DS Compact TBM dealing with complex and unexpected geology in Los Bronces Exploratory Tunnel

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In 2008 a new type of TBM system (Double Shield Compact TBM) was developed by SELI for the excavation of exploratory and hydraulic tunnels in variable rock conditions.
This type of TBM was selected by the Dragados-Besalco Consortium to excavate the 8 km long exploratory tunnel in Chile for Los Bronces mine, one of the largest copper mines in the world owned by Anglo American.
The 4,5 m diameter exploratory tunnel runs at an elevation of 3.600 m a.s.l. and crosses a variety of geological formations of hard and sound rocks with few predicted faults.
The logistic difficulty of accessing the site, the restricted spaces for the portal installations and the required flexibility in relation to geology and rock supports have been the main reasons for the selection of this type of TBM system.

Figure 1. Los Bronces mine

GEOLOGY AND ROCK SUPPORTS

The tunnel crosses several geological formations.
Figure 2 below shows the foreseen tunnel geological profile.

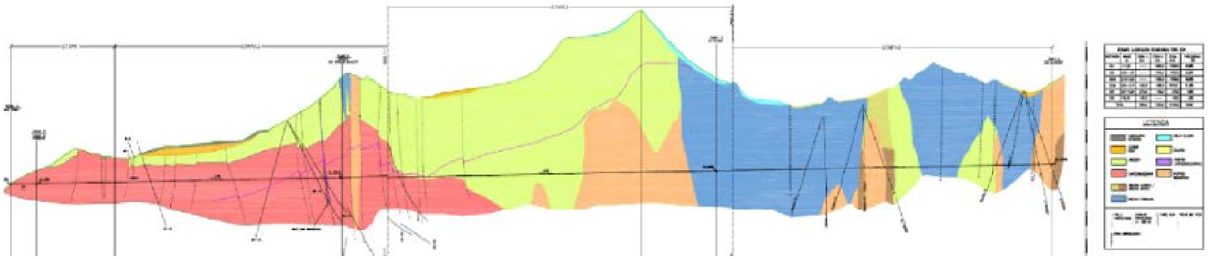


Figure 2. Geological profile

Basically, the following formations were foreseen:

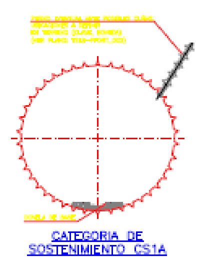
Quartz monzonite for 3.150 m
Andesite for 1.700 m
Rhyodacite porphyry for 1.300 m
Tourmaline breccia for 1.850 m
Chlorite breccia for 100 m
Faults for 25 m

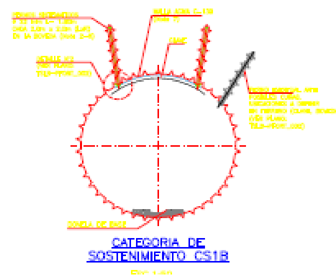
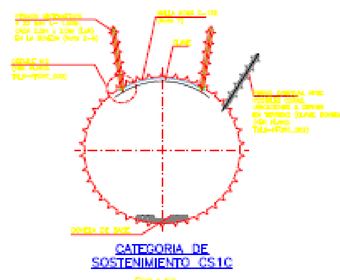
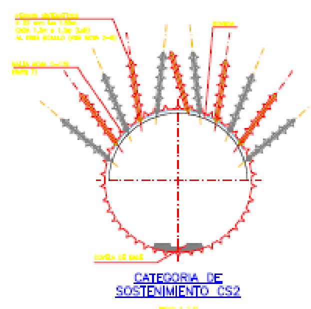
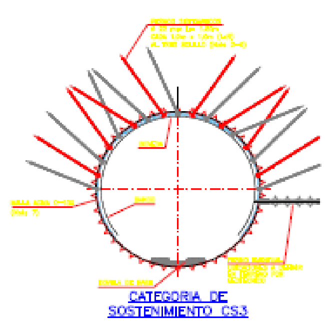
The following table resumes the foreseen characteristics of the different formations:

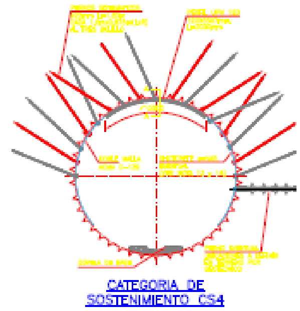
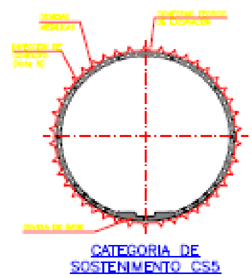
Table 1. Rock characteristics

	γ (gr/cm3)	UCS (MPa)	CLI	quartz content	porosity
Quartz monzonite	2,75	200	10	10%	2%
Andesite	2,8	80 – 150	55	10%	2%
Rhyodacite porphyry	2,55	130 – 200	10	10%	2%
Tourmaline breccia	2,55	75 – 150	10	10%	2%
Chlorite breccia	2,75	125	25	10%	2%
Faults	2,6	100	15	10%	2%

According to the foreseen geology and to the TBM characteristic and features the following rock support system was associated to the different rock classes.

Rock Class	Q factor (Barton)	Rock quality	Rock support	Typical section
Ia	> 10	From Exceptionally Good To Good	CS1A	

Ib	10 – 4	Regular	CS1B	
Ic	4 – 2	Bad	CS1C	
II	2 - 0,4	Very Bad (+)	CS2	
III	0,4 – 0,1	Very Bad (-)	CS3	

IV	0,1 - 0,03	Extremely Bad	CS4	
V	< 0,03	Exceptionally Bad	CS5	

TBM DESIGN AND OPERATIONAL FEATURES

The DSC TBM system consists of an integrated set of equipment composed by:

a. DS Compact TBM

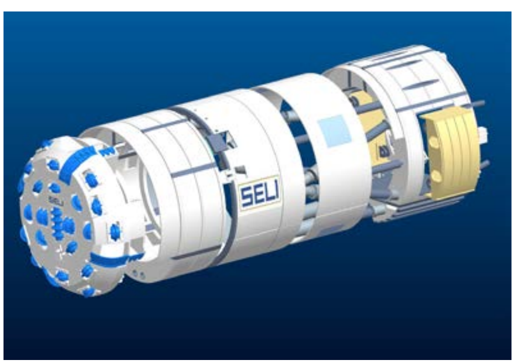


Figure 3. TBM overview

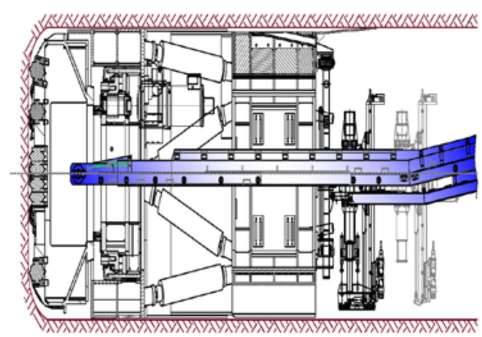


Figure 4. TBM longitudinal section

i. The TBM is a special Double Shield TBM having the following characteristics:

- Extremely short total shields length
- Robust 19” discs cutterhead design
- High main and auxiliary thrust capacity
- Variable Frequency Cutterhead drive
- Long life main components
- Simplified hydraulic and electric circuits
- Two roof drills mounting for rock bolting
- Probe drill mounting for 360° treatment/drainage holes
- Erector for liner plates
- Guidance system for accurate steering
- Bolted structures to facilitate dismounting and transport back inside the tunnel

ii. The TBM specifications are:

- Boring Diameter - 4.500 mm
- Boring Stroke - 1.400 mm
- Cutting Parure - n°27 * 19” Cutters (300 kN/each)
- Maximum Main Thrust – 15.700 kN
- Maximum Auxiliary Thrust - 14.300 kN
- Cutterhead Power- 1575 kW
- Cutterhead Rpm - 0-7,4 Rpm
- Cutterhead Torque - 2.612 kNm (3.395 kNm Unlocking)
- Conveyor Capacity- 320 ton/h
- Maximum Penetration Rate: 120 mm/min

b. Back Up System

It is extremely short (typical length varies from 50 to 65 m depending on muck transport system and optional components).

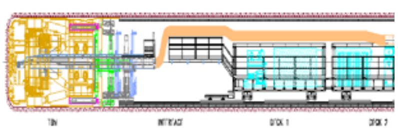


Figure 5. TBM & Back-up longitudinal section

The back-up is made of few decks, for a total of 7, and includes:

- The TBM facilities (Control cabin, lube and hydraulic power packs, VFD units, Cabinets and Trafos)
- The muck conveyor
- The dust scrubber with capacity to treat the entire volume of air arriving in the tunnel pipeline
- The industrial water system
- The HV cable reel
- Water and Compressed Air hose reels
- Ventilation Duct extension/storage unit (not used in this machine)
- Materials crane systems
- Safety walkways
- The tunnel conveyor extension station

The decks are pre-assembled units that allow a very fast assembly and disassembly of the system. A complete assembled deck fits into the container dimensions.

c. Muck Transport system

The back-up conveyor discharges directly into the tunnel conveyor system.
The extension of the tunnel conveyor structures is performed in the last 2 decks of the back-up contemporary with the TBM advance.

TBM MOBILIZATION AND ASSEMBLY

As per the initial design the tunnel was originally divided in two parts: the first 800 m to be executed by traditional method (drill & blast), while the remaining 7.325 m by mechanical method (TBM).
These lengths were progressively modified and finally the drill & blast excavated section was reduced down to 185 m, while correspondingly the TBM bored section augmented to 7.940 m.
This adjustment was the consequence of three aspects mainly:

- The delay in drill & blast excavation due to the adverse climatic and logistic conditions,
- The arrival on site of the TBM & Back-up
- The extreme difficult ground conditions encountered in this initial tunnels section that led the Contractor to advance rates less than 1,5 m/day.

The TBM was then assembled in a smaller than foreseen underground cavern and in August 2009 was ready to bore. To be noted the extremely severe working conditions imposed by the Client (Compulsory mine rules).
For instance:

- each shift rests for a warm meal to be consumed in the external canteen;
- the change of the shift is done at the tunnel entrance;
- at the shift entrance a regular safety meeting is attended.

Figure 6. Climatic conditions

Figure 7. Underground assembly

Figure 8. TBM portal and access road

ADVANCE WITH DSC COMPACT TBM IN CRITICAL GEOLOGICAL CONDITIONS

The TBM, immediately at the start of excavation (actually after a dozen of meters in relatively good rock) entered in a very disturbed area in very adverse geological conditions with continuous face collapses.

Basically the TBM had to cross a very intensively faulted zone with prismatic fragments of rock having a size of few centimetres size mixed with clayish material.

No water inflows were experienced in this area, although the filling material was saturated. No cohesion, no friction. The TBM excavation was performed with no significant pressure on the main trust cylinders.

Figure 9. Face collapse

Figure 10. Blocks on Shield

The installation of liner plates, as primary support, was immediate as well as the foam injection through the cutterhead to fill cavity created by the collapsing ground.
Despite the high rock instabilities the TBM was always in the condition to use gripper pads to advance and it was not necessary to utilise the Single Shield Mode.

Figure 11. Collapse at the rear shield

Figure 12. Intruding debris at the invert placing

The liner plates

The liner plates are composed by 9 “steel panels”, eight of them with an angular development of 36° while the remaining one has about 33°.

The longitudinal length is 1.400mm, while the circumferential length is about 13.696mm.

The internal diameter is about 4.162mm, while the external diameter is about 4.362mm.

Panels are connected among them and among adjacent rings by bolts.

The liner plates are completed in the bottom by a prefabricated concrete invert segment and the connection among it and the steel panels is granted by a screw anchoring system.

A dedicated mechanical erector boom was installing the liner plates, thus leaving the crew always in safety position during critical operations. Sometimes foam injection has been required even to fill gap between the liner plates and the rock.

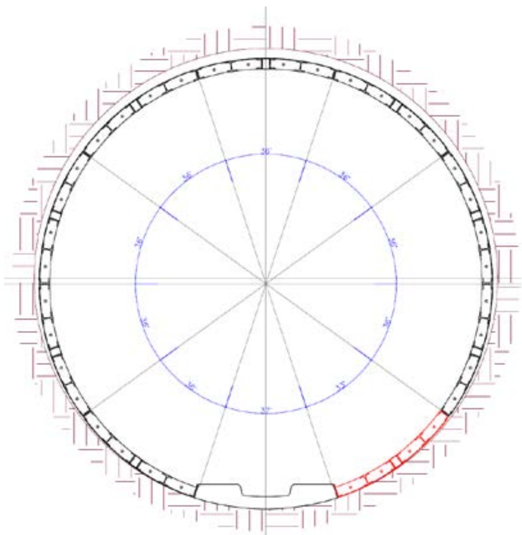


Figure 13. Steel set design

Figure 14. Steel set roof erection

The foam

The use of foam is a great and necessary help to overcome difficult conditions when boring in rock formations.

The foams were used in this initial faulty area to fill the voids and consolidate/support the tunnel face.

The injected material was a fire-resistant bi-component foam (ratio 1:1) with an expansion rate up to 10 times of the initial volume and a reaction time of 30 sec. Hardening is reported between 2 and 5 minutes. The expansion reaction is not affected by water presence.

Figure 15. Filling cavity at the front face

Figure 16. Consolidated material at the cutterhead bucket

As an additional precaution, during the crossing of this very difficult stretch the TBM advancing strokes were partialized to reduce risks connected with a TBM "too long" (see figures 17 and 18).

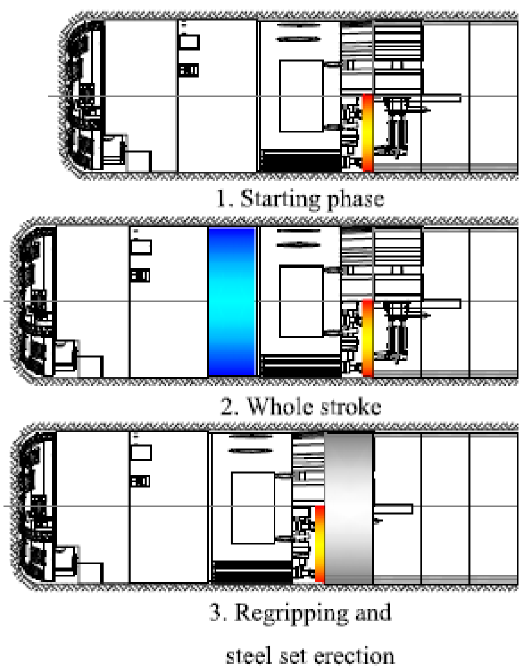


Figure 17. Regular advance

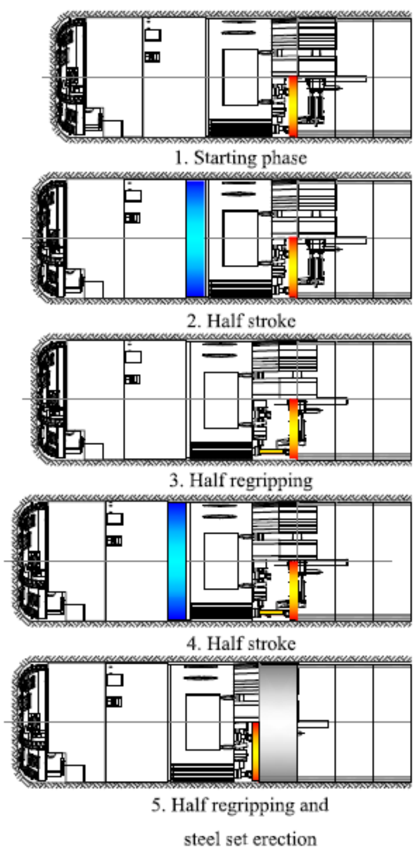


Figure 18. Precautionary advance

The faulty area started at chainage 207 and finish at chainage 521, requiring the installation of 224 liner plates rings; the available working days were 110 thus achieving a production rate of 2,9 m/day, nearly double than Drill & Blast advance.

TBM SPECIAL MEASURES TO FACE THE EXTREME GEOLOGICAL CONDITIONS

Due to the adverse geological conditions, three special mitigation measures were carried on the TBM, namely:

- Extension of the fingers of the tail shield to support the rock while assembling the liner plates.
- Strengthening of the TBM conveyor's hopper, its supports, its structure to better resist to the continuous shocks of the rock blocks entering the cutterhead.
- Overcutting by spacing out the three peripheral cutters that were displaced up to 2 cm and increase excavation diameter

Figure 19. Rock support CS5

MODIFICATION OF THE TUNNEL ALIGNMENT

The adverse and unexpected geology that was encountered since the beginning of the Los Bronces Tunnel excavation convinced the Project Owner to move the tunnel alignment toward higher overburden in supposedly better rock conditions. The original alignment was left at chainage 487 adding two curves of 500m radius. The original and the modified tunnel alignments are shown in figure 20 below.

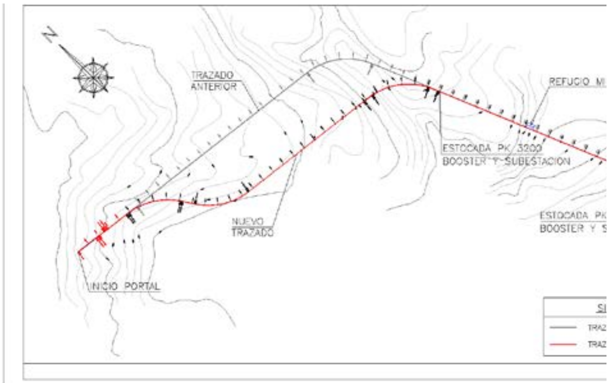


Figure 20. Original and actual tunnel alignments

ADVANCE WITH TBM COMPACT WITH WATER INFLOW

Despite the alignment modification, the TBM, after having advanced about 300m in reasonably good rock, encountered very heavy water inflows in excess of 100 lt/sec at the face. Although it was not a overwhelming quantity, the inflow was carrying a lot of rock debris complicating the invert cleaning and the segment installation. Additional pumping stations were installed as well as a 400mm diameter steel pipe up to the external portal to avoid flooding of the underground yard's structure.

Figure 21. Water and debris at the invert placing

Figure 22. Additional pumping station

TBM and Back-up were not affected by this occurrence and only minor electrical breakdowns consequent to the water inflows were reported.
Probe drill was regularly performed and overlapped to detect and drain water in advance.

Figure 23. Probe drill's dedicated boom

Figure 24. Probe drilling

The high water inflows occurrence was experienced between chainage 830 and chainage 970.

Similar occurrences (150 lt/sec) appear from chainage 1290 to 1600 (aprox. 1140-1450 of the original alignment). From chainage 1600 up 2340 minor water inflows (up to 50 lt/sec) were recorded.

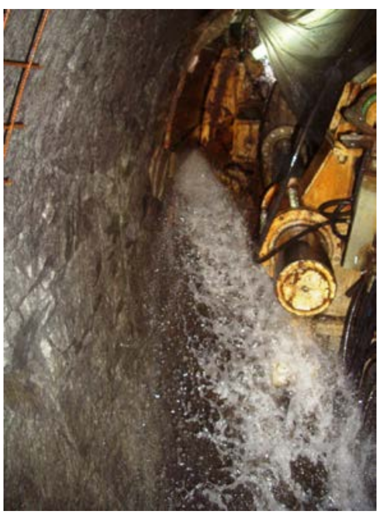


Figure 25. Concentrated water inflow

Figure 26. Distributed water inflow

Considering the available working days (189) this stretch (2236m) was performed with a production rate of 11,8 m/day with a penetration rate of 2,44 m/h.

TBM PERFORMANCES IN QUARTZ MONZONITE ROCK

As a whole, the section bored by TBM in **Quartz Monzonite** formation can be summarized as follows:

Table 2. Quartz Monzonite Features		
	Predicted	**Actual**
Length	2965 m	2573 m
Average overburden	280 m	360 m
Rock support I	0	35%
II	5,4%	44,8%
III	84,8%	6%
IV	9,8%	1%
V	0	13,2%
Cutter Life Index	10	4,9

Beside the initial section in excavated in faulty ground and the sections in fissured rock with heavy ground water, the monzonite formation demonstrates to be very hard and abrasive.

TBM PERFORMANCES IN ANDESITE ROCK

From chainage 2758 (late in September 2010) the expected **Andesite** formation was encountered.
The quality of the rock, with no water appearances, has to be considered good, as summarized in the following preliminary table.

Table 3. Andesite Features		
	Predicted	**Actual (2010 Dec. 10th)**
Length	1300 m	528 m
Average overburden	820 m	650 m
Rock support I	1,5%	0
II	98,5%	100%
III	0	0
IV	0	0
V	0	0
Cutter Life Index	55	8,3

Considering the available working days (24), this stretch (528m) was performed with a production rate of 22 m/day with a penetration rate of 2,55 m/h.

Figure 27. Rock support CS 2

Figure 28. Tunnel appearance (CS5 and CS 2) just at the B/U rear

CONCLUSIONS

- The challenge to bore an exploratory tunnel in the Andean mountains was successful in demonstrating that the DSU Compact TBM was the most adequate machine to face logistic restrictions as well as different rock conditions and supports.
- The DSU Compact TBM (and crew) demonstrated to overcome situations where Q factor was calculated as < 0,03 with the erection of liner plates as primary support, as well as to perform under constant water inflows with wire mesh and rock bolts as primary support.
- DSU Compact TBM has in sound rock the same potentiality of an open TBM while maintains in bad rock the flexibility of a double shield TBM, and this gave confidence of success to the Project's participants.
- The Project Owner was extremely satisfied as far as the safety of the technology is concerned: during this excavation period only 5 accidents were reported with 59 men · days lost.
- At the time being, Owner is discussing with Main Contractor to extend tunnel for 3 more kilometres.