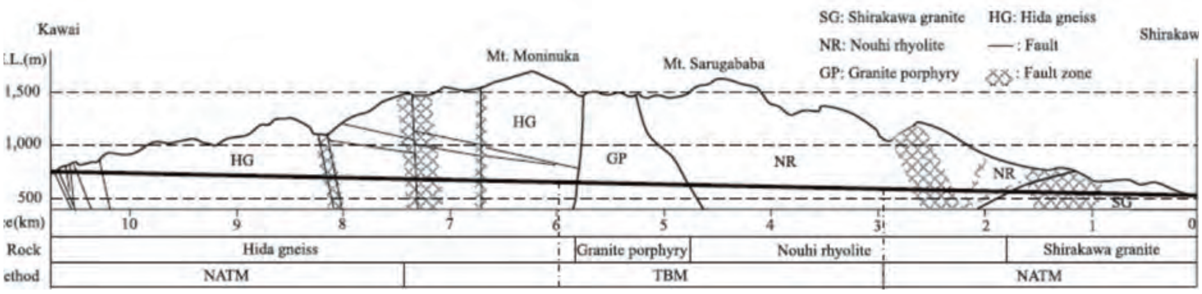


Chart of the joint density contour





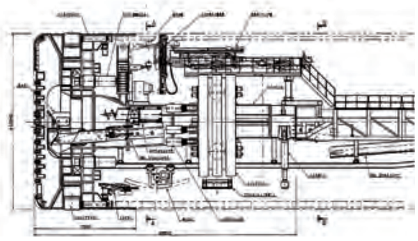
HIDATUNNEL - MAIN TUNNEL

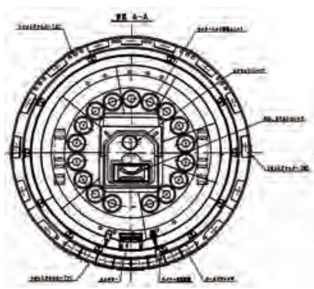
MAIN GEOTECHNICAL HAZARDS

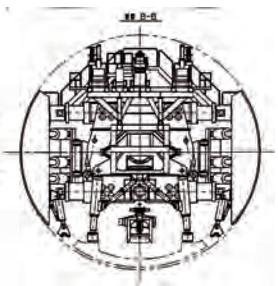
Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Brittle behaviour		
	Rock-burst	✓	Total: 12 times Tunnel face: 4 time
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)	✓	Maximum inflow : 11t/min from boring
	High water pressure	✓	Maximum pressure 6 MPa
	Mud inrush		
Face instability	-	✓	The blocks of rock fall out in the shape of a dome ahead of the face
Environmental aspects	High temperature		

TBM DESIGN DATA

TBM specific design







Improved open-type
Excavation diameter Ø 12.84m
Machine length 19.5m
Machine weight 310tons

Shield Characteristics		Cutterhead	
Shield Length	19,5 m	Nominal cutterhead diameter	12,84 m
Maximal shield diameter	12,84 m	Maximinal cutterhead diameter (overcut on diameter)	-
Minimal shield diameter	12,84 m	Number (excl. gauge cutters) and Diameter of cutterdisks	Center : 4nos, Inner : 77nos, gauge : 3 nos 19i nch
Shield conicity on the diameter	-	Total Power	4250 KW
Nominal top void	50 mm	Maximal Torque	31,84 MNm
Maximal top void	100 mm	Torque at maximal speed	-
		Breakaway Torque	10,14 MNm

Thrust

Total Breakaway Thrust	33,7 MN	Nb of Grippers	2
Total Service Thrust		Grippers Thrust	44 100 kN
Number of Thrust jacks	6	Stress Thrust	2,45 Mpa shoe pressure
		Auxiliarry Thrust	2 943 × 6 kN for friction cut

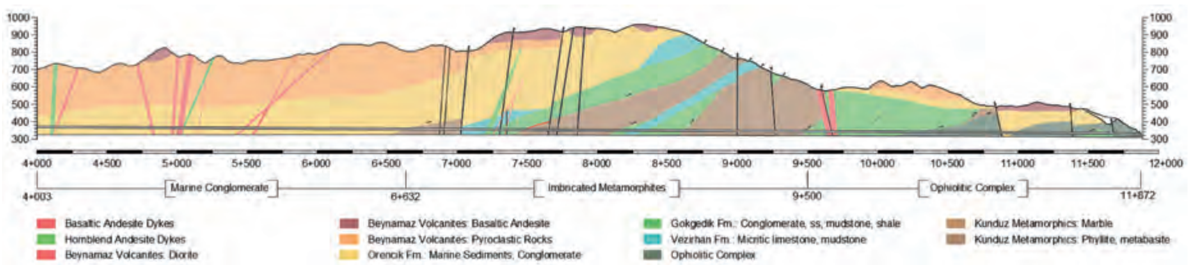
HIDATUNNEL - MAIN TUNNEL			
SUPPORT		FINAL LINING	
Behind the tunnel face (installation distance)	7,5 m	**Precast segments**	
Ribs erector		Number of segments	
Sprayed Concrete Robots		Inner Diameter	1,2 m
Bolts Rigs		Segment Thickness	25 cm
Other support		Ring Length	1 m
On the back up		Different type of segments	Invert liner u
Ribs erector		Steel ratio reinforcement	180 kg/m³
Sprayed Concrete Robots		**Other**	Cast in situ
Bolts Rigs		Thickness	30 cm
Other support		Steel Reinforcement	SFRC kg/m³

CONSTRUCTION EXPERIENCE	
Observations	**Solutions & consequencies**
Due to the structural features of discontinuities and high in situ stress states, the blocks of rock fall out in the shape of a dome ahead of the face. 	The forepilings have been applied in the zones where the joint density is large. Though the large strain has been generated in front of face in the zones where the forepiling has been adopted, it is shown quantitatively that the stability of face has been secured by the effect of the grout injection.

KARGI

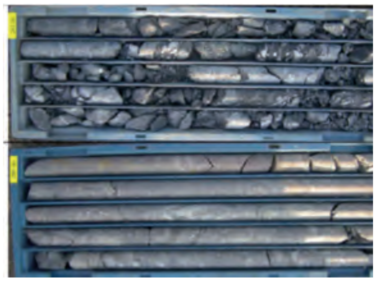
PROJECT CHARACTERISTICS			
Country	Turkey	**Tunnel Length**	11,872 (7,869 km TBM)
Client	Kargi Kizilirmak Enerji A.S. (Statkraft)	**Ø excavated**	9,84 m
Engineers	Gülermak A.S	**Functionality**	Water supply
Contractors	Gülermak A.S	**TBM Type**	Double Shield

GEOLOGICAL CONDITIONS	
Description	The tunnel route lies very close to the East-West trending main branch of the worldwide known, active North Anatolian Fault Zone and within highly tectonized area where complex ophiolitic/metamorphic rock formations are dominating around the region covered by younger volcanic and volcano-sedimentary unit. TBM encountered between km:4+003-km:6+632 Marine Conglomerate, km:6+632-km:9+500 Imbricated Metamorphites and km:9+500-km:11+872 Ophiolitic Complex.
Main lithologies	**Beynamaz Volcanites:** Diorite, basaltic andesite, pyroclastic rocks. **Orencik Formation:** Marine sediments, conglomerate. **Gokgedik Formation:** Conglomerate, sandstone, mudstone and shale. **Vezirhan Formation:** Micritic limestone and mudstone. **Ophiolitic Complex:** Tectonized serpantinite, gabbro, chert, pelagic limestone and shale. **Kunduz Metamorphics:** Marble, Phyllite, metabasite.
Maximal Overburden	610 m
Hydrological conditions	Local ground water flows in crystalline limestone-marble, meta-pelite (Meta-siltstone, shale, phyillite) contacts were recorded
Geological Profile	

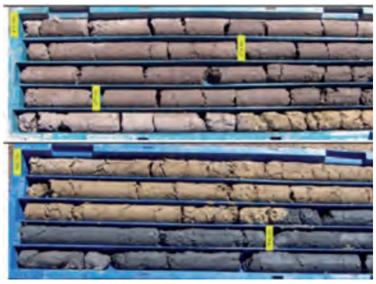


Representative core samples: Borehole SDB-3 (km:8+870)

Depth: 58,0 - 62,0 m.
Formation: Kunduz methamorphics Marbles
Description: Strong rock mass, medium to good quality, several weakness zones due to overthrust



Depth: 241,0 - 245,0 upper box, and 280,0-235,0 lower box, Kunduz methamorphics Metapelites. Weak rock mass, medium to poor / very poor quality, heavily jointed, several major waekness zones due to overthrust and shear. In some sectors the extracted rock appers fresh and with lightly jointed (see lower box)



Depth: 471,0-480,0. Kunduz Metamorphics Metapelites - Faultzone. Inorganic clays of high plasticity, fat clays. Locally inorganic clays of low to medium plasticity, gravelly clays, sandy clays, lean clays with high swelling and squeezing capacity.

MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling		
	Rock-burst		
Highly deformable behaviour	Buckling		
	Squeezing	✓	All shield squeezing and CH blockage were recorded at extensively tectonized ophiolitic rocks (km:9+500 - km:11+872) with minimum 7 days to maximum 52 days.
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature		

KARGI

TBM DESIGN DATA

TBM specific design

For the initial TBM plan it was foreseen segment lining for weak sections roughly some 3,2 km at outlet side (km:11+872 -km:8+600). For last section between Km 0+000 to km:8+600 TBM planned to work with grippers only like hard rock TBM utilizing shotcrete and conventional supports such as bolts, mesh etc. where required.

Due to problems encountered in TBM tunneling construction plan changed. In addition to modifications to TBM to cope actual conditions properly, another conventional attack face from inlet side employed to improve tunneling rates.

Additional studies and expertise works carried out by owner and contractor for identification of problems and plan counter measures / preventions and to organize remedial works. Finally power tunnel constructed as;

- km:0+000 to km:4+003 conventional method
- km:4+003 to km:11+872 TBM (all with precast segments, gripper never used)

Shield Characteristics		Cutterhead	
Shield Length	14 m with cutterhead	Nominal cutterhead diameter	9,84 m
Maximal shield diameter	9,756 m	Maximinal cutterhead diameter (overcut on diameter)	9,89 m
Minimal shield diameter	9,656 m	Number (excl. gauge cutters) and Diameter of cutterdisks	63 no and 17/20»
Shield conicity on the diameter	50 mm	Total Power	4810 (up to 5180 KW)
Nominal top void		Maximal Torque	19 (at 1,9 rpm) MNm
Maximal top void		Torque at maximal speed	8,475 (at 5 rpm) MNm
		Breakaway Torque	28 (at 1,9 rpm) MNm
Thrust			
Total Breakaway Thrust	67,88 (at 450 bar) MN	Nb of Grippers	2
Total Service Thrust	52,04 (at 345 bar) MN	Grippers Thrust	71500 per each
Number of Thrust jacks	12	Stress Thrust	5
Total Breakaway Thrust (with auxiliary)	121,30 MN (at 450 bar)	Auxiliarry Thrust	11 768 kN
Total Service Thrust (with auxiliary)	93,00 MN (at 345 bar)		
Number of Thrust Jacks auxiliary)	18		
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	12 m	**Precast segments**	
Ribs erector	not used	Number of segments	6 + 1 (key stone)
Sprayed Concrete Robots	not used	Inner Diameter	8,7 m
Bolts Rigs	not used	Segment Thickness	40 cm
Other support	precast segment liner	Ring Length	1,5 m
On the back up		Different type of segments	1 u
Ribs erector	not used	Steel ratio reinforcement	73 and 148 kg/m^3
Sprayed Concrete Robots	not used	**Other**	
Bolts Rigs	not used	Thickness	None
Other support	precast segment liner	Steel Reinforcement	None

KARGI

CONSTRUCTION EXPERIENCE

Observations

km:11+756 - CH Blockage, 45 days - maximum overburden: 35 m.
km:10+795 - Shield squeezing, 7 days - maximum overburden: 147 m.
km:10+671 - CH Blockage, 38 days - maximum overburden: 170 m.
km:10+478 - Shield squeezing, 15 days - maximum overburden: 241 m.
km:10+444- CH Blockage, 17 days - maximum overburden: 251 m.
Km:10+295 - CH Blockage, 26 days - maximum overburden: 256 m.
Km:9+712 - CH Blockage - 52 days - maximum overburden: 240 m.

	Advancement (m)		
Km:	11+872 - 9+500	9+500 - 6+632	6+632 - 4+003
	Tectonized Ophiolitc Rocks	Imbricated Metamorphites	Conglomerate
The Best Daily Adv. (m)	28.50	39.00	34.50
The Average Daily Adv.(m)	4.24	19.00	16.60
The Best Monthly Adv. (m)	330.00	660.00	723.20
The Average Monthly Adv. (m)	126.60	569.80	500.60 (*647.14)

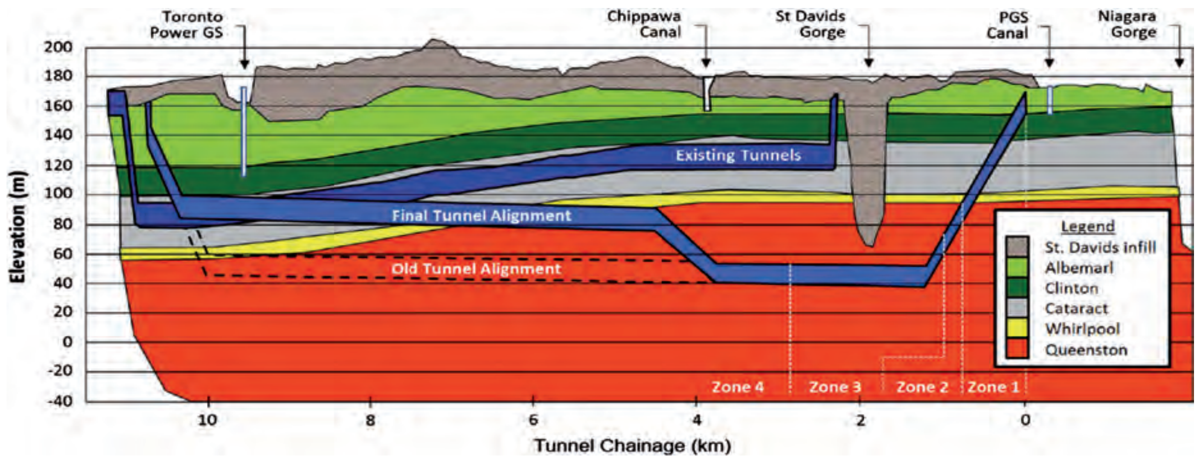
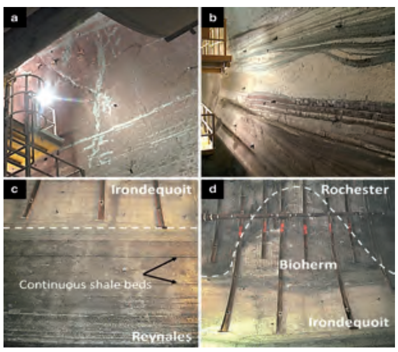
*Excluding main bearing repair delay

Solutions & consequencies

All squeezing and CH blockage phenomenas occured at extensively tectonize ophiolitic rocks (Serpantinite, gabbro, chert, pelagic limestone, shale and thrust faults. Note that this phenomena occured somitimes in low overburden, thus most probably horizantal stress is greater than vertical stress.The TBM rescued with recovery galleries, and below listed G74modifications applied by time.

- Probe Drilling System: Before modification, drilling is carried out by hand and only penetration rate is visually monitored. To overcome this problem an automatic system for self-drilling, dampening system and data logging system had been added, so that it became possible to drill automatically and to collect data such as penetration rate, percussion pressure, rotation pressure, feed pressure, dampening pressure data.
- Increased Thrust and Cutterhead Torque: Additional 19 short stroke cylinders were added and they provide 50% more thrust than normal thrust when TBM is squeezed. So additional gearbox were mounted to the TBM in order to set free the blocked cutter head easily. Torque capacity was increase by 2.4 times and it is electronically limited to only increase torque to 170% for 10 second interval each two minutes. Gearboxes were dismantled after poor ground conditions to restrict maximum speed.
- Additional Drive Motor: Number of the electro motors for cutter head drive was increased to 14 (the preceding one 13) and total power was 5180kW (14x370kW).
- Shield Lubrication: Shield Lubrication was applied in order that reduce friction angle between shield and ground. Therefore, holes were opened through the shield skin to extrude lubrication and pumping system was set. Bentonite and chemicals was used as a lubrication materials.
- Overbore Capabilities: Excavation diameter of the TBM was increased by shimming the outermost gauge cutters. And excavation diameter was increased by 50 mm (total 105 mm) when it was necessary. This system was implemented in order to going ahead before being caught by the squeezing ground.
- Umbrella Drilling and Ground Injection System: For providing to drill and to place fore-poles 11 holes were opened on the top section in the front shield.
- Scalar For Excavated Material: A scalar which includes a load cell was placed to the conveyor belt. So that it became possible to know if there is over excavation or collapse in front of the TBM

NIAGARA TUNNEL PROJECT			
PROJECT CHARACTERISTICS			
Country	Canada	**Tunnel Length**	10,4 km
Client	Ontario Power Generation (OPG)	**Ø excavated**	14,4 m
Engineers	Hatch Mott MacDonald	**Functionality**	Other
Contractors	Strabag AG	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS	
Description	The new tunnel passes under the St. David's Buried Gorge, at roughly 140 m below ground surface, crossing down through the Lockport to Whirlpool Formations and into the upper 60 m of the Queenston Formation before making its ascent back toward the surface.
Main lithologies	Queenston formation: Mudstone and siltstone. Cataract Group including Whirlpool, Power Glen, and Grimsby Formations: Marine sediments, limestone. Clinton Group including Rochester and Irondequit Formations: Dolomitic limestone, calcareous shale, dolomite, sandstone. Albemarle Group including Lockport and Decew Formations: Crystalline dolomitic limestone and mudstone.
Maximal Overburden	140 m
Hydrological conditions	The Decew dolomite has a distinct contact with the underlying Rochester Formation. Water flowing through the karst channels at this contact was a construciton challenge.
Geological Profile (showing revised alignment)	
Representative observational samples	A) reduction banding (greenish grey bands) within the Queenston Formation. Note that the sub-vertical to vertical joints were only observed in the upper most ~50 m of the Queenston. B) Complex interbeds of shale within the Thorold sandstone, C) two continuous, thin shale beds,\0.020 m thick, in the upper Reynales Formation, and D) a bioherm (Irondequoit limestone) protruding up into the Rochester Formation 

MAIN GEOTECHNICAL HAZARDS			
Definition of the hazard scenarios		**Occurence**	**Comments**
Brittle behaviour	Spalling	✓	Seen in Whirlpool-Queenston contact zone, St. David's Gorge, and high stress zones, these overbreak areas were generally seen as the result of stress-induced spalling.
	Overbreak	✓	Overbreak in Queenston Formation associated with formations or interbedded layers less than 50 Mpa UCS. The thickness of the weaker layers determined the depth of the overbreak. The overbreak can be described as gravity slabbing with assistance from stress-induced fracture growth.
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	-		
Environmental aspects	High temperature		

NIAGARA TUNNEL PROJECT

TBM DESIGN DATA

TBM specific design

For the construction of the Niagara Tunnel Project, Strabag A.G. purchased a new Robbins High Performance (HP) Main Beam TBM, and a new H.P. back-up system provided by Rowa Tunnel Logistics A.G. of Wangen, Switzerland. The TBM Model 471-316, nicknamed “Big Becky,” is the world’s largest hard rock TBM ever manufactured. Design of the HP machine included the use of 20” rear mounted cutters, high cutterhead power and state-of-the-art ground support equipment. For ground support, a rotary-type ring beam erector was provided in the L1 area directly behind the TBM cutterhead support. The erector could hydraulically lift the ring beam or channel section into place and hydraulically expand the steel sections against the rock. Also in the L1 area, a dual-function wire mesh erector and material handling cart was provided, as well as two Atlas Copco rock drills installed on 6 m slides. A shotcrete robot supplied by Rowa/Meyco was also supplied in the L1 area that could cover a 180-degree section of the tunnel crown at a rate of 20 cubic meters per hour. In the L-2 area on the back-up, another two drills were provided as well as two more remote-controlled shotcrete robots with 360-degree coverage.

Shield Characteristics		Cutterhead	
Machine Length	45 m	Nominal cutterhead diameter	14,44 m
Back-up length	105 m	Maximinal cutterhead diameter (overcut on diameter)	
Minimal shield diameter		Number and Diameter of cutterdisks	85 no and 20/17»
Shield conicity on the diameter		Total Power	4722 KW
Nominal top void		Maximal Torque	18.8 (at 2.4 rpm) MNm
Maximal top void		Torque at maximal speed	9.025 (at 5.0 rpm) MNm
		Breakaway Torque	
Thrust			
Cutterhead Thrust	19 MN	Nb of Grippers	2
Maximum Cutterhead Thrust	28 MN	Grippers Thrust	
		Stress Thrust	21
		Auxiliarry Thrust	
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)	5 m	**Precast segments**	
Ribs erector	steel channels	Number of segments	6 + 1 (key stone)
Sprayed Concrete Robots	one, top 180 degrees	Inner Diameter	8,7 m
Bolts Rigs	rock bolts up to 6 m long	Segment Thickness	40 cm
Other support	wire mesh 50 mm thick	Ring Length	1,5 m
On the back up		Different type of segments	1 u
Ribs erector	not used	Steel ratio reinforcement	73 and 148 kg/m^3
Sprayed Concrete Robots	two shotcrete robots	**Other**	Cast in situ
Bolts Rigs	two additional drills	Thickness	60
Other support		Steel Reinforcement	Polyolefin waterproof lining

NIAGARA TUNNEL PROJECT

CONSTRUCTION EXPERIENCE

Observations	Solutions & consequencies

Observations

The actual TBM performance on this project was considered quite good, with the machine achieving a world record for TBMs over 11 m in diameter in July 2009.

Best Shift	Best Day	Best Week	Best Month
14 meters	25.4 meters	153.2 meters	467.8 meters

The cutter life was also considered to be good. The total number of cutter changed was 788, or 2,100 cubic meters per cutter. There were some problems with the cutters in the upper rock formations, however. The cutters were prematurely blocked due to the cement-like effect of the fines and water. The wet rock fines and water packed around cutters as is normal, but special problems arose because of the consistency of the fines and the chemical content of the rock. Within a few hours of downtime, the fines hardened into a cement-like mixture, causing cutters not to turn when the cutterhead rotation was restarted. A foaming system was prepared as a corrective action but the situation eventually self-corrected as the machine moved into another rock formation.

Rotation was restarted. A foaming system was prepared as a corrective action but the situation eventually self-corrected as the machine moved into another rock formation.

There were no major mechanical problems with the TBM. There were no major interventions for cutterhead repair, and there were no main bearing or main gear problems as a result of design. Most gear reducers lasted the complete project. There were some problems with the variable frequency drives in the early stages of boring. Due to some erratic steering in difficult ground, the main beam was overstressed and at one point had to be repaired. The machine mined for 6,700 hours and, considering it was inundated with scaled down rock for approximately 3,000 meters, the equipment had very good availability.

Over-break above the TBM

The revised ground support system.

Solutions & consequencies

After about 793 m of excavation the TBM entered the Queenston shale formation, where large rock blocks started to fall from the crown before rock support could be placed. In some cases, significant over-break up to 3 m above the cutterhead support was reported. There was a contractual requirement to scale down loose rock before lining could be placed. The TBM was not set-up to scale down loose rock over the cutterhead or to place ground support outside the periphery of the bore. The ground support system was modified while excavation continued, from essential access by platform system to access by man bucket system.

Strabag ultimately designed a unique ground support system to cope with the geology, which consisted of 9 m long pipe spiles in an umbrella pattern at the crown of the tunnel. Using the new spiling method, over-break was limited to about 0.9 m above the normal tunnel diameter. Nearly 500 m of very difficult ground was excavated using this method, at average rates of about 3 m per day.

The new ground support program, done for all excavated ground, consisted of 3 to 4 m long rock bolts, self-drilling (IBO) anchor bolts, steel straps, wire mesh and wire-reinforced shotcrete. Crews typically bored half a stroke, then began scaling down loose rock and installing rock bolts. After the full 1.8 m stroke, the rest of the loose rock was scaled down before installing more rock bolts, wire mesh, steel straps and a layer of shotcrete.

OPG and the contractor also opted to alter the vertical alignment of the tunnel, raising it 46 m to move the tunnel out of the Queenston shale. After 1,981 m, rock conditions were competent enough that spiling was no longer required.

On large diameter TBMs there has to be a lot of attention to ground support.What we have learned from the Niagara project and other large bore projects is the following:

- Face fall out is a regular occurrence because rock jointing, fissures, jointing etc. and the combination of loose rock at the face on a large area exasperate the condition. It can be expected that rock fall out will extend beyond the periphery of the tunnel in the cutterhead area.
- The rock support system needs to be flexible and adjustable for various types of rock support. The final rock support system at Niagara accommodated this requirement.
- If acceptable, hold loose rock in place. This can be done by rock bolting and the McNally System or a combination of this and other systems (see Figure 10).
- New shotcrete type systems with non-rebound shotcrete material are available that are user friendly and TBM friendly and effective in the cutterhead area.
- Think of an NATM approach for rock support, even though the TBM is in the tunnel.

LESOTHO HIGHLANDS WATER PROJECT

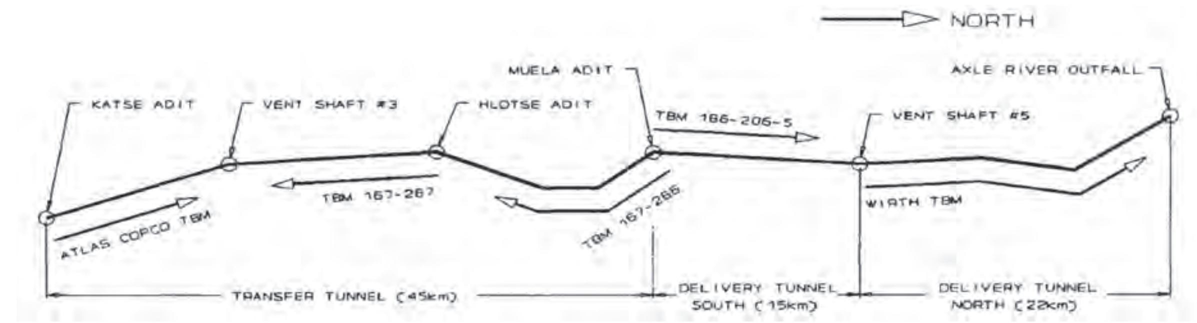
PROJECT CHARACTERISTICS

Country	Lesotho	**Tunnel Length**	82 km
Client	Lesotho Highlands Development Authority /Trans Caledon Tunnel Authority	**Ø excavated**	5 m
Engineers	Hatch Mott MacDonald	**Functionality**	Water supply
Contractors	LHPC (Spie Batignolles/LTA Ltd./Ed Zublin/Balfour Beatty /Campenon Bernard JV)	**TBM Type**	Hard Rock TBM with Grippers

GEOLOGICAL CONDITIONS

Description	Phase 1A began construction in 1991, which involved building the 180 m high Katse Dam, as well as approximately 82 km of TBM-driven tunnels to provide water to South Africa's arid Gaucheng Province. Tunneling operations consist of three main tunnels: The 15 km Delivery Tunnel South (DTS), the 22 km Delivery Tunnel North (DTN), and the 45 km long Water Transfer Tunnel. A total of five hard rock TBMs bored these tunnels--four of them open-type gripper machines from Robbins and one shielded TBM provided by Wirth.
Main lithologies	**Water Transfer Tunnel--Lesotho/Drakensberg Formation:** Basaltic flows, volcanic rock with variable amygdaloidal content, blocky conditions with faulted areas and doleritic dykes. 80-176 MPa UCS. **South Delivery Tunnel**--Stormberg Group, Upper Formation of the Karoo Sequence, a deposit formation in the Karoo Basin: Sedimentary Rock. Clarens Formation: Sandstone with compressive strengths between 20 and 180 MPa. **North Delivery Tunnel**--Elliot and Molteno Formations: Silt, Sand, and Claystones. Beaufort Group: Claystones.
Maximal Overburden	1200 m
Hydrological conditions	Water inflows were mainly experienced in the South Delivery Tunnel from faults and fissures in sandstone.

Geological Profile



Geological Conditions

Project Area Geology

Basalt Type	Modulus GPA Mean	Modulus GPA S.D.	Poissons Ratio	Uniaxial Compressive Strength, MPA Mean	Uniaxial Compressive Strength, MPA S.D.	Brazilian Tensile Strength, MPA Mean	Brazilian Tensile Strength, MPA S.D.	Cherchar Abrasivity Index
1 Doleritic Basalt	51 (4)	2	0.29 (1)	176 (9)	58	15 (15)	2	1.7 - 2.4
2 Basalt with intrusions	43 (57)	12	0.31 (12)	123 (60)	45	12 (50)	3	1.3 - 1.8
4 Moderately Amygdaloidal Basalt	38 (43)	14	0.23 (9)	104 (41)	35	11 (41)	4	1.6
5 Highly Amygdaloidal Basalt	25 (62)	13	0.22 (12)	85 (58)	33	8 (55)	4	0.8
Dolerite	74 (6)	7	0.24 (1)	172 (7)	103	17 (6)	5	3.3 - 3.5
Tuff	13 (1)			80 (1)		4 (1)		n.a.

Rock mechanical test results, from tender documents (Volume 5.1 Contract No. LHDA 124) and from Geotest Laboratory. (Number of samples in brackets.)

MAIN GEOTECHNICAL HAZARDS

Definition of the hazard scenarios		Occurence	Comments
Brittle behaviour	Spalling		
	Overbreak		
Highly deformable behaviour	Buckling		
	Squeezing		
Presence of water	Extremely high water inflow (clear water)		
	High water pressure		
	Mud inrush		
Face instability	Blocky rock	✓	Mainly in the transfer tunnel; blocky rock at the face and rock falls from the crown area.
Environmental aspects	High temperature		

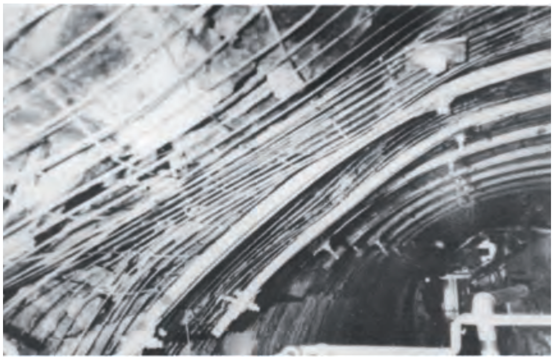
LESOTHO HIGHLANDS WATER PROJECT			
TBM DESIGN DATA			
TBM specific design	Based on the geological conditions in the water transfer and South Delivery Tunnels, it was clear the TBMs should be open-type machines. The first of the Robbins machines, the -206, was rebuilt by Harrison Western Corp and shipped to the jobsite in 1991. A Jarva (Kelly type) MK 15 machine followed that, along with two identical open-type machines, the -266 and -267. The machines were supplied with back-loading cutterheads and could be used with either 432 or 483 mm diameter discs. The 483 mm diameter cutters could achieve a cutter load of 312 kN for difficult ground where increased power might be needed. The machines offered flexible ground support options--on the -266/-267 machines a probe drill mounted on a 7 m long sliding deck about 20 m behind the cutterhead allowed for probe drilling concurrent with TBM advance. The machines were designed to be able to support the tunnel walls with a combination of rock bolts, wire mesh, and ring beams as required. 		
TBM specific design (-206, MK 15, -266/267)			
Shield Characteristics		**Cutterhead**	
Shield Length		Nominal cutterhead diameter	5.18/5.0/5.0 m
Back-up length		Maximinal cutterhead diameter (overcut on diameter)	
Minimal shield diameter		Number and Diameter of cutterdisks	37 no. 17», 34 no. 17», 31 no. 17» or 19» m
Shield conicity on the diameter		Total Power	1110/1680/1575
Nominal top void		Maximal Torque	1.336/1.588/1.475
Maximal top void		Torque at maximal speed	
		Breakaway Torque	
Thrust			
Cutterhead Thrust	7.4/8.3/9.7 MN	Nb of Grippers	2/4/2
Maximum Cutterhead Thrust		Grippers Thrust	
		Stress Thrust	
		Auxiliarry Thrust	
SUPPORT		**FINAL LINING**	
Behind the tunnel face (installation distance)		**Precast segments**	
Ribs erector	steel channels	Number of segments	
Sprayed Concrete Robots	yes, in difficult ground	Inner Diameter	
Bolts Rigs	systematic rock bolts	Segment Thickness	
Other support	wire mesh	Ring Length	
On the back up		Different type of segments	
Ribs erector		Steel ratio reinforcement	
Sprayed Concrete Robots		**Other**	
Bolts Rigs	one additional	Thickness	
Other support		Steel Reinforcement	

LESOTHO HIGHLANDS WATER PROJECT

CONSTRUCTION EXPERIENCE

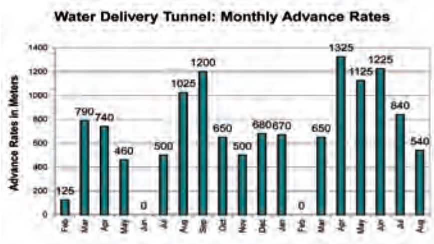
Observations	Solutions & consequencies

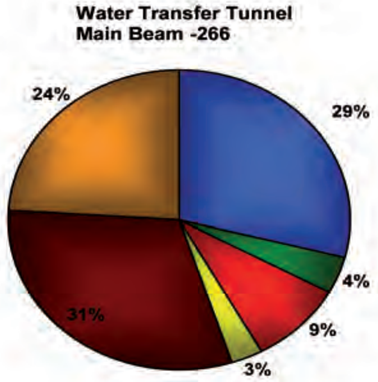
Overall, the TBMs performed well, but the worst conditions were experienced in the transfer tunnel. Poor ground was most liked to be encountered in a mixed face where dolerite sills or dykes occurred in basalt rock. Ring breakages were high in such situations. Where blocky rock was encountered, loose rocks in the face tended to be ground rather than chipped, and this resulted in more wear on the cutters. Both crazing and random closely spaced joints caused problems, as crazing leads to deterioration of basalt when exposed to air or water and with time results in sloughing. Crazing was most notable in the invert where there was a constant flow of water from the rock. In some areas of the invert, crazing lifted track segments for the service trains. Random closely spaced jointing were also a problem because they could caused large wedges to break from the crown and sidewalls. Rockbolts up to 2.5 m in length were thus used in these areas. as well as wire mesh to prevent rock from falling from the crown. Some rock spalling occurred in sections of the transfer tunnels as well; this did not occur in the zones of greatest overburden, but under relatively shallow cover of 120 m where the horizontal stress exceeded the vertical stress. Several dykes were encountered during the excavation, but few required grouting. Lastly, under the zone of greatest overburden (1200 m), the rock temperature rose to 42 degrees Celsius, requiring a large refrigeration unit to keep the temperature at the face below 27 degrees Celsius.
On the South Delivery Tunnel, conditions were better and the machine performed well. The maximum daily advance was 81.9 m, compared to the expected daily advance of 23 m. The excavation program finished 20 months ahead of the scheduled completion date. High groundwater inflows occurred in areas on the drive from fissures and faults in the sandstone, requiring grouting. This included a zone 900 m in length just before breakthough where the TBM encountered weaker fractured rock in contact with underlying formations. About 65 to 70 tonnes of cement grout were injected to reduce inflows of 1880 liters/min at pressures up to 8 bar. Rock support included everything from tensional rock bolts 1.5 m in length (Class I ground) to systemative support with rock bolts 1.8 m long, mesh, and 50 mm of shotcrete (Class IV ground). Support class V was rarely encountered and used 1.0 m long end-anchored bolts in addition to other support.

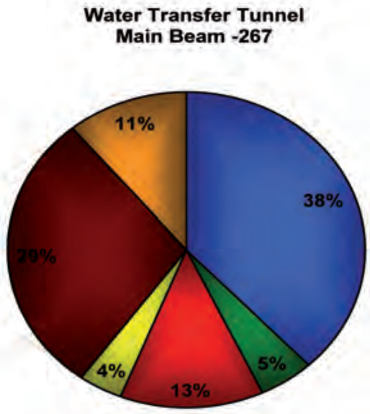


Cracking of basalt in transfer tunnel

Final TBM breakthrough in October 1994







longrine 04 90 14 48 48 - (21619 - 05/17)

ITA Secretariat c/o EPFL - Bât. GC - Station 18 - CH - 1015 Lausanne - Tel. : + 41 21 693 23 10 - Fax : + 41 21 693 41 53
Email : secretariat@ita-aites.org - Web : www.ita-aites.org