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

The design approach of cut & cover excavation in hyperbaric condition applied for Napoli/Cancello high speed railway

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ABSTRACT: In the frame of the high speed railway line Napoli-Bari, it is foreseen the realization of a cut and cover tunnel which partially develops below the ground water level. The top down construction will be performed using the compressed air in order to achieve a dry base during the soil excavation and the cast of the internal structures. All the benefits of this technology are discussed, including the aspects related to the environment. The practical application of the technique has revealed numerous detailed problems from a structural point of view: together with the additional load on structures, the limitation of the air losses has been a relevant topic. The measures implemented for the maintenance of the prescribed pressure are presented in the paper describing the solution developed to minimize the dissipation of compressed air through production joints. The air losses are estimated after a brief survey of the formulations available in literature.

1 INTRODUCTION

The project in question is part of the transport network upgrading along the transversal axis Naples - Benevento - Foggia - Bari. The works are aimed at giving adequate response to the changing mobility needs of travelers and goods and constitute a fundamental element for the development of southern Italy, for a better economic and social integration in the country and in Europe.

In this sense, the construction of the high capacity railway line Naples-Bari, together with the activation of the Rome-Naples high-speed railway system, will favor the integration of the railway infrastructure of the South-East with the Connecting Directories to northern Italy. This upgrading will have a paramount impact for the socio-economic development of the South, reconnecting two areas, Campania and Puglia.

The enhancement of the railway axis connecting the Tyrrhenian and the Adriatic coastlines will also allow the creation of a “tripole” (Rome, Naples and Bari) which will constitute one of the largest metropolitan systems in Europe. On the international front, as part of the new structure of the trans-European corridors (TEN-T) defined by the European Commission on 19 October 2011, the development of the Naples-Bari route, which specifically falls within the Corridor 5 Helsinki - Valletta, has been identified as a priority.

The rehabilitation and development of the Naples-Bari itinerary involves the doubling of the single-track railway sections and the change of the current alignment, in order to ensure the connections speeding up and the increase of the railway transport offer (Figure 1).

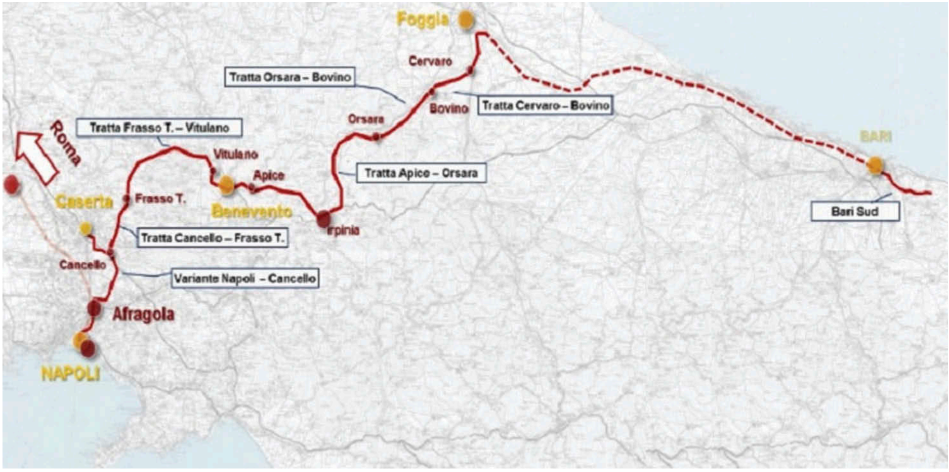

Figure 1. Transport network upgrading along the transversal axis Naples - Benevento - Foggia - Bari.

The entire work was divided into functional sections for realization purposes. The project in question is part of the first section (Naples-Cancello) particularly strategic in the overall arrangement of metropolitan, regional and long-distance connections.

In fact, the variant in the stretch between Naples and Cancello, allows bringing the tracks of the line to the new station of Naples Afragola, which in the future will become the station for passenger interchange between regional and AV services increasing overall accessibility to the railway transport in the Naples hub.

The line, in the section of interest develops for about 15.5 km through the municipalities of Casoria, Casalnuovo, Afragola, Caivano and Acerra (Figure 2). The chainage starts, in the south, from km 0+000.00 (coinciding with km 241+727 of the historical line) and ends, in the north, at km 15+585,066 (coinciding with km 229+530 of the historical line).

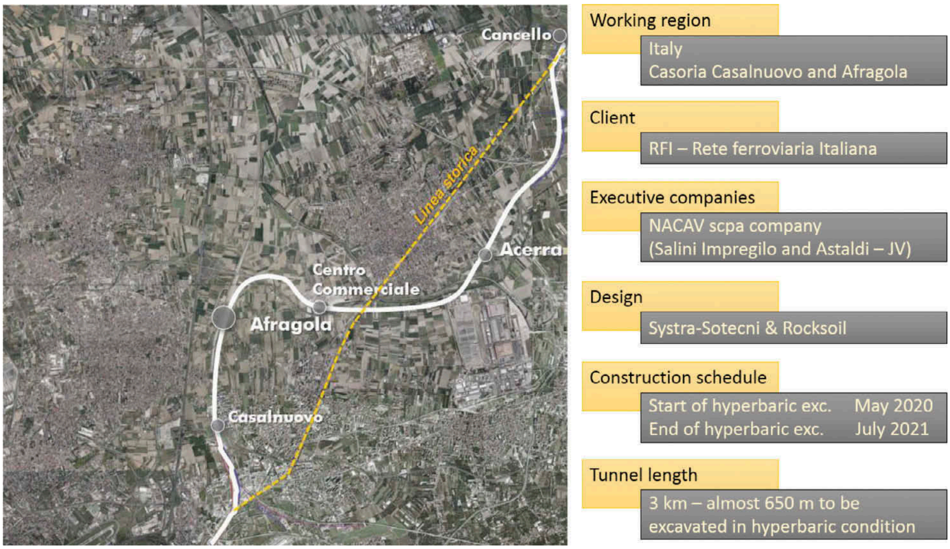

Figure 2. Section Overview.

Although, in general, the preferred solution is that of railway embankment, in some particular points the construction of viaducts or tunnels is envisaged in order to resolve specific interferences and to better integrate with the environment.

The tunnel cross section presents a geometrical variability as summarized below:

1. "Parapioggia" (Figure 3)
   In the first 180 m the tunnel has a rectangular section, in this stretch the tunnel presents a single tube section.
2. Top down tunnel with single-tube section (Figure 4)
   For about 300 m the tunnel continues with a top down section characterized by diaphragm walls horizontally restrained by roof and foundation r.c. slabs. In this stretch the section is a single tube section.
3. Top down tunnel with double-tube section (Figure 5)
   In the following stretch, the Circumvesuviana line joins the new Cassino line, therefore the tunnel presents a double-tube section and is constructed following the top down method
4. Top down tunnel with double-tube section and intermediate slab (Figure 6)
   In this stretch, due to the considerable excavation height an intermediate slab is foreseen to restrain horizontally the structure
5. Casalnuovo Station
   In correspondence of Casalnuovo station, the tunnel maintains the same structural concept. It is different from the adjacent stretches only in terms of width that is greater due to architectural purposes.
6. Top down tunnel with double-tube section
   In the last portion, the surface level decrease allowing to foresee only two horizontal slabs that correspond to the double-tube section

The tunnel interferes with the phreatic level in the first stretch, from pk 0+550 to pk 1+600. In order to perform all the excavation and construction activities in dry condition the tender design foresaw the execution of jet grouting plug. The soil treatment reduces the soil perme-

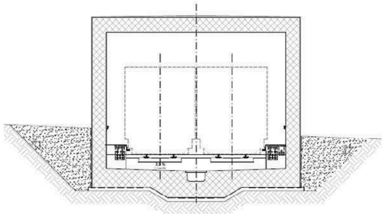

Figure 3. "Parapioggia".

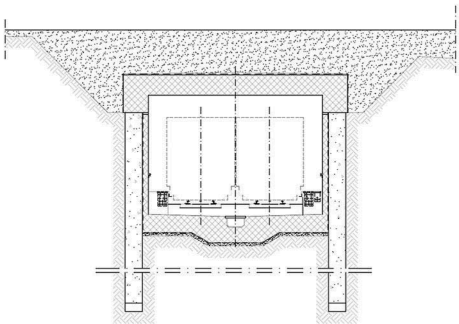

Figure 4. Top down tunnel with single-tube section.

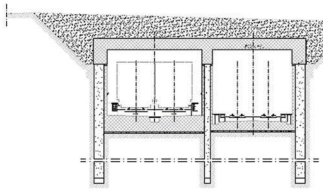

Figure 5. Top down tunnel with double-tube section.

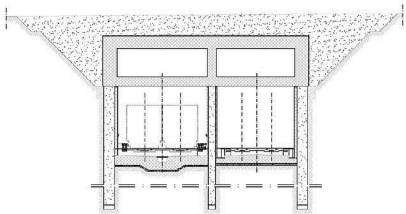

Figure 6. Top down tunnel with double-tube section and intermediate slab.

Table 1. Comparison of the alternative solutions.

	COMPRESSED AIR	JET GROUTING
Aquifer pollution	✓	✗
Duration of works	✓	✗
Flexibility	✓	✗
Production plant cost	✗	✓
Soil improvement cost	✓	✗
Soil to landfilling	✓	✗

ability, allowing creating a waterproof layer. Due to the water height to be counter-balanced the thickness of this treatment reached high values.

With regard to the bid issued by Italferr in 2016, it was requested to the Competitors to study an original technical solution which could solve the interference with the groundwater, par-ticularly with the possibility to get an easy compartmentalization between the following work-ing phases. For this purpose, NACAV scpa company, a JV between Salini Impregilo and Astaldi, decided to choose an original technical solution, already successfully used abroad, consisting in making use of pressurized air dig. Such choice allowed NACAV scpa company to get the job. Table 1 summarize the comparison of the alternative solutions.

That is the use of compressed air, whose application has a double advantage:

- a higher flexibility of the system in order to adapt to ground water level fluctuation;
- no impact on the environment due to the exclusion of any contamination of the groundwater, which serves as a reservoir for the water supply of the city.

2 COMPRESSED AIR EXCAVATION

2.1 *Famous historical applications*

The use of compressed air for excavation under water table has been used for long time especially for the mechanized excavation (TBM). In the field of artificial tunnels this technique has been developing in recent years, particularly in the countries of northern Europe, as, in certain contexts, it represents a valid alternative to traditional solutions, bringing improvements and advantages.

Historically, this type of technology finds its most widespread applications in the construction of underwater foundations and in particular through the use of pneumatic caissons. For example, the most important geotechnical applications include the foundations of the Eiffel Tower. In Italy, on the other hand, a well-known example is represented by the bridge of the Hach Industry in Rome for which the compressed air foundation was used for the first time in Italy, a caisson technique whose origin should be searched in France in 1841. Another mention must be made regarding the metro line 4 in Paris for which compressed air was applied for the Seine under-passing.

Among the underground tunnel in hyperbaric condition projects developed abroad are mentioned below (Schwarz & Hehenberger, 2004):

- Chlodwig-Platz, Cologne, Lot South - North-South suburban railway, Cologne Oil-free screw compressor;
- Stans/Terfens Tunnel - Inntal, construction lot H4-3 oil-free screw compressor;
- Vomp/Terfens tunnel - Inntal, construction lot H5 oil-free screw compressor;
- Allmend Tunnel Lucern - Central railway - double track - construction on lower level oil-free screw compressors;
- BF Olympiapark North, underground railway line 3 North - Ventilation;
- Fritzens/Braumkirchen - Inntal tunnels, construction lots H7-1, H7-2, H-3 oil-free screw compressors;
- AUDI Tunnel in Ingolstadt (Germany).

2.2 *General operating principles*

The excavation with compressed air of artificial tunnels built with the top-down method, as in the case of the GA01, generally requires a similar methodology dictated by technological needs, even if, depending on the site and the specific characteristics of the work, small variations are found in the examined cases.

In general, a r.c. wall in c.a. is constructed at the entrance of the tunnel and two watertight doors are installed for people and vehicles access. These accesses lead to a watertight seal chamber where the air is gradually pressurized to reach the design pressure value.

Through two more doors, the workers and the vehicles can access to the working construction site inside the tunnel, which is in a hyperbaric environment at the established pressure.

Through other two doors, both the vehicles and the workers can enter and exit (separately) in the compensation chamber, which must therefore be subjected to time periods of compression (entry) or decompression (exit).

The pressure value to be applied in the tunnel is equal to the corresponding value of hydrostatic pressure acting on the excavation bottom due to the water head at the time of the excavation under the top slab.

As the excavation proceeds, the pressure to be applied in the tunnel must be adjusted to the value of hydrostatic pressure to be balanced at the different advancement steps.

The internal pressure is thence an additional load acting on the structure in the temporary phase that should be considered in the structural analyses. It is to be remarked that in general the air pressure acts in the opposite direction of the most demanding loads: for both the retaining walls and the top slab the internal pressure partially counteract the earth and water pressure acting inward the tunnel. In other words, this methodology does not require a strengthening of the structure and furthermore, assuming the air pressure is maintained during the whole excavation process, it reduces the internal actions associated to the temporary phase.

While the compressed air system is active the global equilibrium toward the possible uplift should be checked: the internal pressure, determined to counteract the water pressure at the bottom of the excavation, can lead to a structure uplift in case of low backfilling. This condition should be taken into account performing a specific check, which should consider the internal pressure of the air, the weight of the structure, the backfilling load, the anchoring strength of the diaphragm walls in the ground.

The tunnel construction phases will thence be:

- Excavation to the diaphragm wall execution level;
- Realization of the diaphragm walls;
- Cast of the r.c. roof slab;
- Backfilling above the roof slab;
- Excavation below the roof slab, between the diaphragm walls, to the foundation level with the application of the prescribed air pressure;
- Cast of the internal structures and finishes installation;
- Deactivation of the internal air pressure.

3 THE APPLICATION TO THE CASE OF STUDY

3.1 *Technical and methodological aspects*

In the case of study, the maximum excavation level varies according to the T.O.R. of the alignment. Moreover, the excavation section changes due to the section type variability foreseen by the design and to the fact that the tunnel locally widens for the STI exits, for the wasteawater lifting plants and the relative inspection chambers and for the niches.

This configuration would require the adjustment of the air pressure of compressed air at each advance. For logistic purpose and to avoid excessive air losses at the tunnel face, the tunnel has been divided into compartments (n.14, Figure 7) limited on the sides and on the top by the tunnel structures and at the front by specific diaphragm walls.

The diaphragm walls that constitute the transversal partitions are executed together with the longitudinal ones and are placed at a variable distance each other, determined considering the expected losses.

At each of the 14 compartments will correspond a uniform design value of the air pressure (maximum value of the water head in the stretch individuated by the compartment) and fixed volume. To define correctly the design pressure to be maintained in each compartment, a specific piezometric monitoring has been performed during the development of the design, see Table 2. Since the records showed a certain variability due to weathering and to seasonal fluctuation, the maximum water level recorded has been considered. Furthermore, an addition possible raising of 1 m is precautionary assumed.

Considering the maximum hydraulic head in each compartment, he design pressure required for lowering the water table below the excavation surface ranges between 0.2 and 1 bar. The range already takes into account the variability of the excavation level in correspondence of a local structures such as the wastewater lifting plant.

The fact that the maximum pressure required by the system is equal to 1 bar confirms the effective advantage of the solution. The safety of workers in hyperbaric conditions represents an important aspect to be considered in the design phase since can have strong impact on the indirect costs of the project. Despite the regulatory environment is still developing on this topic and is not homogeneous comparing the references from different countries, the safety measures to be implemented always depend on the working pressure. In addition, all the standards available on the subject consider 1 bar as a limit for the first level of safety equipment since the human beings can easily adapt to such a pressure.

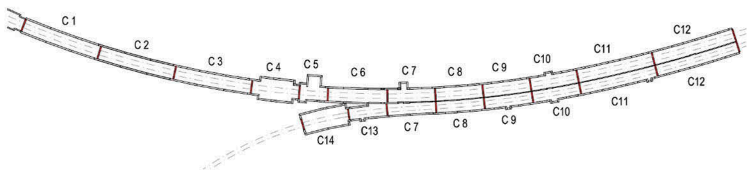

Figure 7. General plan with compartments.

Table 2. Piezometric readings from the geotechnical campaign.

		Head	H max	H min	08/03	22/03	23/03	16/04	14/05	01/06
	PK	mslm	mslm	mslm	m from head					
E1PZ	0+735,35	17.44	14.39	14.04			3.4	3.20	3.05	3.13
E3PZ	1+150.98	22.89	15.15	15.04		7.85		7.81	7.74	7.72
E4PZ	1+276.58	26.35	15.05	14.77	11.58			11.49	11.3	11.24
E5PZ	1+705.99	34.60	15.51	15.20		19.4		19.26	19.09	19.02

3.2 *Construction phases*

Once the slab is cast and backfilled according to the design final ground level, the compressed air plant shall be switched on and, when the design pressure value is achieved the tunnel excavation could start.

The excavation will be performed without any partialization of the face and proceeding by compartments: the excavation of a compartment will begin only after completion of the final structures of the previous one. The excavation muck will be transported out of the hyperbaric work area by means of a conveyor belt devised to ease the working process.

The choice of this system requires a certain space for its installation and, consequently, leads to postpone the application of the compressed air to the second compartment.

After the excavation of the first compartment and the cast of the internal structures the compressed air system is switched on. In order to guarantee the pressurization of the next compartment, some holes are provided in the partition wall before its demolition that is followed by the excavation. The compartment will be excavated up to its end, proceeding simultaneously in the two tubes if the tunnel present a double tube section.

At the end of the excavation process the waterproofing system will be installed and fixed to the structures in order to limit the air losses in the next phase. Once the cast of the internal structure is complete it's possible to proceed with the same construction process for the next compartment.

3.3 *Construction details*

In order to minimize the air losses during the excavation with compressed air, the construction joints have been studied in detail to improve the tightness both to water and to air. The calculations for the sizing of the plants depend on the equivalent overall permeability to air of the surfaces exposed to the air pressure. For the case of study, considering the average permeability of the soil to water measured by means of specific tests in situ, the following assumptions were made:

– During the excavation the structures and the soil present an equivalent overall permeability to air equal to 10^{-6} m/s;
– After the cast of the internal structures the equivalent overall permeability is assumed equal to at 10^{-8} m/s.

These values have been estimated considering all the precautions actuated to reduce the air losses and should be confirmed before the start of the excavation by means of a field test.

In order to optimize the design and to reduce the cost related to the compressed air plant the tightness of the structure should be studied in detail focusing on the weak points of the system with respect of the air leaks that are:

– The connection between the roof slab and the diaphragms;
– The longitudinal joints between diaphragms: this context shows the greatest number of discontinuities (every 2.5 m);
– Joints (casting joints and expansion joints) present on the slabs (linings, top and foundation slabs);
– Interface between the waterproofing sheets and the internal structures on the base slab and on the linings at the end of each compartment.

The precautions to be taken to improve the hydraulic seal of the structural joints and of the construction joints in the different parts of the structure must therefore be studied in order to obstruct also the air passage.

For the joint between the roof slab and the diaphragm wall, a waterstop is installed between the latter and the linings in order to stop a possible ascent of the ground water (Figure 8). Moreover, the waterproofing layer installed on the roof slab is mechanically fixed to the diaphragms below the contact section with the roof slab abutment providing protection against the rainwater inlet. This mechanical fixing also guarantees an excellent seal against compressed air, limiting considerably the air losses.

For the joint between the partition walls and the roof slab a waterstop is installed at the top of the capping beam as shown in Figure 9.

To limit the air losses that could occur at the joint between two adjacent diaphragm walls, in addition to the particular dovetail shape, a waterstop is inserted. This detail is foreseen for all the diaphragm wall, both the one of the tunnel and those of the partitions.

In correspondence of the construction or expansion joints, the detail studied to guarantee water tightness perform very well also as a barrier against air. In fact, while for the construction joints the continuity of the membrane is foreseen, in correspondence of the expansion joints a waterstop which allows to compensate the differential shrinkage of the structures is inserted guaranteeing continuity of the waterproofing system (Figure10).

At the end of each compartment, the waterproofing membrane is mechanically fixed to the linings and to the foundation slab to allow a perfect seal of the already executed portion: this allow considering for that part a lower permeability to air as cited before.

The TNT layer placed between the PVC and the lean concrete to protect the waterproofing membrane constitute an escape route for the air. In correspondence of the structural joints, the waterproofing package is fixed to the r.c. structure by anchored waterstops, but it is also necessary to secure it outward (on foundation slab and diaphragm walls).

Since the operations (excavation, laying of the waterproofing and casting of the internal structures) will be carried out compartment by compartment, it is envisaged to create this kind of joint at the end of each compartment (Figure 11).

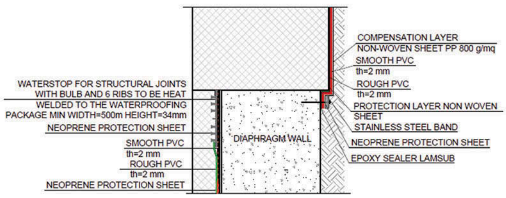

Figure 8. Joint between the roof slab and the diaphragm wall.

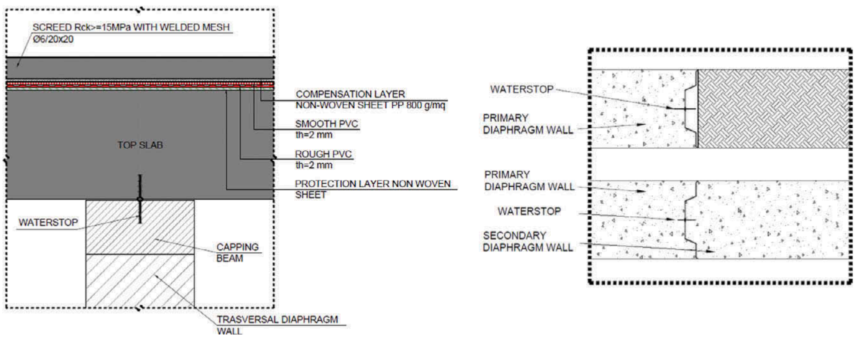

Figure 9. joint between the partition walls and the roof slab (left) joint between adjacent diaphragm walls (right).

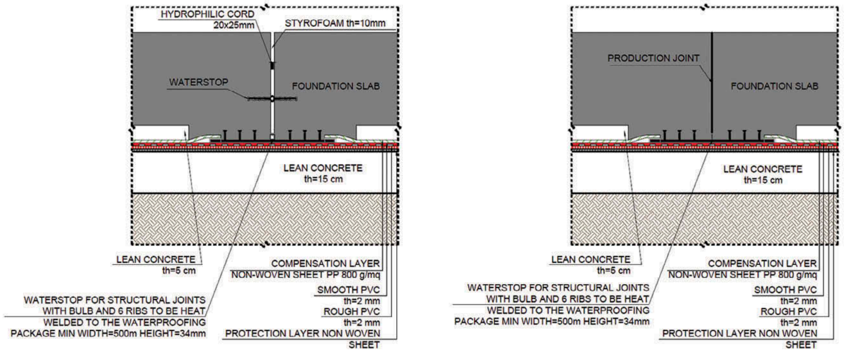

Figure 10. Longitudinal joint - foundation slab.

In detail, the waterproofing in correspondence of the lining is fixed to the diaphragm walls and the one in correspondence of the foundation slab is fixed to a specially made joist.

4 AIR LOSSES EVALUATION

The plant for the compressed air should be dimensioned considering all the factors that determine the required flow. In particular, once the volume of work is put under pressure, the main contributions are:

– Losses through structural joints
– Losses due to the opening and closing of access doors for vehicles and personnel
– The forced aspiration required to maintain healthy conditions in the workplace.

While the last contribution is a requirement dictated by the workers' safety manuals, the others must be estimated for a correct sizing of the plant (ITA-AITES WG5, 2015).

Of the two, the one linked to the opening and closing of the access doors has a minimal influence since it is foreseen a compression/decompression chamber for muck, means of transport and workers.

The contribution that have to be evaluated is therefore the one due to losses through ground and structural joints. For this purpose, the formulation of Schenck and Wagner, developed to evaluate air leaks during tunnel excavation, is applied (Semprich & Scheid, 2001).

$$Q = 2 \cdot k_a \cdot \frac{(P_1 - P_2)}{\gamma_w \cdot L} \cdot A \cdot \frac{P_1}{P_2}$$

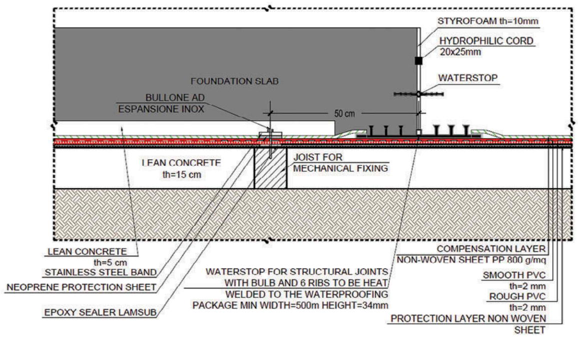

Figure 11. Mechanical fixing at the end of each compartment - Foundation slab.

- k_a is the permeability coefficient of the ground in the air that can be assumed equal to 70kw
- kw is the permeability coefficient of soil to water
- P_1 is the absolute pressure inside the tunnel that corresponds to the pressure necessary to lower the pitch below the excavation bottom plus the atmospheric pressure (Ptun + 1) atm
- P_2 is atmospheric pressure equal to 1 atm
- γ_w is the specific weight of water
- L is he length of the air path that corresponds to the tunnel overburden
- A is the area through which losses occur

It should be noted that it is not possible to determine the permeability coefficient of the soil to air by means of laboratory tests, since it is strongly dependent on the in-situ boundary conditions. For this reason, the aforementioned relation is used to estimate this coefficient starting from the water permeability of the medium. Obviously, the assessments made here shall be confirmed in the execution phase through specific in situ tests performed before the start of the excavation. On the basis of these results, it will be possible to adjust the design pressures in order to better control the lowering of the water table (Bull, 2003).

In order to guarantee a correct application of the internal pressure, the system also provides a series of instruments that allow a constant monitoring of losses: in every instant the incoming and outgoing air volume and the actual air pressure will be measured.

The Schenck and Wagner formulation is valid for laminar flow, which can be foreseen in material where $k_w < 1 \cdot 10^{-3}$ m/s (Jardine & McCallum, 2001). Given that in our case study, the permeability of the soil that varies between $1 \cdot 10^{-4}$ m/s and $1 \cdot 10^{-6}$ m/s the basic requirement is met.

The above formulation refers to the tunnel excavation with the traditional method, therefore there is no structure that prevents the escape of the air but the ground itself. For an artificial tunnel the volume of soil to be excavated is enclosed in a box consisting of diaphragm walls (laterally and frontally) and top slab. At the bottom of the excavation there is no structural element, but considering that the soil is saturated its permeability to air is very low.

In light of these considerations, the permeability value assumed for the calculation of the losses is equal to $1 \cdot 10^{-6}$ m/s before the final linings are casted and equal to $1 \cdot 10^{-8}$ m/s when the internal structures are finished.

Precautionary considering the maximum permeability until the installation of the mechanical fixing at the end of the compartment, the required air flow rate estimated considering one compartment not lined and a cumulative loss in the previous ones ranges between 45 and 95 m^3/min.

For the sizing of the plants it is considered appropriate to consider, in addition to the strictly necessary equipment, an additional compressor able to guarantee 50% of the estimated flow.

5 TECHNOLOGICAL ASPECTS

5.1 *Hyperbaric chamber*

Salini Impregilo and Astaldi designed a concrete structure for the access of personnel and equipment for the excavation of the pressurized tunnel.

For the case of study the transversal section of the hyperbaric chamber, 40 m long and 13 m wide, has been divided in three compartments: two for the accumulation of the excavated material (compartment A and B, see Figure 12) and one for the passage of vehicles and personnel (Compartment C, divided vertically in two volumes in order to separate the passage of vehicles and personnel). Considering that to entry in and exit from the excavation site it is necessary to follow specific procedures for the gradual compression and decompression, the construction site has been studied with the aim of minimizing the number of passages. In particular, in order to manage the muck transport it is envisaged the use of an extensible conveyor belt, hanged which will discharge the material coming from the front on a reversible belt feeding two shuttle belts. The shuttle belts will store the muck alternatively in one of the two compartments addressed to this specific function (Comp. A and B). When compressed they are used to collect the excavated material from the belt conveyor, and when depressurized, to load and transport away the ground, loading by a wheel loader. They are built with concrete walls and closed by self-sealing steel doors. One door, on the

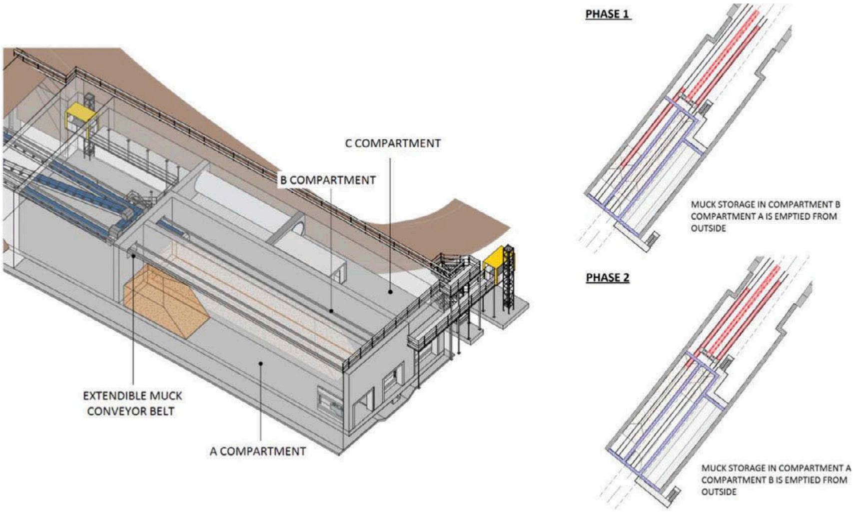

Figure 12. Hyperbaric Chamber.

atmospheric pressure side is large enough to accommodate the wheel loader; the other one, located on the pressurized side, presents the minimum dimensions to let in the conveyor belt and is controlled by hydraulic jacks.

The chamber dedicated to the equipment transfer is also equipped on both ends with self-sealing steel doors fitted with a remote-control device, to operate the door from the control cabin.

The personnel transfer chamber is a classical hyperbaric chamber steel made, including a main and an access chamber. The purpose of the access chamber is to make sure that at any time it is possible to shelter the crew retreating from the front, or to have a rescue team compressed for help the compressed crew.

A control cabin will be supplied and will be designed and equipped to manage all the information and controls for the excavation of the tunnel and the operations of the hyperbaric chambers, as well as the compressed air supplies. The hydraulic power pack to operate the jacks of the doors of the locks will be installed in the control cabin.

The hyperbaric equipment includes: all the 6 doors with relevant operating jacks and seals, the man-lock and relevant control panel, the hydraulic power pack, several steel plates, 600 x 600 mm size with relevant fixing frames, for concrete wall penetrators.

All pressurized equipment will be designed and constructed to meet the CE 12110 standard for air locks and compressed air shields. In particular, all parts which could not be hydraulically tested will be calculated with a safety coefficient 2 relative to the expected service pressure (in this case is 1 bar and safety coefficient 2).

The two ground locks and the equipment lock will be equipped with a closed circuit color video system which will be displayed by a screen installed into the control cabin.

A pressure recorder, installed in the control cabin, will be able to control: the pressure of the tunnel, the pressure of the man lock, the pressure in the ground locks and the pressure in the equipment lock. There are 3 pressure sensors installed in each of the different chambers and the recording interval is from 1 sec to 12 h.

5.2 *Compressors and pipelines for compressed air*

Compressors have been provided, placed outside, to supply and maintain the air at the desired pressure in the tunnel according to the design prescriptions. The compressed air system will have, in addition to the compressors:

– filtration system suitable for ensuring breathable air certified according to the regulations;
– cooling system to feed air in the tunnel at the correct temperature;
– extensible steel pipeline to carry the air to the front and a spare line placed in a position faraway from the operating area with the aim of having at least one operational pipeline even in case of damage to the other;
– control system, located in the tunnel near to the working front, able to maintain the air pressure established, compensating the decrease in pressure due to any leaks to the outside;
– system with a controlled air flow, allocated at the beginning of the tunnel, to allow the air to flow outwards in order to ensure an renewal of the air, according to the norm, that takes into account the number of people operating in the tunnel.

Inside the tunnel, in a closed environment, the operation with the electric motors of the equipment causes the air to heat up. To contain this air heating within the limits of comfort for people an air cooling and recirculation system will be provided. This system will consist of a cooling coil and an electric fan placed towards the tunnel entrance in order to recirculate the air from the working front. The cooled air that passes through the electric fan will be addressed directly to the working front by a flexible tube. This system therefore ensures that the personnel work in an environment with the correct temperature and humidity values.

In order to ensure the continuous operation of the "vital" systems inside the tunnel in case of shut-down of the power supply line, emergency generators located outside are designed to satisfy all the functions considered particularly sensitive for the operating personnel like breathing air, lighting, opening of doors, fire system, etc.

Every opening, even the small ones, that remain cause air leaks from the already excavated tunnel. To counter the consequent decrease of the desired pressure a sensor is installed near the working front which will automatically manage the operation of the compressors. This sensor can be adjusted so as to ensure the correct value of the air pressure for each working field.

6 CONSTRUCTION MACHINERY AND PLANTS

6.1 *Conveyors*

Inside the tunnel, in hyperbaric conditions, the fundamental criterion is to maintain conditions of wellbeing for the workers that are reflected in the air parameter control systems. A solution in this direction is the adoption of only electric motors in the tunnel for all the operating machines. Therefore the transport of excavated material along the tunnel is implemented with the use of a system of conveyor belts equipped with electric motors that are stretched to follow the excavation front. This system will be equipped with all the safety measures suitable for the particular environmental conditions in the tunnel as non-flammable components, temperature sensors, etc.

6.2 *Excavators*

The excavation of the materials and the consequent loading on the belt conveyor system is provided by Shaeff ITC machines. Indeed these machines combine the excavation function and the loading through a conveyor able to feed the conveyor belt system with continuity. Infact the conveyor belt system is designed with mobile elements able to follow the excavator and then receive anytime the excavated material.

6.3 *Electric construction vehicles*

All the operating machines and the equipment used inside the tunnel will be equipped with electric motors. This solution allows zero emissions into the tunnel environment and thus ensures a perfectly breathable air quality. Depending on the availability from the market and the required functions, some machines will be powered through the 380-volt power line while others will be equipped with rechargeable batteries; for this case an external installation will be provided for recharging the spare batteries.

6.4 *Molds*

The project foresees that, after having affixed the waterproof sheath under the base slab and the walls, a concrete base slab and a finishing concrete layer on the walls will be carried out. In particular, for the walls works a series of formwork sets are provided. The formworks will be equipped with anchors at the base and upper section and with wheels suitable for permitting translation. They will also be equipped with wall-mounted vibrators and concrete filling mouths positioned at various levels to facilitate the regular laying and a perfect surface finishing.

7 CONCLUSIONS

The choice adopted by Salini Impregilo and Astaldi for the excavation of the artificial tunnel Casalnuovo has proved innovative and represents an avantgarde in the national landscape.

The chosen solution allows controlling the water table, avoiding any risk connected to the transport of fine materials in case of a drowning and those induced by possible heaving due to jet grouting and above all the ground water pollution.

Following a careful design procedure, the safety of workers is guaranteed in any construction phase and assured by a redundancy of safety measures.

According to this technology Rocksoil has developed the structural design taking into account the additional actions acting on the bearing elements. In addition to it, all the construction joints have been studied in detail in order to limit as much as possible the air losses during construction.

Finally, the whole team, including both constructors and designers have worked side by side in order to define the construction process that could guarantee the success of the excavation and assure the workers safety.

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