Cut&Cover Excavation in Hyperbaric Condition: an innovative solution applied for Napoli/Cancello High Speed Railway

G. Lunardi[a]
G. Cassani[a]
A. Bellocchio[a]
C. Nardone[a*]
M. Cafaro[b]
G. Ghivarello[b]
R. Sorge[c]
F. Carriero[c]
[a] Rocksoil S.p.A., Milano, Italy
[b] Salini Impregilo S.p.A., Milano, Italy
[c] Astaldi S.p.A., Roma, Italy

* corresponding author: chiara.nardone@rocksoil.com

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 water table 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. This method was abandoned in Italy a long time ago due to the high risks to workers' health, but to-day, with the latest technology and with a careful control of all the health implications, can be safely applied to prevent ground water inflow, where the required lowering of the water table does not exceed 10 m. This is the first time that such technology is applied in Italy and the paper describes its general principles focusing on the construction phases and the safety and health procedures to be strictly followed for this innovative tunnelling approach.

Key words: Cut&Cover, Compressed air, Hyperbaric Chamber, Construction Phases, Connection Detail

1. Introduction

The Naples-Bari route is part of the Scandinavia - Mediterranean Corridor of the Trans-European Network (TEN). Its requalification and development aim to improve the competitiveness of rail transport, integrate the south - east railway network with the high-speed service, and increase the share of goods transported by rail [1].
The Trans-European Transport Network (TEN-T) aims to develop an integrated multimodal transport network allowing people and goods to move quickly and easily across the EU (Fig.1). This is intended to support the development of the internal market and reinforce economic and social cohesion.
The Scandinavian-Mediterrean Corridor (5) is the longest of the TEN-T Core Network Corridors and is partially based on a series of former Priority Projects. It links the major urban centres in Germany and Italy to Scandinavia and the Mediterranean whilst crossing seven different Member States: Finland, Sweden, Denmark, Germany, Austria, Italy and Malta. The development of the Naples-Bari route, falling within the Corridor 5 Helsinki - Valletta, has been identified as a priority.
Referring to the national point of view the construction of the high capacity railway line Naples-Bari, together with the activation of the Rome-Naples high-speed railway system, will favour the integration of the railway infrastructure of the South-East with the Connecting Directories to northern Italy. This upgrade will have a paramount impact for the socio-economic development of the South, reconnecting two areas, Campania and Puglia.
The variant in the stretch between Naples and Cancello, particularly strategic in the overall arrangement of metropolitan, regional and long-distance connections, 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 high-speed services increasing overall accessibility to the railway transport in the Naples hub.

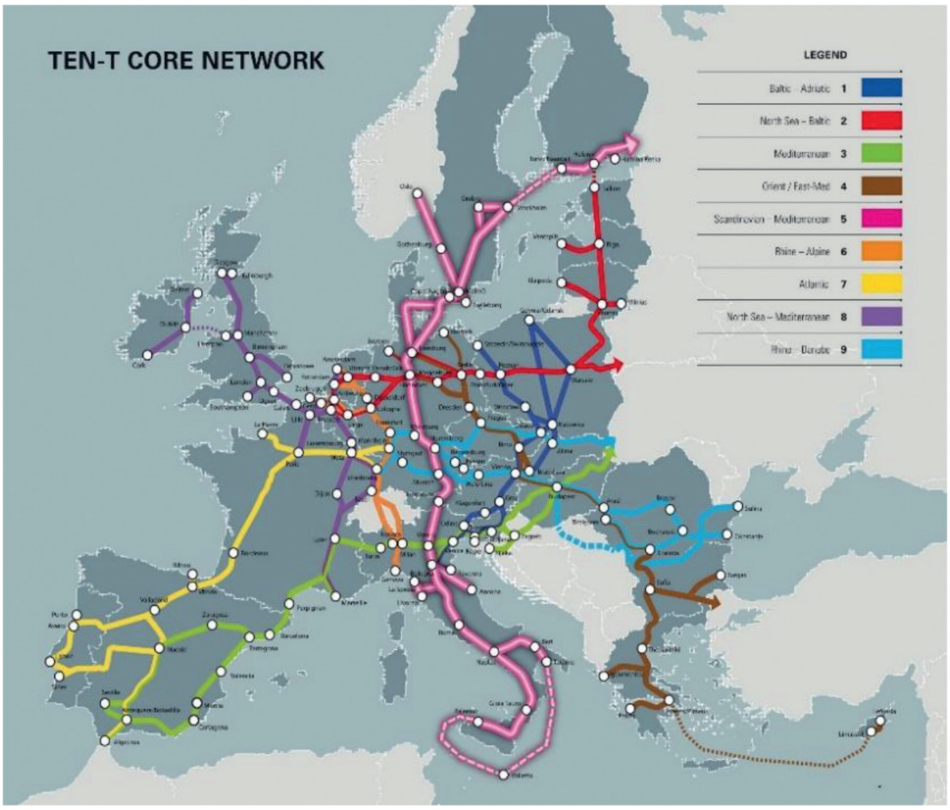
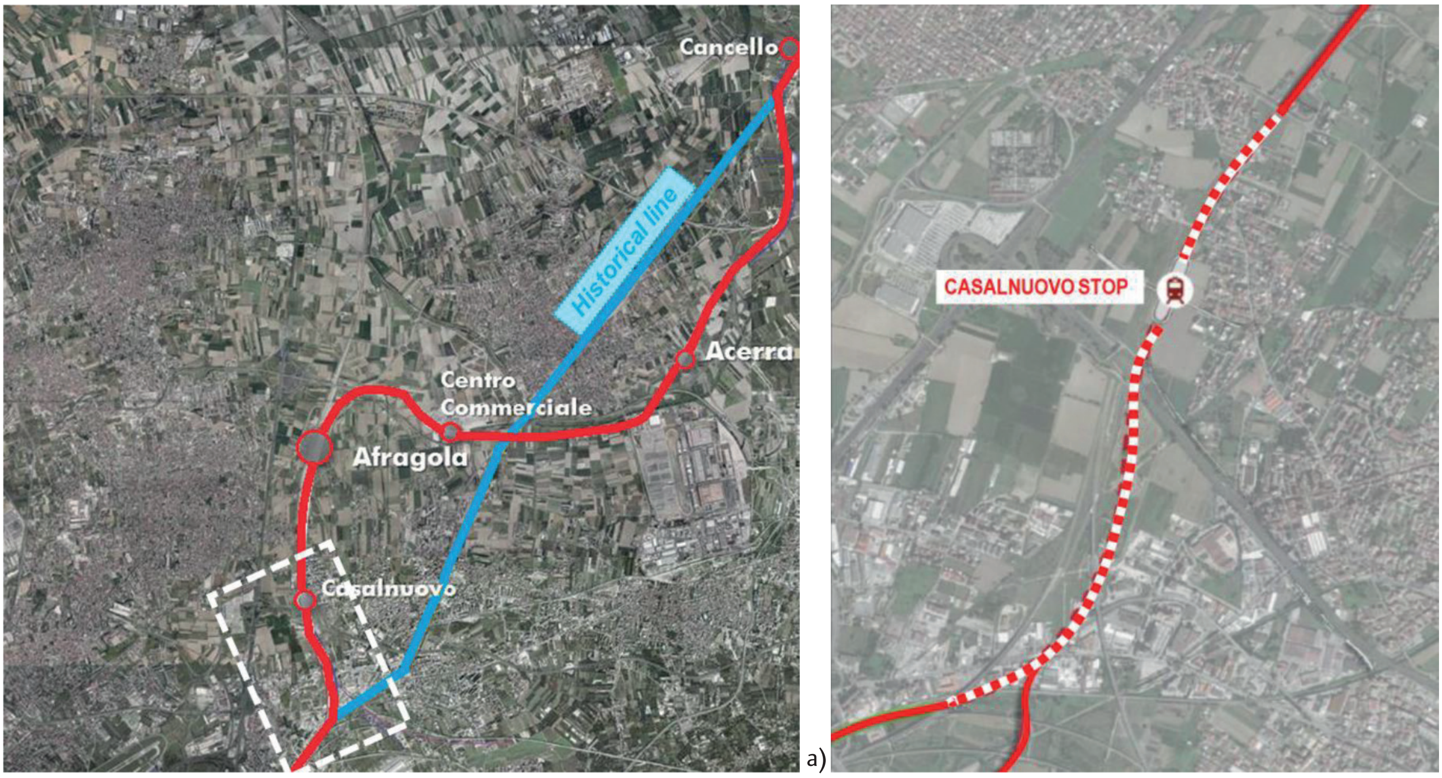


Fig.1 – Trans-European Transport Network: Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals [1].

1.1. The project and the proposed solution

Commissioned by ITALFERR S.p.A., the project is scheduled for completion by 2022 and comprises the first section of the Naples - Bari line. The section will extend for about 15.5 km across the Casoria, Casalnuovo, Afragola, Caivano and Acerra areas and includes, together with viaducts, railway embankments and trench stretches (Fig. 2a), an cut & cover tunnel named "Casalnuovo" developing between chainages 0+550.00 and 2+860.21 km (Fig. 2b). After a first stretch called Parapioggia, casted in situ without any ground retaining structure, the tunnel is excavated between diaphragm walls horizontally restrained by reinforced concrete slabs, which constitute the roof and bottom slab. The new Cassino line, in correspondence of the chainage 1+026.75, joins the Circumvesuviana line, which runs almost parallel for the remaining part of the tunnel: the transversal section, characterized by a single tube in the first stretch, becomes a double tube section (Fig. 3).

With regard to the bid issued by Italferr S.p.A. in 2016, it was requested to the Com-



a) b)

Fig. 2 – Railway section Napoli-Cancello: (a) general layout and intersection with the historical line (dashed white line define the limit of section detail); (b) section detail of the cut and cover tunnel "Casalnuovo".

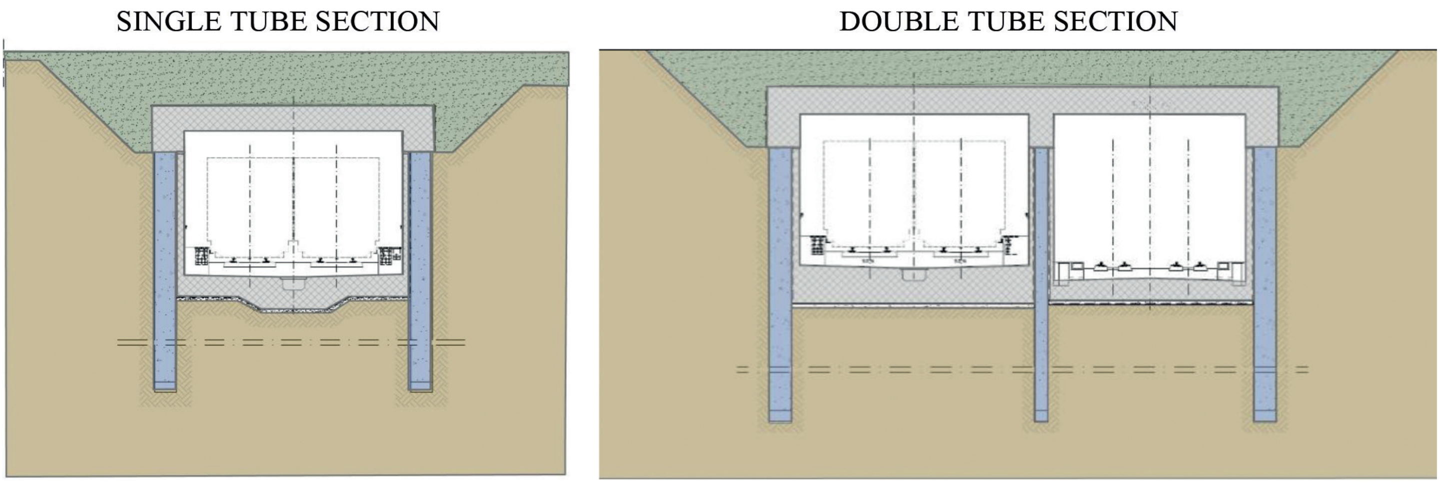


Fig. 3 – Typical cross sections of the cut and cover tunnels.

petitors to study an original technical solution that could solve the interference of the tunnel with the groundwater (from its beginning till chainage 1+600), analysing the working phases with the aim of getting an easy management from a construction point of view. For this purpose, NACAV s.c.p.a. company, a JV between Salini Impregilo S.p.A. and Astaldi S.p.A., decided to choose an original technical solution, successfully used abroad in the recent period (i.e. Allmend Tunnel in Luzern, Switzerland and Audi Tunnel in Igolstadt [2]), consisting in using pressurized air dig for the tunnel excavation between diaphragm walls. Such choice allowed NACAV s.c.p.a. company to get the job.
The scope of the paper is to describe this specific technique focusing on the construction process and on how the latter influenced the design phase.

1.2. Geological Overview

The vast flat area, between the Tyrrhenian Sea, the Massico Mountain, the mountains of Caserta and the Vesuvius, is called Piana Campana. In this area, in historical times and in particular during the recent Quaternary, volcanic phenomena occurred which contributed to define the current morphological structure.
From the structural geological point of view of the region, the area affected by the project alignment is entirely located in the so-called "Piana Campana".
The Piana Campana is a structural depression stretched in the direction of NO/SE, filled with sedimentary and volcanic deposits of the plio-quaternary age. The northern, southern and eastern margins are constituted by Mesozoic carbonate soils and by Miocene, calcareous and siliciclastic soils between the Burdigalian and the Upper Tortonian (Miocene). These soils derive from the deformation of the westernmost areas characterized by carbonate sediments.
The Piana has been progressively filled by marine deposits, alluvial and marsh, by the products of Campi Flegrei and those of the Somma-Vesuvio complex. The thicknesses of these deposits have been estimated to be at least 4500 m based on geophysical and gravimetric analyses. The thickness of the vulcanoclastic and debris cover gradually increases from the carbonate slopes

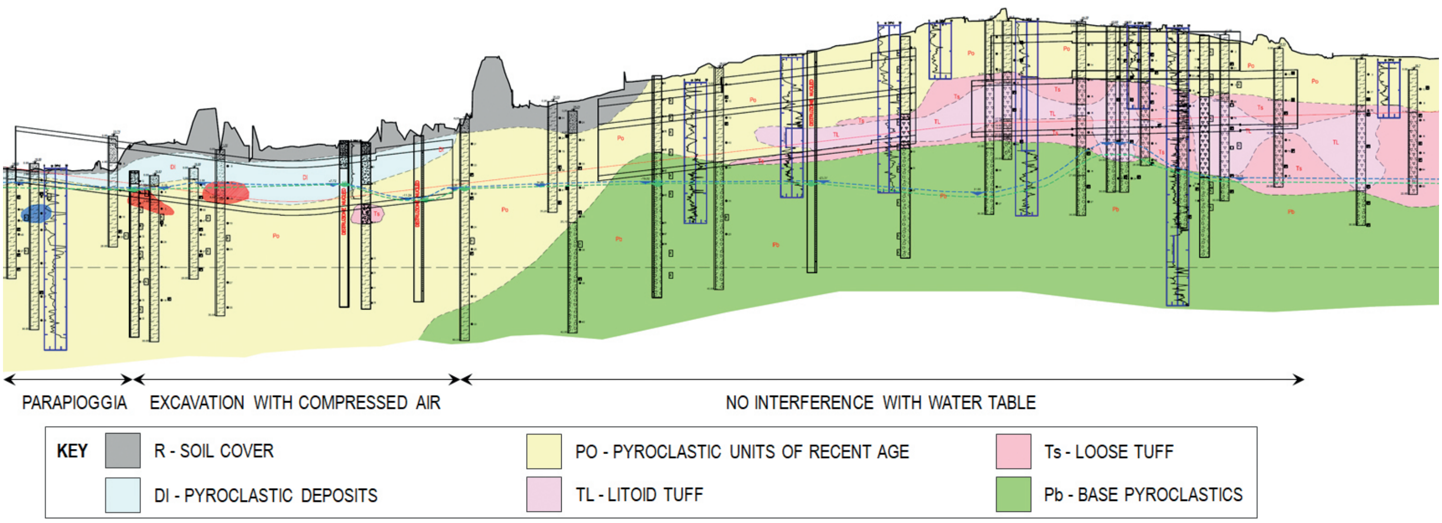


Fig. 4 – Geological-stratigraphical section.

Fig. 5 – (a) Pyroclastic deposits (DI); (b) 2. Pyroclastic units of recent age (PO).

towards west, with thicknesses of about 2000 m in the central and southern part of the plain. Geologically the lands of the Piana Campana are young, no more than 30000 - 39000 years.
Among the pyroclastic events for the constitution of the plain, the most important is represented by the event that marked the "putting in place" of the Ignimbrite Campana, erupted from the Campi Flegrei volcanic complex, about 37000 - 39000 years ago. The lithostratigraphic units that are found along the alignment (Fig. 4) of the cut and cover tunnel are listed below:

- soil Cover (R);
- pyroclastic deposits (DI);
- pyroclastic units of recent age (PO);
- litoid tuff (TL);
- loose Tuff (Ts);
- base pyroclastics (Pb).

In the area of interest, the main aquifer is located in the Base Pyroclastics which are confined at the top level by the Ingnimbrite Campana (Litoid and Loose Tuff). In the upper layer, where the tunnel will be excavated, it is located a superficial aquifer punctually connected with the deeper one.

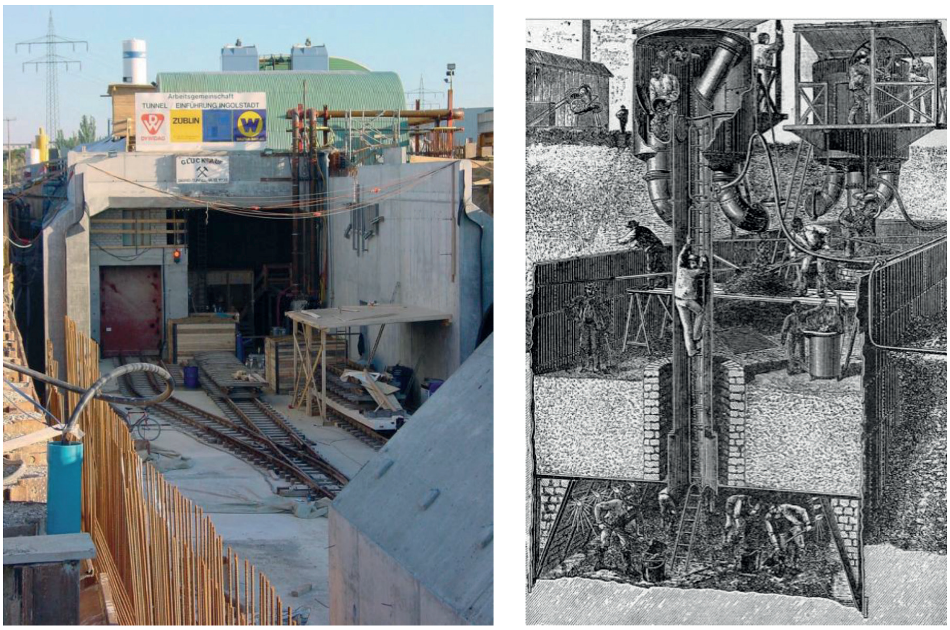


Fig. 6 – Application of the proposed solution: (a) AUDI Tunnel, Ingolstadt, Germany; (b) foundations of the Eiffel Tower, Paris, France.

The average permeability ranges from 10^{-3} to 10^{-6} m/s.
The tunnel stretch interfering with the ground-water is mainly excavated in DI (Fig. 5a) and PO (Fig. 5b) units which can be classified respectively as silty-clayey sands - clayey/silty sands and medium to coarse sands with silt and gravel derived from volcanic deposits. The soil nature thence requires a specific intervention in order to avoid the water inflow and the likely consequent fine transportation.

2. The proposed solution

In recent years, the technique which foresees the use of compressed air for excavation under ground-water has been applied for the construction of cut and cover tunnels. In northern Europe and in Switzerland, some application demonstrated it is a valid alternative to the traditional solutions suggesting its use for a wider range of cases also not involving the mechanized excavation (Fig. 6a). Although this method seems to be one of the last avant-gardes, it finds its origin in the caisson technique born in France in 1841. Starting from that application, it became more and more widespread for the construction of underwater foundations such as the foundations of the Eiffel Tower in France (Fig. 6b) or of the Hach Industry bridge in Rome [2].
However, if on the one hand this technique allowed the realization of some invaluable historical works, on the other, it was very

Tab. 1 – Comparison between jet grouting and compressed air.

	Jet grouting	Compressed air
Watertightness in the construction phase	*Partial:* due to the impossibility of a comprehensive field test, it is quite frequent to have preferable water inflow path.	*Perfect:* all the water inflow paths are counteracted by the air pressure.
Environmental impact	*Possible:* the chemical components of the jet grouting mixture could pollute the ground water.	*Null:* no chemical substances are introduced in the ground.
Management of unexpected water height	*Difficult:* the jet grouting plug is dimensioned in the design phase and can manage ground water fluctuation limited to the safe factors assumed.	*Easy:* it is sufficient to increase the air pressure to counteract the higher water head.
Costs	High costs due to the soil improvement execution.	The higher cost of the construction plant is compensated by the elimination of the soil treatment.
Works duration	Long time needed for the soil improvement execution and possible delays during excavation due to the partial water-tightness which could require integrative grouting.	The technology requires a construction process industrialized in every phase: this need leads to a longer time for the installation of the machinery and the start of the excavation followed by a very fast advance.

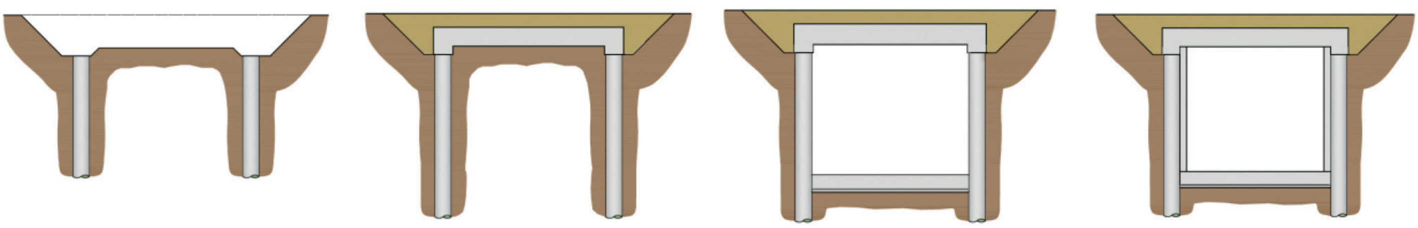


Fig. 7 – General construction method.

dangerous for the workers who, working at high pressures, were subjected to a high health risk. This is the reason why it was abandoned in Italy, but today, with the latest technology and with a careful control of all the health implications, can be safely applied to prevent ground water inflow, where the required lowering of the water table is limited.
In order to perform all the excavation and construction activities in dry condition traditionally it is foreseen the execution of a jet grouting plug, which compared to the use of compressed air presents various disadvantages:
difficulty in controlling the design requirements have been actually fulfilled;
a lower flexibility of the system in order to adapt to ground water level fluctuation;
possible impact on the environment due to the contamination of the groundwater, which frequently serves as a reservoir for the water supply.
The Table 1 compares the alternative solutions.

3. General Construction Method

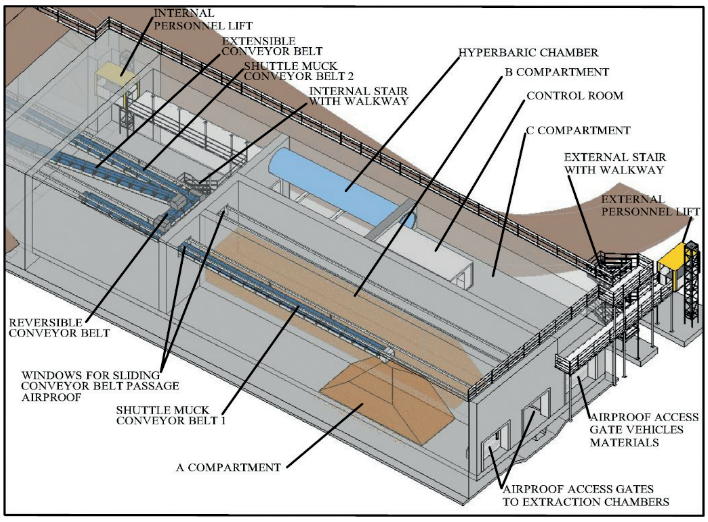
The tunnel will be constructed following the top down method (see Fig. 7) which foresees the following phases:

1. Excavation to the diaphragm wall execution level and realization of the diaphragm walls;
2. Cast of the reinforced concrete roof slab and backfilling above the roof slab;
3. Excavation below the roof slab, between the diaphragm walls, to the foundation level and cast of the bottom slab;
4. Cast of the lining walls and finishes installation.

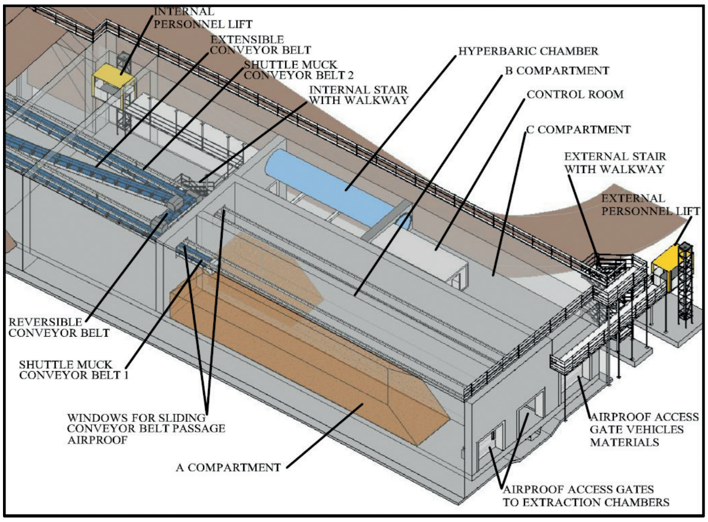
In order to perform the excavation and the cast of internal structures in dry condition, a pressure higher than the atmospheric one is applied in the tunnel after the execution of the backfilling, before the start of digging operations. The pressure value to be applied is equal to the corresponding value of hydrostatic pressure acting on the excavation bottom due to the water head at that time: by means of piezometers specifically foreseen to monitor the ground water table during the excavation it is possible to adapt the pressure to the required value.
After the internal structures are casted and sealed it is possible to deactivate the internal air pressure.

3.1. Design Compliance

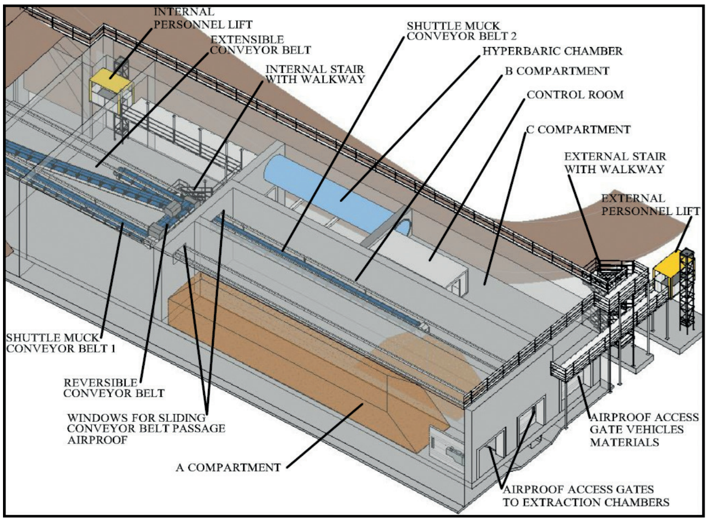
The application of the compressed air in the tunnel construction should be taken into account in order to consider all the relevant load cases and global equilibrium scenarios.
The internal pressure is an additional load acting on the structure in the temporary phase that should be considered in the structural analyses. It has 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 counteracts the earth and water pressure acting inward the tunnel. In other words, this methodology does not require a



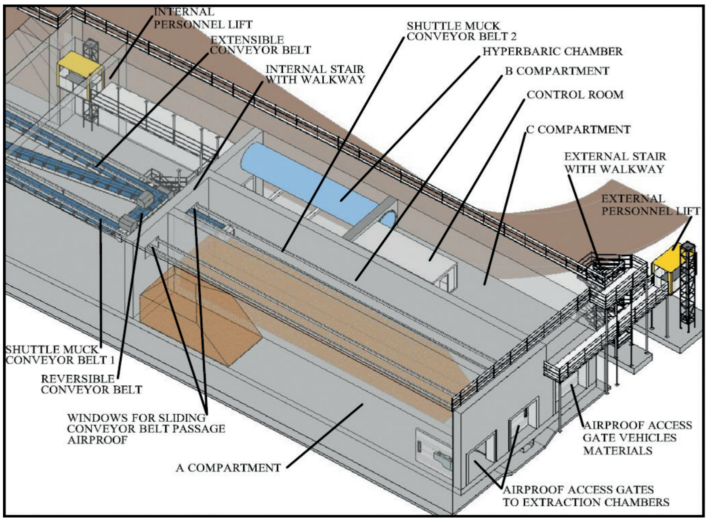
PHASE 1
- COMPARTMENT A:
  Starting of muck storage through shuttle conveyor belt 1;
  Access Gate closed;
  Sliding window open;
  Compartment under tunnel pressure.
- COMPARTMENT B:
  Shuttle conveyor belt 2 retracted;
  Access Gate open;
  Sliding window closed;
  Compartment under atmospheric pressure;
  Starting mucking with underground loader.



PHASE 1.1
- COMPARTMENT A:
  Continue of muck storage through shuttle conveyor belt 1;
  Access Gate closed;
  Sliding window open;
  Compartment under tunnel pressure.
- COMPARTMENT B:
  Shuttle conveyor belt 2 retracted;
  Access Gate open;
  Sliding window closed;
  Compartment under atmospheric pressure;
  Continue mucking with underground loader.



PHASE 2
- COMPARTMENT A:
  Shuttle conveyor belt 1 retracted;
  Access Gate open;
  Sliding window closed;
  Compartment under atmospheric pressure;
  Starting mucking with underground loader.
- COMPARTMENT B:
  Starting of muck storage through shuttle conveyor belt 2;
  Access Gate closed;
  Sliding window open;
  Compartment under tunnel pressure.



PHASE 2.1
- COMPARTMENT A:
  Shuttle conveyor belt 1 retracted;
  Access Gate open;
  Sliding window closed;
  Compartment under atmospheric pressure;
  Continue mucking with underground loader.
- COMPARTMENT B:
  Continue of muck storage through shuttle conveyor belt 2;
  Access Gate closed;
  Sliding window open;
  Compartment under tunnel pressure;

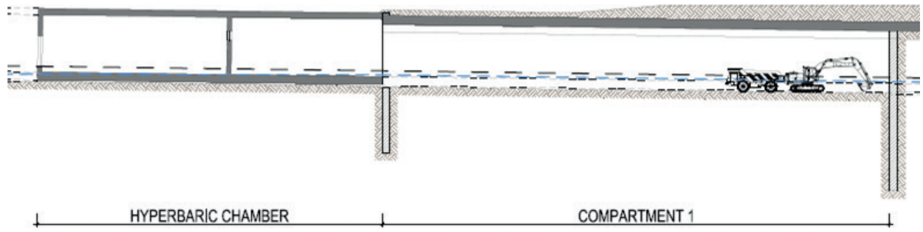
Fig. 8 – Operative phases performed inside the Hyperbaric Chamber.

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.

3.2. Operational Phases

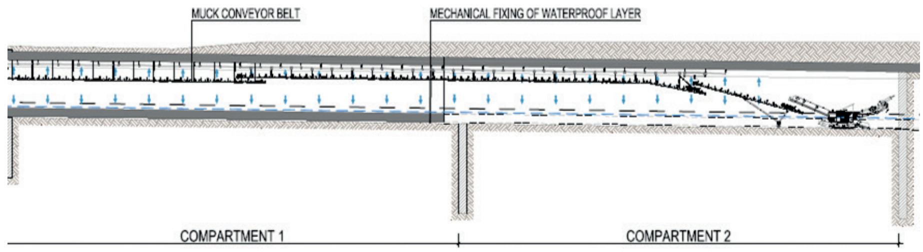
In order to allow the application and management of the air pressure, a hyperbaric chamber should be constructed at the tunnel entrance, following the specific standard reference [3]. The chamber should be designed to let the workers/machinery pass through and the excavated ground be transported to the landfilling, always maintaining the design pressure value. In general, this main function is accomplished by two water-tight doors, one connecting to the excavation front and one to the external work area, that will be activated alternatively in order to gradually adapt to the internal or external (atmospheric) pressure respectively in case of ingress or egress. The adopted solution is compliant to the ITA Guideline [4].
For the case of study, the transversal section of the hyperbaric chamber, 40 m long and 13 m wide, has been divided into three compartments: two for the accumulation of the excavated material (Compartments A and B) and one for the passage of vehicles and personnel (Compartment C, divided vertically in two volumes in order to separate the transit of construction materials vehicles and personnel). Fig. 8 summarises the operative phases performed inside the Hyperbaric Chamber. 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 num-

Compartment 1



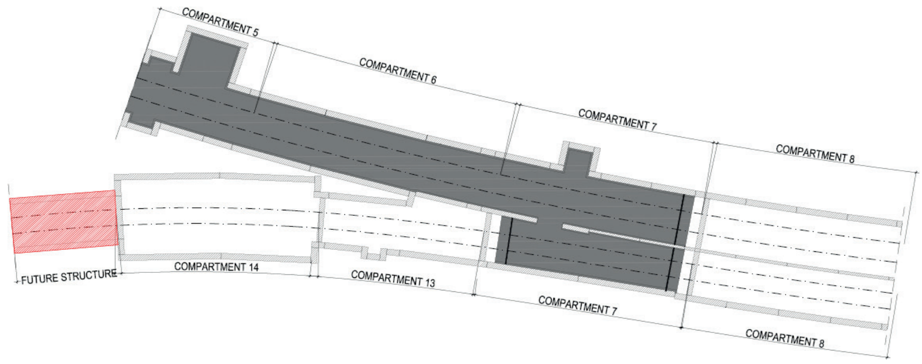
- After the construction of the hyperbaric chamber, demolition of the compartment diaphragm walls and excavation under top slab of the soil volume above GWL at atmospheric pressure;
- Well point installation for GWL lowering and excavation completion at atmospheric pressure;
- Waterproofing system installation and casting of internal structures;
- Installation of production plant and air pressure management facilities in the hyperbaric chamber (including the conveyor belt for muck transport).

Compartment 2-6



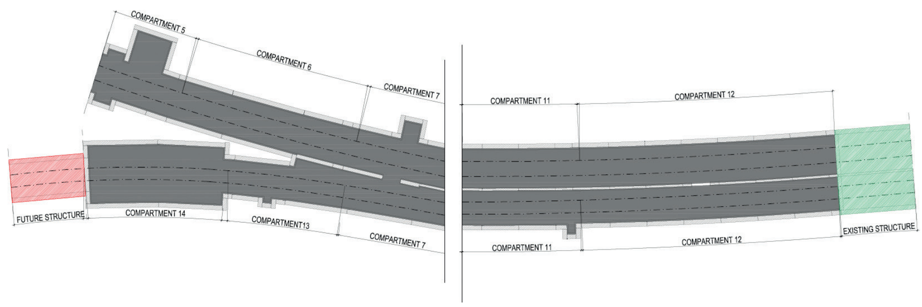
- Activation of compressed air system. In order to guarantee the pressurization of the next compartment, some holes are provided in the partition wall. After its demolition the work proceeds with the top-down excavation;
- At the end of the excavation process the waterproofing system will be installed 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;
- 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.

Compartment 7-13



- Air pressure adjustment to the value foreseen for compartment 7 and start of excavation till reaching the opening in the central alignment of diaphragm walls; the excavation proceeds in both tubes at the same time;
- 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 is possible to proceed with the standard construction process for compartment 13, and after 14, on the Circumvesuviana branch;
- In compartment 14 specific construction details are foreseen considering that in the future the tunnel under construction will be connected to the adjacent portion (in red - new realization).

Compartment 8-12



- Air pressure adjustment to the value foreseen for compartment 8 and start of excavation proceeding in both tubes at the same time. The standard construction process continues till the last compartment without specific adjustment;
- At the end of the excavation process of compartment 12, the waterproofing system will be installed foreseeing specific details in order to allow the connection with the adjacent existing portion and a structural continuity.

Fig. 9 – Work phases related to the construction of Casalnuovo Tunnel.

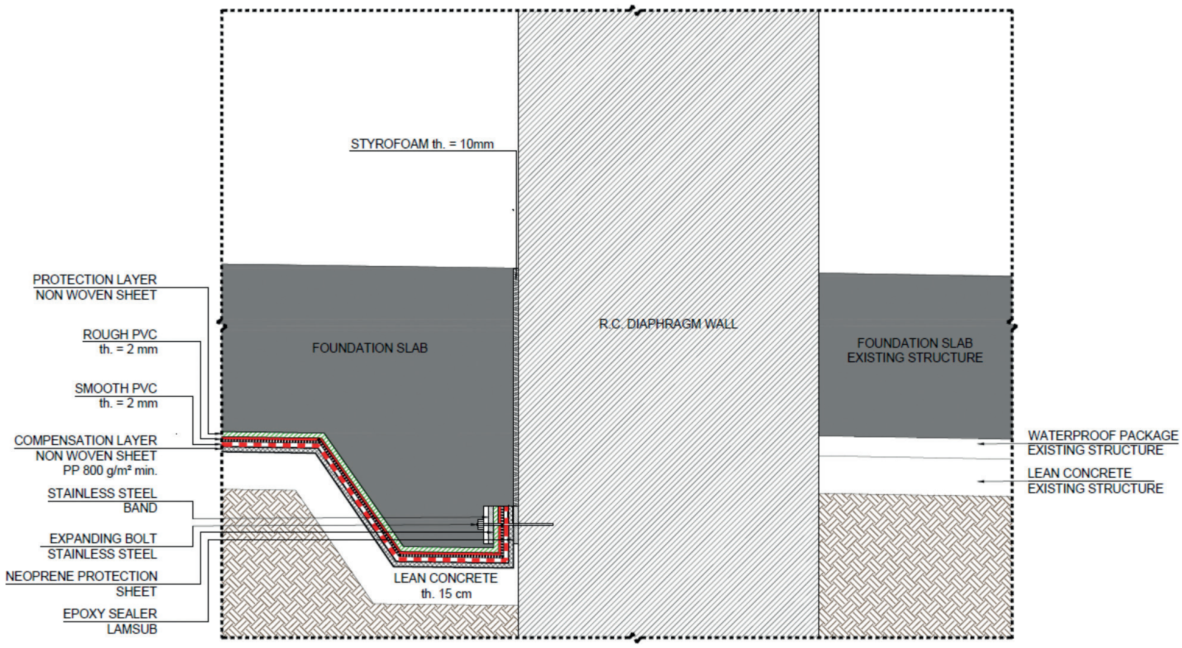


Fig. 10 – Waterproofing mechanical fixing at the end of compartment 12.

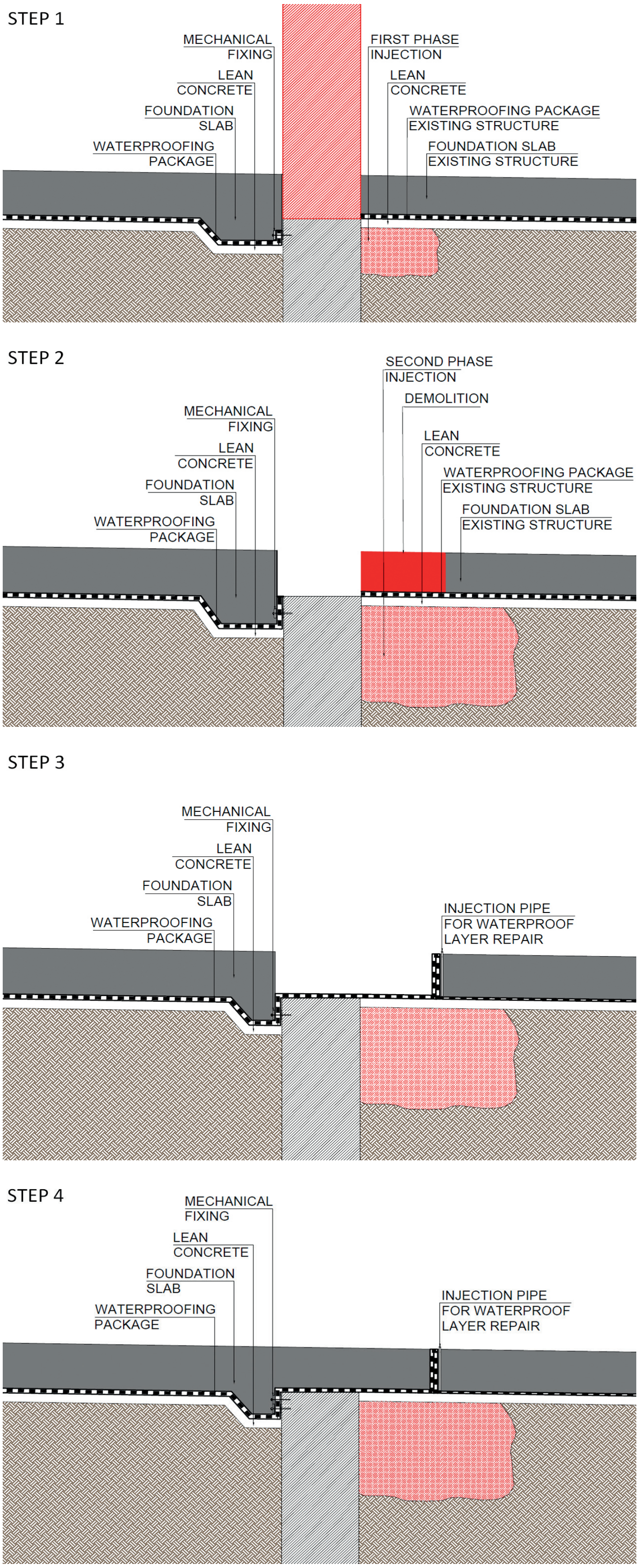
ber of passages. In particular, to manage the muck transport, it is envisaged the use of a hanged extensible conveyor belt, which will discharge the material coming from the front on a reversible belt feeding two shuttle belts. The shuttle belts will store the muck alternatively in one of the two compartments addressed to this specific function (Compartments A and B).
The pressure value to be applied for the excavation, depending on the water-head has to be adapted while the excavation proceeds. In the case of study, the maximum excavation level varies along the alignment and the excavation section widens for the STI exits, for the wastewater lifting plants and the relative inspection chambers and for the niches (air losses evaluation through Schenck & Wagner formula [5]).
This configuration would require the adjustment of the air pressure of compressed air at each advance, not applicable in practice. For logistic purpose and to avoid excessive air losses at the tunnel face, the tunnel has been divided into compartments (n.14) limited on the sides and on the top by the tunnel structures and at the front by specific partition diaphragm walls.
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.
Fig. 9 summarises the work phases applied in the case of the Casalnuovo Tunnel.

4. Connection with existing structures

The tunnel stretch to be excavated with the application of compressed air ends at chainage 1+337.65 that corresponds to the start section of a tunnel portion already existing. Between chainages 1+337.65 and 1+448.35 the tunnel alignment underpasses an existing railway embankment: since the project in object was already scheduled at the moment of the embankment construction, the construction of interfering portion of tunnel was anticipated in order not to cause subsidence to the surface railway line in the future.
With the aim of getting a continuous entity both from a structural and water-tightness point of view, a specific construction detail has been studied at the end of compartment 12. In correspondence of the contact section, in fact, it is necessary on the one hand to seal the new structure, so as not to have any water inflow at the deactivation of the air pressure, and on the other hand, to allow for the connection of waterproofing layers and structural elements.
In Fig. 10 the solution adopted for the foundation joint is described in detail, showing also the construction phases foreseen to actually realize the connection between the two structures. The same concept has been applied to the connection in correspondence of the lining walls.
At the end of the last compartment, the waterproofing layer is mechanically fixed to the partition diaphragm: the fixing is located below the design level of the extrados of foundation slab in order to maintain the water-tightness also after the partition diaphragm demolition. A Styrofoam layer 10 mm thick is placed between the foundation slab and the partition diaphragm in order to protect the structure during the demolition works.
Once the structure is completely sealed, the air pressure is lowered to the atmospheric value and it is possible to proceed realizing the connection with the existing structure. The execution phases are described in Fig. 11.

Conclusions

Casalnuovo Tunnel, part of the high-speed railway line Napoli-Bari, will be excavated with the use of compressed air: the air is pressurized at the tunnel face in order to lower the water head and perform all



- Chemical injection realized through the partition diaphragm in order to reduce the soil permeability in the volume adjacent to the structural joint;
- Demolition of the partition diaphragm walls: in the lower portion, close to the foundation slab of compartment 12 the demolition should be executed from the existing stretch in order to preserve the recently casted structures.

- Additional chemical injection in order to extend the volume of treated soil to all the intervention area;
- Partial demolition of the foundation slab of the existing stretch trying not to damage the waterproofing layer.

- Cleaning of the waterproofing layer uncovered in the first portion of the existing structure;
- Installation of the new waterproofing layer welded to the existing one: in correspondence of the future structural joint between the two stretches the waterproofing layer is folded in order to guarantee the water-tightness also in case of differential displacements. An injection pipe is set up to repair the waterproofing layer as a redundancy measure;
- At the connection with the already casted portion of compartment 12 another mechanical fixing is provided.

- The foundation slab is casted guaranteeing a structural continuity with compartment 12 by means of post installed rebars (or coupled bars).

Fig. 11 – Work phases related to the connection with existing structures.

the operations in a dry environment. Although this technology finds its origin in the 1th century, its application nowadays can be considered innovative due to all the constraints related to worker health and safety.
The construction process has been deeply studied in the design phase with the aim of reducing air losses and adapting to the variable water head always guaranteeing the worker safety and the instantaneous implementation of the emergency procedures. The paper describes the construction process focusing on the operative phases for the ingress and egress of personnel, machinery and muck through the hyperbaric chamber and on the advance phases related to the particular stretch geometry. For a successful application of this excavation method, all the construction details should be meticulously analysed: in particular the waterproof layer fixing at the extremities of the stretch has been studied considering the need of connecting to the adjacent existing structures.

References

[1] Regulation (EU) No. 1315/2013. *Council of 11 December 2013, European Parliament.*

[2] Schwarz J., Hehenberger F. (2004) – *Compressed air for top down. In Tunnels & Tunnelling International*, 36 (2).

[3] EN 12110. *Tunnelling machines - Air locks - Safety requirements*.

[4] ITA-AITES WG5, 2015. *Guidelines for good working practice in high pressure compressed air.*

[5] Jardine F.M., McCallum R.I. (1992) – *Engineering and Health in Compressed Air Work. Proceedings of the International Conference. Oxford.*

Sommario di:

Cut&Cover in condizioni iperbariche: una soluzione innovativa applicata all'alta velocità ferroviaria nella tratta Napoli/Cancello

G. Lunardi[a]
G. Cassani[a]
A. Bellocchio[a]
C. Nardone[a]*
M. Cafaro[b]
G. Ghivarello[b]
R. Sorge[c]
F. Carriero[c]
[a] Rocksoil S.p.A., Milano, Italy
[b] Salini Impregilo S.p.A., Milano, Italy
[c] Astaldi S.p.A., Roma, Italy

* corresponding author: chiara.nardone@rocksoil.com

Lungo la linea di alta velocità ferroviaria Napoli-Bari, è prevista la realizzazione di una galleria artificiale che si sviluppa parzialmente sotto falda. Lo scavo, top-down, verrà eseguito con l'applicazione dell'aria compressa in modo da garantire un fondo scavo asciutto durante le operazioni di smarino e il getto delle strutture interne. Questo metodo venne abbandonato molto tempo fa a causa dell'alto rischio per la salute dei lavoratori, ma oggi con le recenti tecnologie e un attento controllo delle possibili ripercussioni in termini di sicurezza può essere applicato in modo sicuro per prevenire l'ingresso di acqua durante lo scavo nei casi in cui l'abbassamento di falda necessario non eccede i 10 m. Questa è la prima volta che una tecnologia del genere viene applicata in Italia; nell'articolo si descrivono i principi generali di funzionamento focalizzando l'attenzione sulle fasi costruttive e sulle procedure di sicurezza che devono essere seguite secondo questo approccio innovativo.