The application of Semi-Automatic Tubular Arch inside Boscaccio Tunnel: a new concept of primary lining.

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ABSTRACT: Tunnel excavation is a particularly hazardous activity due to working in confined spaces. In addition, uncertain ground conditions and the use of heavy equipment creates additional occupational safety and health hazards for site personnel. One of the most important requests of the underground construction market is an increase in safety levels during the excavation stage. The risks are well known and this give the possibility to managed them. Semi-Automatic Tubular Steel Arch and EKIP 2104 introduced within the tunneling industry a solution whit improved performance, time saving and as a consequence cost saving, with respect to the health and welfare, increasing safe working conditions of the workers. The paper describes the application of this new reinforcing element installed by EKIP 2104 inside Boscaccio Tunnel, which mitigates the hazards typical in this work phase. The economic benefit related to time and material saving will also be addressed.

1 INTRODUCTION

Ground-lining interaction control is one of the most critical processes during the implementation of a tunneling project. The design and construction decisions throughout the tunnel project are very critical to reduce the ground movements around the excavated tunnel.

These movements have a direct effect on the tunnel stability and the design loads of the lining system (Lunardi P. et al., 1994)

Tunnel linings are structural systems installed during and/or after the excavation to provide ground support, to maintain the tunnel opening, to limit the ground water inflow, to support appurtenances and to provide a substrate for the final finished exposed surface of the tunnel. Tunnel linings can be used for initial stabilization of the excavation, permanent ground support or a combination of both (Hoek E. et al., 1981)

Although tunnel linings are structural systems they differ from other structural systems in their interaction with the surrounding ground, which is an integral aspect of their behavior, stability and overall load carrying capacity. The loss or lack of support provided by the surrounding ground can lead to a failure of the lining. The ability of the lining to deform under load is a function of the relative stiffness of the lining and the surrounding ground (Beniawski Z.T. 1984). Frequently, a tunnel lining is more flexible than the surrounding ground. This flexibility enables the lining to deform in sympathy with the surrounding ground deformations during and after tunnel excavation. This deformation allows the surrounding ground to develop strength and stability. The tunnel lining deformation allows the moments in the tunnel lining to redistribute the axial and eccentric loads within the lining. Accordingly, the most efficient tunnel lining is one that has flexibility and ductility.

The development of the tubular steel arch has good compatibility with underground operational needs (Zenti C.L. et al. 2012) and the applications have been described in previous papers (Lunardi P. et al. 2013, Zenti C.L. et al. 2014, Zenti C.L. et al. 2015). The tubular arch is very stable and easy to handle during transportation and installation. The buckling risk during installation has been virtually eliminated due to its high rigidity. This reduces the risks to operatives and is therefore safer to install than other less-rigid support arches.

These days the increase in levels of safety is one of the most important drivers for innovation and research. The risks associated with this work phase are well known and have to be addressed and managed. In this paper, the authors discuss the application of Semi-Automatic Tubular Arch inside Boscaccio Tunnel, which represents a new concept of primary lining. The paper also briefly introduce the machine EKIP 2104, which has been developed for the installation of semi-automatic tubular arches without the presence of workers at the excavation face.

2 TUBULAR ARCH

2.1 *Design aspect*

In order to excavate the opening required for the tunnel, the natural properties of the ground are disturbed. The ground is rarely a homogeneous mass but has been subjected to massive natural forces and has been substantially altered. Once the opening has been excavated it must be supported in order for the workers to be protected from falling material, collapse or other deterioration of the tunnel roof or crown.

Stress and strain of the rock or ground masses are normally analyzed, by many authorities, in two dimensions within a transverse section of a tunnel. In the vicinity of the tunnel face where the predominant deformation and stress redistributions occur, as the stressed rock is dislodged during excavation, the third dimension assumes a vital role. The open steel profiles (IPE, HE, IPN), typically used as the primary lining support, show performance weakness in their static structural properties, in directions other than the normal and central position. These problems can be solved using a profile with a symmetrical axial cross section, like a tubular rib. By substituting the open profile with a circular profile, a better stress redistribution is provided. This enables the resistant cross section the ability to accommodate and control axial and eccentric loads, acting along any direction. (Zenti et al. 2012). This fact is relevant in all those cases in which not homogeneous load conditions are expected, such as: skin effect in case of a tunnel excavated inside a landslide, squeezing condition which could generate cavity convergence or face extrusion, fault zone.

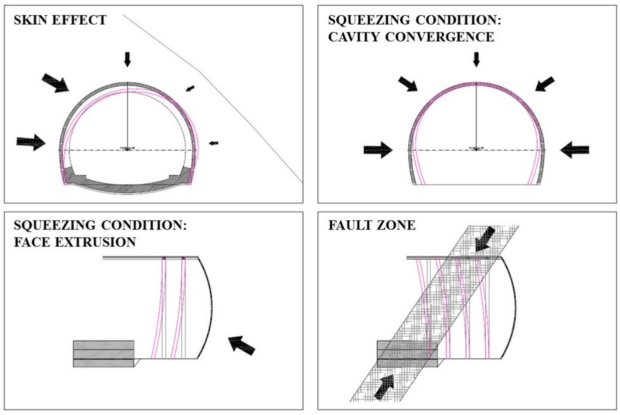

Figure 1. Not homogeneous load conditions acting on first lining

2.2 *Semi-automatic evolution*

One of the most important requests from the underground construction market is an increase in the safety level during the excavation stage. The risks are well known and should be managed in a better way.

The excavation can be carried out in different methods depending on the type of material to be excavated. With reference to the “full excavation face” method, the excavation proceeds through the use of an excavator equipped with a "hammer" or by drill and blast. Subsequently, after removing portions of unstable rock it is possible to install the primary lining comprising of steel arch and fibre reinforced shotcrete.

Before starting the assembly of the arches, it is necessary to ensure that the operations barring face are taken. Only after the cleanliness and integrity of the excavated surface has been ascertained, is it possible to proceed to the assembly and positioning of the steel arch by a telehandler (or similar equipment). Usually the presence of workers close to the excavation face is necessary during some specific phases: arch assembly, foot arch positioning, arch lining and bracing installation.

From an operational point of view the tubular rib behaves in a very stable manner and is easy to handle during transport and installation. This ensures a high safety level to the workers. The high rigidity of the proposed profile virtually eliminates the risk of possible buckling during the installation.

The risks are well known and this give the possibility to manage them. By using tubular arches the risk of workers related to the buckling of arch during handling and uplift has been eliminated but the new challenge is to completely remove the presence of workers during the specific work phase.

This new type of primary lining reinforcing system is characterized by a semi-automatic installation procedure. The arch, assembled, yet "folded" closed (Figure 2), is transported to the excavation face. When the reinforcing element is adjacent to the desired installation position, it is lifted, whereupon it automatically opens. The bracing elements are pre-installed in the factory during the production of the arch. Therefore the steel arch can be quickly connected to those arches already in-place without the intervention of workers by using EKIP 2104.

Figure 2. The arch, assembled, yet "folded" closed

The development of this solution required the detail design of the innovative automatic unfolding hinges, arch-to-arch connection device and the arch foot support system (Figure 3). The performance of these solutions was assessed on the basis of calculations and job site tests, all the details have been rendered in a previous paper (Zenti C.L. et al., 2015).

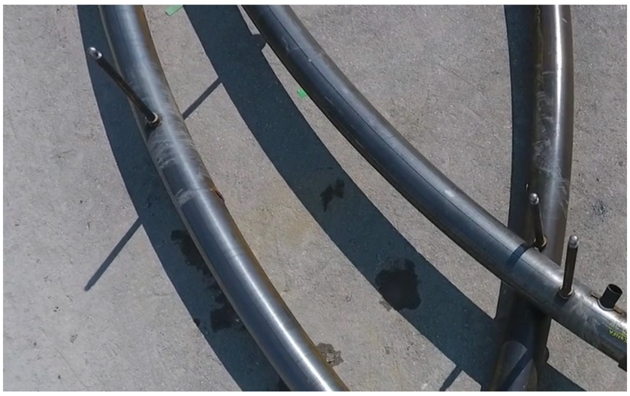

Figure 3. Unfolding hinges, arch-to-arch connection device and the arch foot support system.

3 THE MACHINE

Underground construction is inherently a dangerous undertaking. Work progresses in a noisy environment in close quarters with moving heavy machinery. Careful attention must be paid to the layout of the worksite and workers must be protected at all times.

The real challenge is to remove the presence of workers during the specific work phase. EKIP 2104, a three armed radio controlled equipment (Figure 4), represents a new concept of machinery in order to install steel ribs without the presence of workers at the front of the excavation. This mitigates the hazards associated typically with installation of immediate steel ribs support which includes: falls from heights, restricted operator visibility, and exposure to continuous construction noise, assuring a semi-automatic installation in a considerably safe, precise and time saving manner.

Figure 4. EKIP 2104

3.1. *Semi-Automatic Tubular Arch installation stage*

The arch, assembled, yet folded "closed" is transported to the excavation face. When the reinforcing element is adjacent to the desired installation position it is lifted by the central arm of EKIP 2104 (Figure 5), whereupon it automatically opens. When the arch is positioned to the required position, the lateral arms of the machine open the arch (Figure 6).
The bracing elements are pre-installed in the factory during the production of the arch and once in the approximate position, the machine pulls the arch towards the arches that are already in position. This procedure engages the bracing systems on the adjacent arches, locking them together at the appropriate spacing (Figure 7).

Figure 5. Tubular Arch lifting.

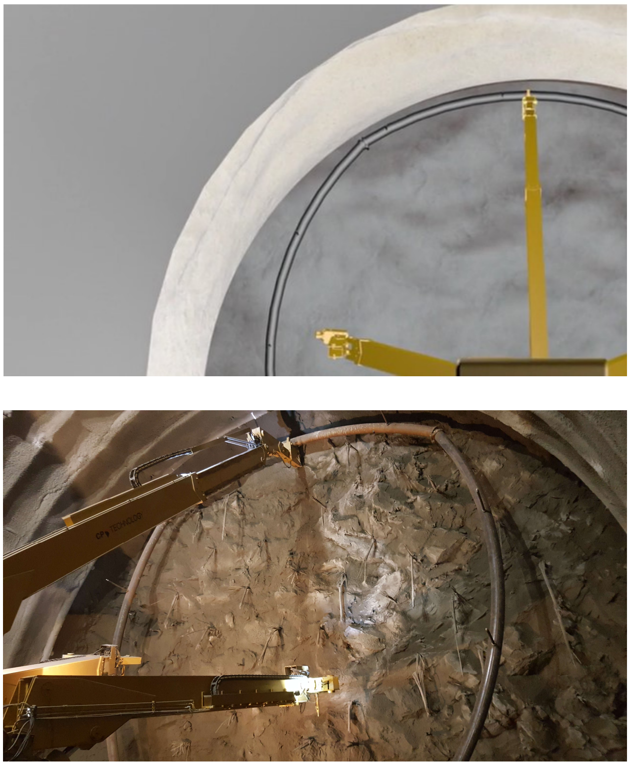

Figure 6. Tubular Arch opening.

The final operation is the positioning of the foot of the arch to the correct level (Figure 8), thereby ensuring the correct positioning of the arch. Usually this procedure is performed by an operative inserting timber packers under the foot; this can be dangerous and from a technical standpoint is not a robust solution. To address this a special telescopic foot to the tubular arch has also been developed that can be extended by machinery, thereby enabling the positioning of the arch only with the use of a machine operated arm.

The installation of this kind of steel arch does not require the presence of the worker during the installation, either to assemble the constituent sections of the arch, to install the bracing or to position the foot.

Figure 7. Tubular Arch connection by insertion of the bracing elements.

Figure 8. Tubular Arch foot extension and positioning.

This mitigates the hazards typical in this work phase including: steel profile buckling, falls from heights, restricted operator visibility and continuous loud site noise. The presence of a worker close to the excavation face during this working phase is not necessary and this represents a very important enhancement for related safety aspects (Figure 9). The machinery is radio-controlled and the worker can control it from a safe position.

The equipment can be supplied with topographical reference system CP track. CP track system (CTS) allows the site to obtain the information of the topographical position of the steel rib just using a USB key for data download from the machine once steel rib positioning operation is completed.

Figure 9. Tubular Arch installation by EKIP 2104.

The last phase is related to the first lining completion. It consists of arch filling and spraying of the concrete shield. The arch filling is rapid and functional to ensure the complete filling of the profile (Figure 10). The junction plates of the tubular arch are characterized by a central hole which enables the creation of a continuous concrete arch within the tubular profile at the completion of the filling phase (Figure 11). This Tubular Arch System assures the effective collaboration between the steel circular hollow profile and the concrete filling, thereby producing a composite system with enhanced performance behavior.

The spraying procedure for the realization of the concrete shield results in an important saving due to the reduction of rebound during the placement of shotcrete between the tubular profile arches. From an operational point of view when an operator tries to fill the space between the webs of an open profile support arch, a significant rebound of 50% (or more, in the case of coupled profiles) of the shotcrete has been recorded. This problem does not occur in the case of tubular profile arches and a complete shotcrete filling between the arches is possible.

Figure 10. Tubular Arch filling.

Figure 11. Tubular Arch: junction plate detail.

4 THE BOSCACCIO TUNNEL CASE

The tunnel is located on highway A1 Milan-Naples, it is actually under construction and is a part of the extension of the third lane along the section Barberino-Firenze Nord.

4.1. *The geological and geotechnical condition*

The tunnel stretches crosses an important geological Apenninic context. Boscaccio tunnel is located among two important tectonic geosynclines: Mugello Area (in the north) and Firenze – Valdarno Area (in the south).

The sedimentary evolution of the Northern Apennines geosyncline is divided into a geosynclinal stage proper. The late geosynclinal stage is defined mainly on the basis of tectonic criteria: sediments deposited over folded eugeosynclinal rocks, later subjected to lateral tectonic transport in the same manner as their allochthonous substratum. Owing to the eastward progression of tectonic movements in the Northern Apennines, the tecto-sedimentary stages tend to overlap and coexist (e.g., Oligocene-Miocene miogeosynclinal flysch and late geosynclinal sediments).

Tunnel geological section is characterized by flysch sequences: Monte Morello Formation and Sillano Formation. Lithologies involved are: rhythmic sequences of marl, marl limestones and claystones.

4.2. *Calculation approach and applied tubular arch*

The detailed design considered steel arch constituted by open profile but on the basis of structural calculation has been possible to apply tubular arch following the substitution listed in Table 1.

The primary lining is a structure and it has been verified by ultimate limit state applying the following load combination:

$E_d=\gamma_G G_k$ (permanent load only)

and considering the following design load

$N_d=1.4*N$

$M_d=1.4*M$

In current tunnel design, M (bending moment) and N (axial force) are obtained from numerical analyses.

In a typical tunnel design in which support consists of steel sets embedded in shotcrete, the designer needs to know the contribution of each of these support elements and to be able to adjust the number and dimensions of each to accommodate the loads imposed on the lining. In current tunnel design, these loads are obtained from numerical analyses in which “beam elements” are attached to the tunnel boundary and the axial thrust, bending moments and shear forces induced in these elements are computed directly.

In order to calculate the moments and axial thrusts induced in the steel sets and the shotcrete shell and to compare these with the capacity of the steel sets and shotcrete, the following steps are required:

- An “equivalent” rectangular section with a width of b, a thickness t_{eq} and a modulus of E_{eq}, is determined.
- The capacity of the steel sets and the shotcrete lining are determined.
- A numerical model of the tunnel is constructed and beam elements representing the equivalent rectangular section are applied to the tunnel perimeter.
- The bending moments and axial thrusts are redistributed back onto the steel sets and shotcrete lining.

The sprayed concrete shells tends to be of constant thickness, the most effective verification approach is to develop an interaction diagram (N,M) allowing the combined moment (M) and the axial load (N) values to be checked against the envelope of allowable loads.

The calculation approach follows the prescription given by:

- AFTES Recommendations: “Design of Sprayed Concrete for underground support”.
- EN 1993-1-1:2005 - Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings

The report produced by the designer (Rocksoil S.p.A.) proofs that it is possible to substitute:

- steel arch 2 IPN 220 characterized by a S275 steel grade with a tubular arch characterized by a 273 mm diameter with a thickness of 8 mm and S275 steel grade. In both cases the steel profile has been considered embedded in the same sprayed concrete section (thickness = 30 + 5 cm and installation step = 1,00 m);
- steel arch 2 IPN 240 characterized by a S275 steel grade with a tubular arch characterized by a 273 mm diameter with a thickness of 10 mm and S275 steel grade. In both cases the steel profile has been considered embedded in the same sprayed concrete section (thickness = 35 + 5 cm and installation step = 1,00 m);
- steel arch 2 IPN 220 characterized by a S275 steel grade with a tubular arch characterized by a 273 mm diameter with a thickness of 8 mm and S275 steel grade. In both case the steel profile has been considered embedded in the same sprayed concrete section (thickness = 30 + 5 cm and installation step = 1,00 m)

The shotcrete sections of 1m characterized by the thickness listed above have been considered cast in place with a concrete class C30/37

Table 1 summarize the technical modification applied in the case of Boscaccio Tunnel.

Table 1. Steel arches substitution: The case of Boscaccio Tunnel (concrete class C30/37).

Traditional Arch				Tubular Arch			
Open Profile	Steel Grade	Sprayed Concrete [cm]	Installation Step [m]	Tubular Section S275	Steel Grade	Sprayed Concrete [cm]	Installation Step [m]
2 IPN 220	S275	30 + 5	1.00	Ø 273 th. 8mm	S275	30+5	1.00
2 IPN 240	S275	35 + 5	1.00	Ø 273 th. 10mm	S275	35 + 5	1.00
HEB 280	S275	35 + 5	1.00	Ø 323.9 th. 12.5mm	S355	35 + 5	1.00

The figures 12, 13 and 14 show the interaction diagram which validate the substitution. The graphs underline the interaction diagram of the tubular arch is bigger than those of steel arches made by open profile. In addition, looking into detailed graphs and in reference to the Bending Resistance, it is possible to underline the difference in terms of M_{xRd}. The value is represented by the intersection of the graphs and M axis.

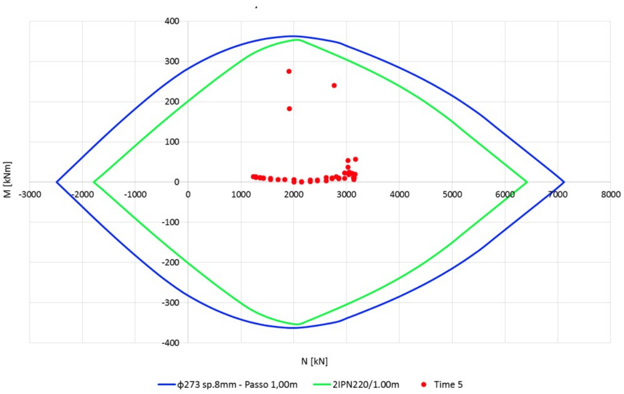

Figure 12. 2 IPN 220 – S275 versus Ø 273 th. 8mm S275 embedded in a sprayed concrete section (30+5) cm x 1.00m

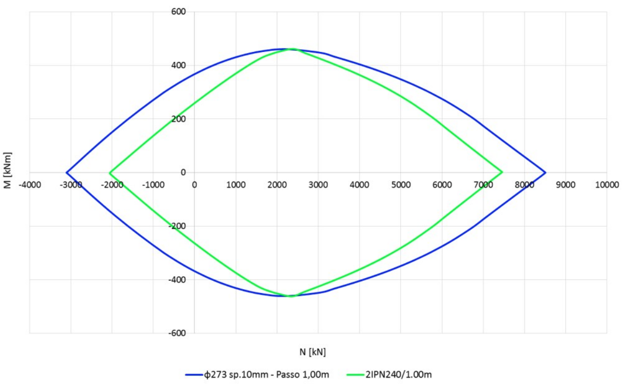

Figure 12. 2 IPN 240 – S275 versus Ø 273 th. 10mm S275 embedded in a sprayed concrete section (35+5) cm x 1.00m

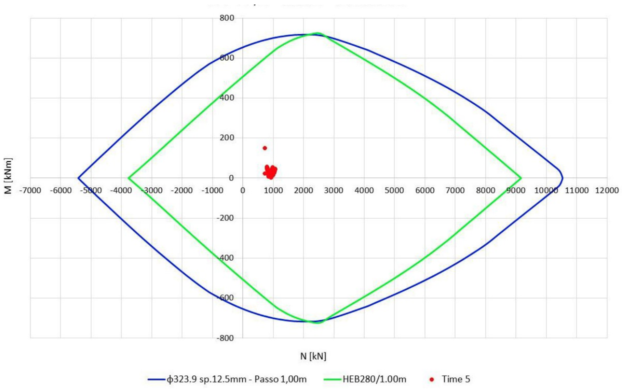

Figure 14. HEB 280 – S275 versus Ø 323.9 th. 12mm S355 embedded in a sprayed concrete section (35+5) cm x 1.00m

4.3. *Saving analysis*

The Boscaccio Tunnel experience also gave the possibility to analyze the saving in terms of time and materials.

The Table 2 summarize the installation timing. The installation and connection of semi-automatic tubular arches performed by EKIP 2104 led to save 30 minutes compared to the installation and connection of arches constituted by open profile. The reasons lie in the following motivations:

- the tubular profile is characterized by a high stiffness compared to the ones of open profile. Without the buckling risk the installation of the arch is faster;
- the installation and connection of semi-automatic tubular arch is performed with the same machinery (EKIP 2104) and only one operator works on the specific phase. The waiting time due to the machinery change is cancelled.

The 30 minutes of time saving for each arch considered for the entire length of the tunnel led to a global saving of around 40 days.

Table 2. Steel arch installation timing.

ARCH TYPE	Handling to the Excavation Face [minutes]	Lifting, installing and Connection to previuos arch [minutes]	Total Length Boscaccio Tunnel [m]	Installation Step [m]	Steel Arch Number [n°]	Total Time [h]
TRADITIONAL	=	45,0	1962,0	1,00	1962	1472
B.ZERO AUTO	=	15,0	1962,0	1,00	1962	491
Δ Time saving for each arch		**-30**			**Δ Hours**	**-981**
				Δ Time	**40 DAYS & 21 HOURS**	

In addition, the normal shift for arch installation and connection is composed of five workers plus one tunneling expert with a supervisor role. The semi-automatic tubular arch installed by EKIP 2104 required only one worker for installation and connection plus one tunneling expert with a supervisor role.

Another important saving is related to the sprayed concrete in both terms of time and material quantity (see Table 3). The tubular arch is characterized by an easier filling procedure by which the rebound is around zero. The spraying procedure for the realization of concrete shield, related to the primary lining completion, led to obtain an important saving due to the reduction of rebound during the placement of shotcrete between the tubular profile arches. The shotcrete savings related to the Boscaccio Tunnel are more than 9.000 cubic meter in terms of material and more than 19 days in terms of time.

Table 3. Shotcrete analisys - material quantity & timing.

ARCH TYPE	Average Consumption for 6 m section [mc]	Average Consumption for Linear Meter [mc]	Total Length Boscaccio Tunnel [m]	Total Consumption Boscaccio Tunnel [mc]	Shotcrete Pump Production mc/hour [mc]	Total Time [h]
TRADITIONAL	181,67	30,3	1962,0	59405	20	2970
B.ZERO AUTO	153,14	25,5	1962,0	50078	20	2504
			Δ SHOTCRETE	**-9327**	**Δ Hours**	**-466**
			Δ Time		**19DAYS & 10HOURS**	

The total time saving is around 60 days, and compared to the initial estimation of total construction time equal to 1000 days means a reduction of 6%. A tunnel completed in advance with a time reduction of 6% means a reduction in terms of direct costs and over heads of 6%.

5 CONCLUSION

These days, the increase in safety levels is one of the most important considerations for innovation and research and it is one of the most common demands from the underground construction market. The risks are well known and this enables the possibility to manage and mitigate them.

Stress and strain of the rock or ground masses are normally analysed, by many authorities, in two dimensions within a transverse section of a tunnel. In the vicinity of the tunnel face where the predominant deformation and stress redistributions occur, as the stressed rock is dislodged during excavation, the third dimension assumes a vital role. The open steel profiles (IPE, HE, IPN), typically used as the primary lining support, show performance weakness in their static structural properties, in directions other than the normal and central position. These problems can be solved using a profile with a symmetrical axial cross section, like a tubular rib. The use of tubular steel arches within tunnelling and underground mining operations offers numerous technical, operational, safety and cost benefits compared to traditional steel section arches.

Responding to the demand for further improvements in safety, in this paper the authors describe the case of Boscaccio Tunnel. A new type of primary lining reinforcing system, characterized by a semi-automatic installation procedure, has been installed by using new machinery developed for its installation. The presence of workers close to the excavation face is not required. Underground construction is inherently a dangerous undertaking and work progresses in a noisy environment in close quarters with moving heavy machinery. Careful attention must be paid to the layout of the worksite and workers must be protected at all times. The case of Boscaccio Tunnel underline that it is possible to increase safety levels by the use of the innovative solution, which also led to obtain economic savings.

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