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Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)

The longest Robodrilled tunnel in the world

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ABSTRACT: The excavation in the lot named "Mules 2-3", being the biggest construction lot of the BBT Italian side, has been done by the "traditional method", which is including drill & blast and parts of consolidation & excavation under faulty zones. The works are related to the excavation and lining of the Access Gallery at the Trens Emergency Stop, Exploratory Tunnel, Main Tunnel south direction east and west tube and 19 Connecting Side Tunnels linking the two main tubes. In total ca.12 km. The use of Robodrill has improved the technologies adopted in order to fulfil the challenging needs of the job site. The paper will report about various data related to the production and costs in the different working sections, taking in account, for example, synthetic information about explosive consumption, drilling material, spritz beton and consequent lining concrete overconsumption.

1 INTRODUCTION

The Brenner Base Tunnel forms the central part of the Munich-Verona railway corridor. The project as a whole consists of a straight, flat railway tunnel, which reaches a length of 55 km and connects Fortezza (Italy) to Innsbruck (Austria); next to Innsbruck, the tunnel will interconnect with the existing railway bypass and will therefore reach a total extension of 64 km.

The tunnel configuration includes two main single-track tubes, which run parallel and 70 m across each other in most of the track, and connected to each other every 333 m by side tunnels.

Between the two main tunnels, and running 12 meters below them, an exploratory tunnel preliminary construction. The exploratory tunnel's main function during the construction phase is to provide detailed information about the rock mass; its position also allows it to perform important logistic support during the construction of the main tunnel, for the transport of the excavated material as well as for the transport of construction materials. During the operations, it will be essential for the drainage of the main tunnel.

In the next years, CIPA will perform most of the tunnel excavations in the lot named "Mules 2-3" by "traditional method". In addition to being the biggest construction lot of the Brenner Base Tunnel, it is the main part of the route on the Italian side, between the border of the State on the North (km 32.0+88 tube East) and the adjacent lot "Isarco river Underpass", on the South (km 54.0+15 tube west). Main tunnel configuration are shown in Fig. 1.

The works Cipa is responsible for are:

– Excavation and lining of the Access Gallery at the Trens emergency stop and the Central Tunnel, with a total length of approx. 4,500 m;

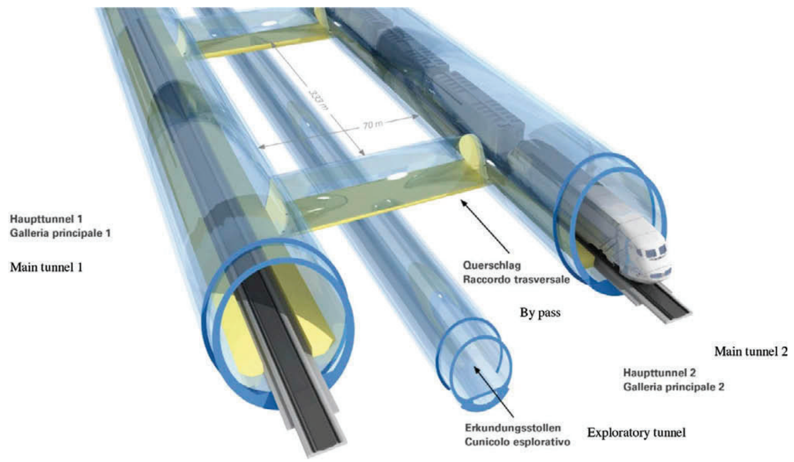

Figure 1. Main Brenner Basis tunnels configuration.

- Excavation and lining of the Exploratory Tunnel by traditional method, with a total length of approx. 830 m;
- Excavation and lining of the Main Tunnel, South direction East tube and West tube, in single track section, with a total length of approx. 7,320 m;
- Excavation and lining of the Main Tunnel, South direction East tube and West tube, in double track section, with a total length of approx. 2,590 m;
- Excavation and lining of 19 Connecting Side Tunnels linking the two main tubes, with a total length of approx. 900 m.

2 GEOLOGICAL DESCRIPTION

As anticipated, the Brenner Base Tunnel is the high-speed rail link between Italy and Austria, and therefore to Northern Europe. It consists of a system of tunnels, which include two one-track tubes, a service/exploratory tunnel that runs 12 m below and mostly parallel to the two main tunnels and bypasses between the two main tubes placed every 333 m, and three emergency stops located roughly 20 km apart from each other. The bypasses and the emergency stops are the heart of the safety system for the operational phase of this line.

Overburden is, on average, between 900 and 1000 m, with the highest points about 1800 m at the border between Italy and Austria.

The excavation will drive through all the geological formations that make up the eastern Alpine Area. Most of these are metamorphic rocks, consisting of Phyllites (22%), Schist (Carbonate Schist and Phyllite Schist, 41%) and Gneiss of various origin (14%). In addition, there are important amounts of plutonic rock (Brixen Granite and Tonalite, 14%) and rocks with various degrees of metamorphism, such as marble (9%).

Among the tectonic structures in Italy, we find the above-mentioned Periadriatic Fault. As stated, the unknown characteristics of the rock masses along this stretch lead to excavate the exploratory tunnel long before the main tunnels, allowing identification of the lithological sequences of the various types of rock mass within this heavily tectonized zone, as well as a study of their responses to excavation. These studies were subsequently useful to adjust the consolidation and support measures both for the exploratory tunnel and for the main tubes. The excavation of the exploratory tunnel inside the Periadriatic Faults allowed determining the actual sequence of lithologies within this area.

Fig. 2 shows a summary of the encountered rock sequences.

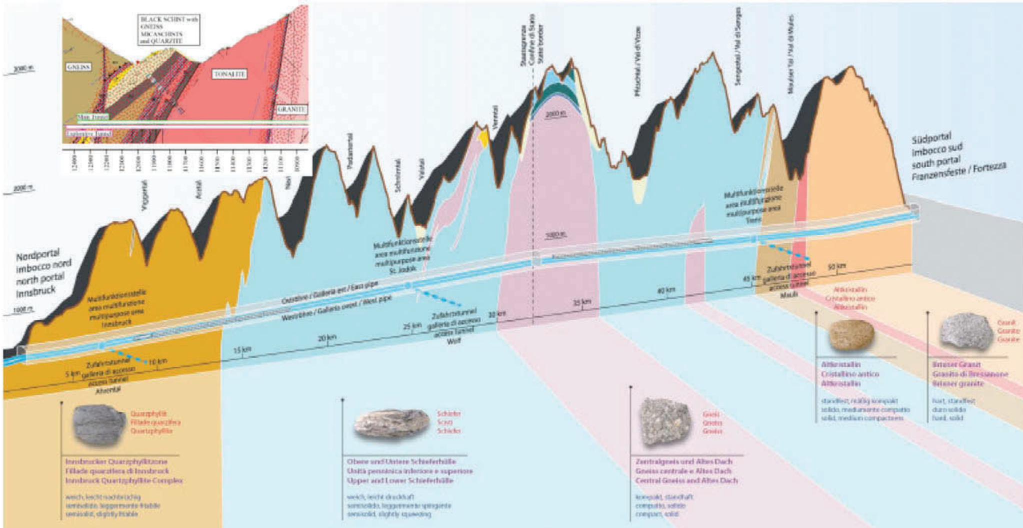

Figure 2. The geological sequence.

3 ACCESS TUNNEL AND TRENS CENTRAL CROSS PASSAGE

Access tunnel (GA), ending in the Trens Emergency Stop, whose length is approx. 3,805 m, starts in the Mules Adit (in a diversion tunnel at 1,4+79 m). After a long parallel and straight stretch to the West Main Tunnel, GA ends at the starting point of the Trens Central Cross Passage (CcT), ca. 680m long and linked with the Transversal Trens Cavern.

GA is excavated in full section, variable from 85 up to 105 sqm (Fig. 3), while CcT section has from 88 to 170 sqm but it’s excavated partialzed.

Fresh air pumps through the Access Tunnel along the technical areas and in the Emergency Stop. In case of need, exhaust fumes are available for use from the Emergency Stop, too. The realization of the design of the separation of the two airflows used an intermediary slab (35 m thickness, 830 m length).

The tunnel then lines with a 41 cm thick concrete for definitive train use.

Access Tunnel (GA) and Trens Central Cross (CcT), from South to North, cross the following homogenous geological rock formation sectors: Brixen Granite (km 3+800 - 3+150 circa GA), Pusteria’s Fault (km 3+150 - 2+950 circa GA), Mules’ Tonaliti (km 2+950 - 2+350 GA), Mules Valley Fault, South (km 2+350 - 1+780 GA), Austrian-Alps Parascists and Anfibolites (km 1+780 - 0+200 GA), Superior Schieferhülle Calcescists and Anfibolites (km 0+200 GA - km 0 CcT). First drilling (blasting) and supporting are shown in Fig. 4.

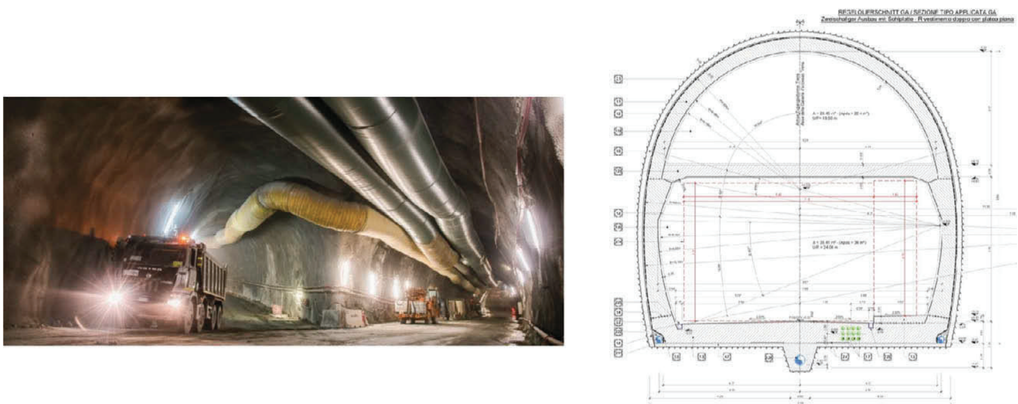

Figure 3. GA typical section and mucking out in the same tunnel.

Figure 4. First drilling (blasting) and supporting operations with Robodrill in GA Trens.

3.1 *GA Trens – consumptions and overconsumptions*

Synthetic data reported:

- Explosive consumption index: 1,30 kg/m^3
- Explosive type: Nonel detonators, emulsion and gelatin
- Explosive cost index: approx. 8,20 euro/m^3
- Average over excavation compared to the theoretical design profile: approx. +76 %
- Drill & blast consumable costs index: approx. 0,45 euro per drilled meter
- Spritz beton overconsumption compared to the theoretical designed thickness: approx. +25 %

There is to note that the average excavation radius increased is in the range of 25 cm, the cause relies on the geological conditions. Spritz beton overconsumption is very low due to the frequent steel arches absence.

4 EXPLORATORY TUNNEL IN ROBODRILLED METHOD

The final design states that the excavation and lining of the Exploratory Tunnel in the section between pk10+419 (connection with the Mules emergency access) and pk13+060, is carried out with the "traditional method". In this section, in fact, the excavation crosses the fault of "Val di Mules" first, and then a rock mass with better geo mechanical characteristics characterized by the presence of Parascists (the covers in this section vary from a minimum of 600 m up to a maximum of 1,135 m).

The excavation of the tunnel section between pk10+419 and pk12+459 already occurred within the Lot Mules 1. CIPA has been entrusted with the excavation and lining of the section from pk12+459 to pk13+060 (for a total length of approx. 600 m) with an excavation front section between 30 to 39sqm, two logistic chambers between pk12+580 and pk12+605 and between pk12+930 and pk12+955 (with an excavation section of approx. 80 sqm), as well as a cavern between pk13+000 and pk13+060 (with an excavation section of 137 sqm) inside which the first shielded TBM has been assembled for the mechanized excavation of the next section included in the lot "Mules 2-3".

The excavation works began in February 2017; during the first 8 months, CIPA almost entirely completed the planned section of approximately 600m, with an average production of 2.5 m/day and with the following typical sections:

- In the section between pk12+459 and pk12+524 ("Val di Mules" fault) section type CT-5 (Fig. 5), excavation with excavator and demolition hammer, maximum steps of 1.50 m, laying of steel ribs with profile type 2 x IPN160, fiber-reinforced shotcrete 5cm thick +

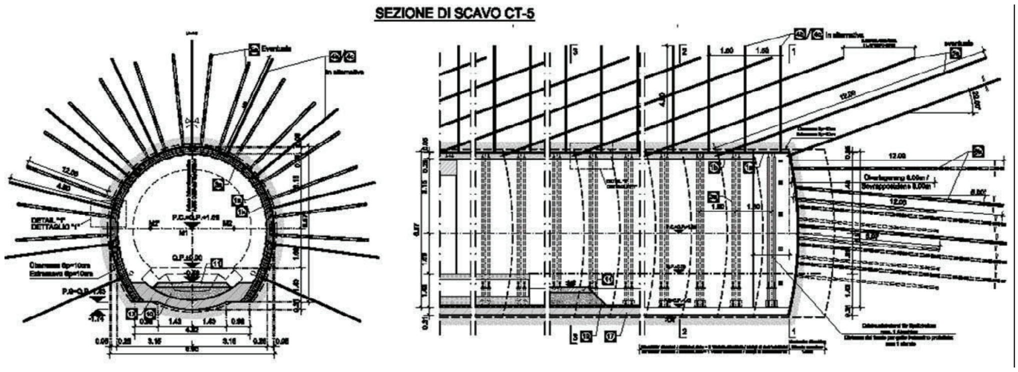

Figure 5. Typical CT-5 section.

25cm at the edge and 5cm at the front, pre-consolidation at the front with 26 self-drilling bars R51, pre-consolidation at the edge with 16 self-drilling bars R51 and radial consolidation with 11 self-drilling bars R38.

– In the section between pk12+459 and pk12+524 ("Val di Mules" fault) section type C-T5, excavation with excavator and demolition hammer, maximum steps of 1.50 m, laying steel ribs with profile type 2 x IPN160, fiber-reinforced shotcrete 5cm thick + 25cm at the edge and 5cm at the front, pre-consolidation at the front with 26 self-drilling bars R51, pre-consolidation at the edge with 16 self-drilling bars R51 and radial consolidation with 11 self-drilling bars R38.
– In the section between pk12+524 and pk12+569 section type C-T4, blasting excavation with maximum steps 1.5 m, laying steel ribs profile type 2 x IPN160, fiber-reinforced shotcrete 5cm thick + 25cm in the crown and 5cm at the front, radial consolidation with 11 rock bolts type Swellex PM24 L = 4.5 m. In Fig. 6 are shown some operative pictures in confined space.

For the excavation works and primary lining works, the following are the used equipment in the tunnel front:

– 1 Jumbo ROBODRILL with two booms for the drilling, for the blasting and for the rock bolting;
– 1 crawler excavator Hitachi ZX135 for digging, loading and unloading operations in the current section, equipped with a demolition hammer, bucket and hydraulic shears for bolt cutting at the front of the excavation;
– 1 crawler excavator Hitachi ZX240 for digging, loading and unloading operations in the bigger sections as logistic chambers and cavern (Fig. 7).
– 1 wheel loader Hitachi ZW310 and 4 trucks with 4-axle (which transport the excavated material to the logistic chambers for primary crushing);
– 1 shotcrete pump Cifa CSS3 for spraying the shotcrete;
– 1 telescopic handler Pegasus with man basket Fops.

Figure 6. Excavation in a narrow and confined space and self drilling anchors with a 2 boom Robo Jumbo.

Figure 7. Mucking out in the Exploratory tunnel after the drilling for blast execution.

The realization of the final lining of the entire sections (except for the invert in the fault zone that built along with the excavation) will occur by means of a formwork panels and shoring towers only after the excavation with the TBM.

4.1 *Exploratory tunnel – consumptions and overconsumptions*

Summarized data reported:

- Explosive consumption index Sez. CT3 (ca. 29 m^2): 2,06 kg/m^3
- Explosive type: Nonel detonators, emulsion and gelatine
- Explosive cost index: approx. 13,50 $euro/m^3$
- Explosive consumption index Sez. PL-C-T3 (ca. 72 m^2): 1,06 kg/m^3
- Explosive cost index: approx. 8,10 $euro/m^3$
- Explosive consumption index Sez. CMC-T3 (ca. 138 m^2): 1,06 kg/m^3
- Explosive cost index: approx. 7,10 $euro/m^3$
- Average over excavation compared to the theoretical design profile: approx. +80 %
- Drill consumable costs index (in the self-drilling zone): approx. 1,10 euro per drilled meter
- Drill & blast consumable costs index: approx. 0,27 euro per drilled meter
- Spritz beton overconsumption compared to the theoretical designed thickness: approx. +22 %

There is to note that the average excavation radius increased is in the range of 25 cm, the cause appointed to the geological conditions. Spritz beton overconsumption is very low due to the frequent steel arches absence.

5 MAIN TUNNELS, SOUTH DIRECTION

The sections of the Main Tunnel, which are to be excavated within the Lot Mules 2-3 with traditional method, are placed between km 49+083.7 and 54+015 (East Tube) and between km 49+058 and 54+042 (West Tube).

The project includes a single track for a first section of 3,500 m of tunnel for the East tube and approx. 3,800 m for the West tube (excavation area of approx. 65 sqm). Follows an enlarged section with double track (excavation area of approx. 114 sqm) with a length of approx. 1,400 m for the East tube and 1,200 m for the West tube. Within this section, 19 side tunnels connecting the two tubes (transversal tunnels with an average length of approx. 45 m); therefore requiring a further 900 m of excavation and lining connect the two tubes (Fig. 8).

The Connecting Side Tunnels have the following basic functions: connection of the two tubes of the main tunnel, escape and rescue routes in case of emergency, space for technical installations and drainage of the infiltration waters into the Exploratory Tunnel.

A single lithological unit, the "Bressanone Granite", divided into 11 homogeneous geomechanical sectors, characterizes this area.

In order to meet the requirements of the execution phase, the designs of the two main tubes and the connecting side tunnels include a final concrete lining (generally not reinforced) with a nominal thickness of 40 cm.

The excavation and lining of these 9,900 m of tunnel is going to be entirely with traditional method by CIPA, starting from the entrance of the logistic chambers and going south towards the end of the lot.

The excavation works began in April 2017, and will be brought to completion by the end of October 2020: the challenge is therefore to excavate an average of almost 9 m/day nonstop.

To date (31.07.18), 2,655 m of excavation have already been completed, consisting of the excavation section GL-TRB-TER, which considers an excavation with explosives with maximum steps of 3 m, fibre-reinforced shotcrete (and also reinforced with electro-welded mesh) 5cm thick + 10cm at the edge and 5cm at the front, radial consolidation with rock bolts type Swellex PM24 L = 4.5 m.

In addition, the first five connecting side tunnels (total length of approx. 220 m) were executed according to section CT1-TRB (Fig. 8). This considers an excavation with explosives with maximum steps of 1.5 m, fiber-reinforced shotcrete (and reinforced with electro-welded mesh) 5cm thick + 10cm at the edge and 5cm at the front, radial consolidation with rock bolts type Swellex PM16 L = 3.0 m.

For the execution of the excavation and of the primary lining in the two work fronts of both Main Tubes heading south, the following equipment has been used:

- 1 Jumbo ROBODRILL with 3 booms for drill and blast operations and for rock bolting (main tunnel);
- 1 spare quite aged jumbo Atlas as spare machine
- 1 Jumbo ROBODRILL with 2 booms for the drill and blast operations and for rock bolting (connecting side tunnels);
- 1 crawler excavator Case 370 + 1 crawler excavator CAT 330 for the scaling operations (refer to Fig. 9 for this and the next point);
- 1 wheel loader Hitachi ZW310 equipped with side unloading bucket and 10 4-axle trucks (which transport the excavated material to the logistic chambers for primary crushing);
- 2 shotcrete pumps Cifa CSS3 for spraying the shotcrete;
- 2 telescopic handlers Pegasus with man basket Fops.

The final lining of both tubes will be done simultaneously with the excavation with of 2 self-reacting formworks mounted on 12.5 m long tracks and 2 formwork systems wall/slab movable on wheels (Fig. 10).

5.1 *Main tunnel GL South – consumptions and overconsumptions*

Summarized data reported:

- Explosive consumption index Sez. GLTRb-Ter (ca. 65 m^2): 1,66 kg/m^3
- Explosive type: Nonel detonators, emulsion and gelatin
- Explosive cost index: approx. 9,00 $euro/m^3$

Figure 8. Excavation section CT1-TRb, by-pass and Main Tunnel direction south single track.

Figure 9. Scaling and muck tipping loading operations.

Figure 10. Systems and formworks in use and . . . St. Barbara!

- Explosive consumption index Sez. CT1-TRb (ca. 29 m^2): 2,2 kg/m^3
- Explosive cost index: approx. 14,00 $euro/m^3$
- Average over excavation compared to the theoretical design profile: approx. +60 %
- Drill & blast consumable costs index: approx. 0,35 euro per drilled meter
- Spritz beton overconsumption compared to the theoretical designed thickness: approx. +26 %

There is to note that the average excavation radius increased is in the range of 25 cm, the cause appointed to the geological conditions. Spritz beton overconsumption is very low due to the frequent steel arches absence.

Just a note: GL excavation along the South direction in D&B is the result of a design variation along the initial project phase; the first idea was to use the two TBMs, which were planned afterwards to excavate in northwards.

6 ROBODRILL: THE DRILLING PARTNER

Robodrill has been part of the Brenner's project almost ever since the beginning; 3 years with PAC involved in the excavation of all the logistic down the Mules adit, currently also working with Europea92 and the Consortium Salini-Impregilo & Strabag in Isarco projects, too.

Robodrill has been able to serve in a quite difficult environment various jobs sites and Companies for years, providing jumbos, manpower, elettro-mechanical services.

It has also contributed to develop new drilling strategies designing efficient systems, for example machines (with 4 drilling booms), which are able to work with self-drilling anchors in difficult sections, as well 2 booms, computerized, able to D&B in narrow niches in some of the main sections.

Through the collaboration with CAT and Montabert new heavy-duty jumbos have been designed and used on hard granite as well as on faulty areas. An excellent and updated computerized system has been able to limit drilling positioning time and over breaks at the maximum possibilities. Some visual images can be seen in Fig. 11.

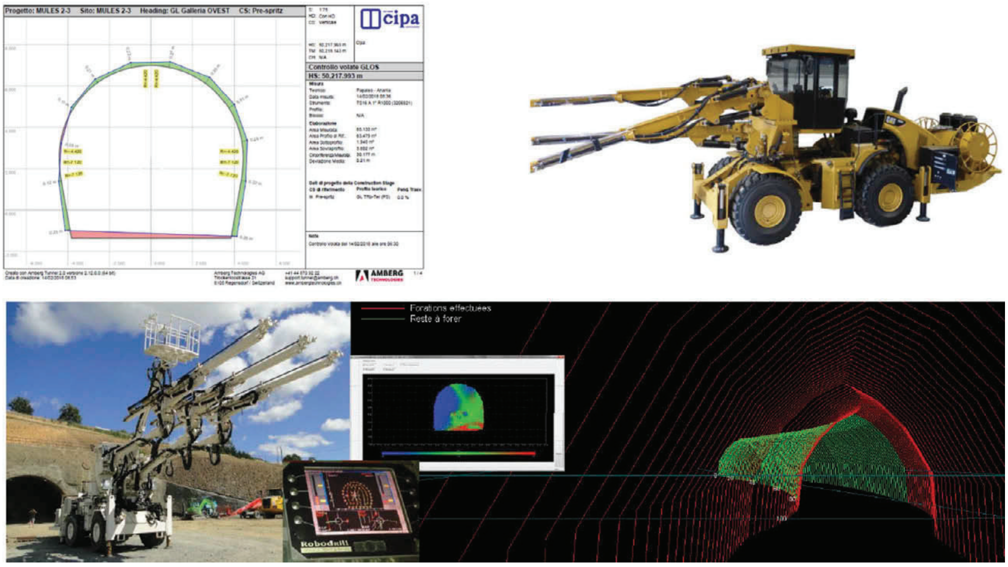

Figure 11. Accuracy in Brenner tunnel, new CAT jumbos and I4.0 PLC Robo-Geo-Controlled system.

7 DRILLING PERFORMANCE IN THE SITE

Cipa's Company has been able, in such a complex situation, to perform at the limit of human possibilities. As follows, a synthesis of the production data up to end July 2018 (Fig. 12,13).

EXCAVATION MONTHLY PRODUCTION GL EAST SOUTH				
REF [month]	MONTHLY PRODUCTION [m]	DAILY RATE on MONTHLY PRODUCTION [d.a.c.]	MONTHLY CUMULATIVE PRODUCTION [m]	DAILY RATE on MONTHLY CUMULATIVE PRODUCTION [d.a.c.]
ottobre-17	162,20	5,23	162,20	5,23
novembre-17	128,10	4,27	290,30	1,00
dicembre-17	91,70	2,96	382,00	4,15
gennaio-18	130,70	4,22	512,70	4,17
febbraio-18	116,80	4,17	629,50	4,17
marzo-18	113,50	3,66	743,00	4,08
aprile-18	103,50	3,45	846,50	3,99
maggio-18	155,90	5,03	1.002,40	4,13
giugno-18	146,60	4,89	1.149,00	4,21
luglio-18	163,70	5,28	**1.312,70**	**4,32**

EXCAVATION MONTHLY PRODUCTION GL WEST SOUTH				
REF [month]	MONTHLY PRODUCTION [m]	DAILY RATE on MONTHLY PRODUCTION [d.a.c.]	MONTHLY CUMULATIVE PRODUCTION [m]	DAILY RATE on MONTHLY CUMULATIVE PRODUCTION [d.a.c.]
maggio-17	52,20	1,68	52,20	1,68
giugno-17	109,20	3,64	161,40	2,65
luglio-17	135,70	4,38	297,10	3,23
agosto-17	90,90	2,93	388,00	3,15
settembre-17	154,30	5,14	542,30	3,54
ottobre-17	165,10	5,33	707,40	3,84
novembre-17	142,80	4,76	850,20	3,97
dicembre-17	83,40	2,69	933,60	3,81
gennaio-18	134,80	4,35	985,00	3,57
febbraio-18	122,80	4,39	1.107,80	3,64
marzo-18	129,60	4,18	1.237,40	3,69
aprile-18	123,00	4,10	1.360,40	3,73
maggio-18	153,10	4,94	1.513,50	3,82
giugno-18	144,00	4,80	1.657,50	3,89
luglio-18	159,30	5,14	**1.816,80**	**3,98**

Figure 12. Productivity in GL East and West South tubes.

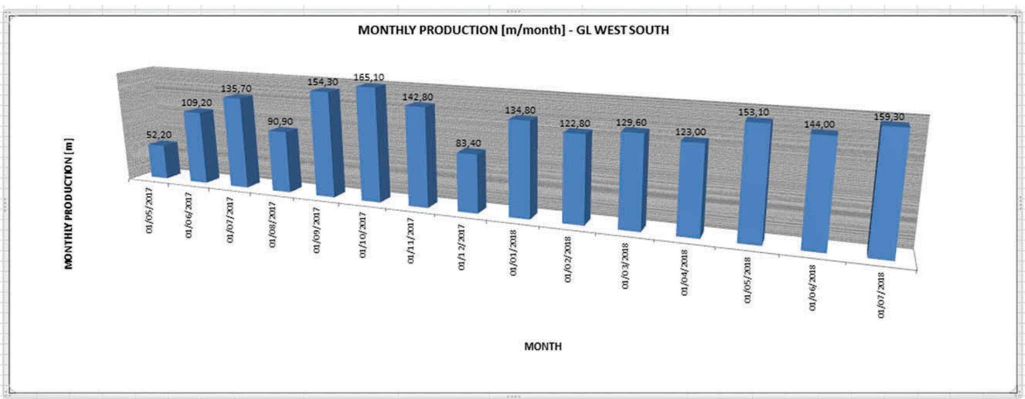

Figure 13. Productivity in GL East and West South tubes.

CONSUMPTION & OVERCONSUMPTION

				Year 2017			Year 2018						
				October	November	December	January	February	March	April	May	June	July
GL South - Tube EAST	Explosive	Rate (kg/cm)	Partial month	1,68	1,78	1,73	1,87	1,7	1,56	1,89	1,69	1,78	1,67
			Progressive	1,68	1,72	1,72	1,76	1,75	1,72	1,74	1,73	1,74	1,73
	Spritz beton	Extra quantity (cm)	Partial month	60,89	109,92	101,39	118,91	120,05	152,3	151,78	98,12	131,88	91,58
			Progressive	60,89	170,81	272,2	391,11	511,16	663,46	815,24	913,36	1045,24	1136,82
		Percentage (%)	Partial month	20,36%	20,93%	27,43%	29,12%	31,03%	39,56%	44,33%	15,48%	21,87%	13,38%
			Progressive	20,36%	20,73%	22,80%	24,75%	26,17%	28,53%	30,67%	24,10%	23,79%	22,39%
	Final lining concrete over consumption calculated	Extra quantity (cm)	Partial month	929,6	845,13	709,51	681,18	725,17	822,31	261,48	1510,66	822,7	412,2
			Progressive	929,6	1774,73	2484,24	3165,42	3890,59	4712,9	4974,38	6485,04	7307,74	7719,94
		Percentage (%)	Partial month	55,00%	64,00%	76,00%	51,00%	60,00%	78,00%	78,00%	73,00%	52,00%	50,00%
			Progressive	55,00%	59,03%	62,99%	60,04%	60,13%	62,67%	63,32%	65,41%	63,58%	62,66%
GL South - Tube WEST	Explosive	Incidenza (kg/mc)	Partial month	1,68	1,78	1,73	1,87	1,7	1,56	1,89	1,69	1,78	1,67
			Progressive	1,68	1,72	1,72	1,76	1,75	1,72	1,74	1,73	1,74	1,73
	Spritz beton	Extra quantity (cm)	Partial month	63,5	100,16	163,6	114,31	136,52	149,64	161,56	97,89	96,25	144,02
			Progressive	63,5	163,66	327,25	441,56	578,08	727,72	889,28	987,17	1083,42	1227,44
		Percentage (%)	Partial month	21,49%	17,27%	47,78%	25,02%	30,50%	32,64%	36,61%	16,10%	15,84%	21,99%
			Progressive	21,49%	18,70%	26,87%	26,30%	27,26%	28,27%	29,54%	24,94%	23,73%	23,51%
	Final lining concrete over consumption calculated	Extra quantity (cm)	Partial month	953,2	838,79	425,73	656,64	1081,01	1111,65	859,53	1388,52	637,46	538,81
			Progressive	953,2	1791,99	2217,72	2874,36	3955,37	5067,02	5926,55	7315,07	7952,53	8491,34
		Percentage (%)	Partial month	58,00%	57,00%	50,00%	48,00%	86,00%	96,00%	104,00%	75,00%	53,00%	61,00%
			Progressive	58,00%	57,47%	55,80%	53,83%	60,00%	61,69%	64,14%	65,37%	64,51%	64,37%
Transversal tunnel	Explosive	Incidenza (kg/mc)	Partial month	Explosive incidence calculated in average rate GL SOUTH - specific rate approx 2,22 kg/cm									
			Progressive										
	Spritz beton	Extra quantity (cm)	Partial month	10,51	17,24	-2,34	36,52	0	39,58	0	1,67	13,65	0
			Progressive	10,51	27,75	25,41	61,93	61,93	101,51	101,51	103,18	116,83	116,83
		Percentage (%)	Partial month	11,00%	21,00%	-16,00%	45,00%	0,00%	54,00%	0,00%	12,00%	21,00%	0,00%
			Progressive	11,00%	14,00%	11,95%	21,13%	21,13%	27,70%	27,70%	27,17%	26,30%	26,30%

Figure 14. Consumption and spritz & final lining concrete overconsumption rate.

8 CONCLUSIONS

Let's talk about overconsumption! The tunnel is not lined with steel arches which means that the spritz rebound should be quite limited, in the range of 10%. In reality, due to geological conditions, even if in presence of competent granite (but frequently bursting, spalling and not only . . .), the job site suffered 10% higher spritz beton consumption (mainly for profile regularization) plus an average of ca. 50-60% concrete over consumption for the final lining (data reported in Fig. 14), costs which should need to be professionally discussed (and absorbed by the Client). An average of excavated radius increase, in the range of 20-25 cm, has been systematically detected, whatever kind of action taken in order to limit it.

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