Tunnelling for a Better Life – Yan, Celestino, Thewes & Eberhardt (Eds)

The use of jet grouting technology: An overview of the different applications in tunnelling

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ABSTRACT: “Jet-grouting” is a jet injection technology that has widely been used in geotechnical works since the 1970s. Nowadays, it is one of the most popular ground improvement techniques due to its applicability in almost all soil types. Its peculiarity is to change drastically ground characteristics, thanks to the effect of very high-speed jets, able to break up the soil and to mix it with cementitious slurry, improving soil’s mechanical parameters and reducing its permeability. In the paper, a general overview of the technology will be given, together with the design criteria for the particular tunnelling applications.

Keywords: jet grouting, vertical, sub-horizontal, portal, excavation face

1 INTRODUCTION

Nowadays, jet-grouting technology is one of the most popular ground improvement techniques due to its applicability in almost all soil types. Its peculiarity is to change drastically ground characteristics, thanks to the effect of very high-speed jets, able to break up the soil and to mix it with cementitious slurry, improving soil’s mechanical parameters and reducing its permeability. Several techniques and construction processes can be used for jet-grouting execution, depending on the types of fluid injections and on working parameters.

Jet-grouting has a fundamental role in the progress that has been achieved over the last thirty years in tunnel construction (Lunardi, 1986). Jet-grouting treatments can be executed by surface, where space is available and overburden is limited, or directly at the tunnel face. Horizontal jet-grouting made possible to overcome all the difficulties connected with excavation in cohesionless soils. Sub horizontal jet-grouting is used to create a series of columns of improved ground, side by side ahead of the face around the profile of the extrados of the tunnel to be excavated. Jet-grouting technology is also applied for the construction of tunnel portals in cohesionless or slightly cohesive soils too. Tunnelling can be performed with a very low overburden, by jet-grouting shell, arch shaped, thus minimizing the risk of slope instability and providing outstanding results from an environmental and landscape point of view.

2 JET-GROUTING

The technology involves the injection of a high-speed fluid (water jet or grout jet) through small-diameter nozzles into the subsoil to erode the surrounding soil, while the nozzles are rotated and lifted towards the ground surface at a constant speed. The eroded soil is simultaneously mixed with the injected grout to form the admixture, and a soil-cement column with a quasi-cylindrical shape would be formed after some days of solidification. It is possible to reach columns with diameters ranging between 500 mm and up to 2,500–3,000 mm, owing to the adopted systems, the working parameters and the soil types. Grout pressure, rate of ascent, angular speed, and number and diameters of nozzles are the main parameters to be controlled to obtain the improved soil of the desired shape and size. Soil investigation and field tests must be carefully planned for each application.

2.1 *Classification*

Based on the different methods of fluid injection, jet-grouting technology can be conventionally classified into three basic types of systems (Figure 1):

a) single-fluid system (only grout);
b) double-fluid system (grout and air);
c) triple-fluid system (water, grout and air).

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DOI: 10.1201/9781003495505-103

The “single-fluid” system utilizes grout as the cutting jet to achieve cementation of the eroded soil. In the most common case of drilling without casing, a self-drilling monitor will be used, by rotation or roto-percussion system, with the drilling rod equipped both with injection nozzle and with cutting tool. In the “double-fluid” system, a compressed air shroud is introduced around the grout jet to enhance the cutting distance of the grout jet; the construction process is the same of the single-fluid system, adding an additional nozzle for the air. In the “triple-fluid” system, water is used for the cutting jet together with a compressed air shroud, and grout is injected separately through a lower nozzle at a much smaller pressure to mix with the eroded soil. The adoption of a lower viscosity fluid such as water (in comparison with that of grout) allows the cutting distance to be further enhanced, especially in cohesive soils. The three methods are represented in Figure 1 (Cassani et al., 2022).

2.2 *Parameters*

The key jet-grouting operational parameters governing the jetting performance are as follows:

- Characteristics of jetting fluid, i.e. water-cement ratio of grout (W/C).
- Pressure (MPa) and flow rate of jetting fluid (Q = m^3/h).
- Jetting time, which is a function of the traverse velocity of nozzle, and hence the withdrawal rate (m/min) and rotation speed (rpm).
- Characteristics of nozzle: nozzle diameter (mm), number of nozzles (N) and nozzle shape.

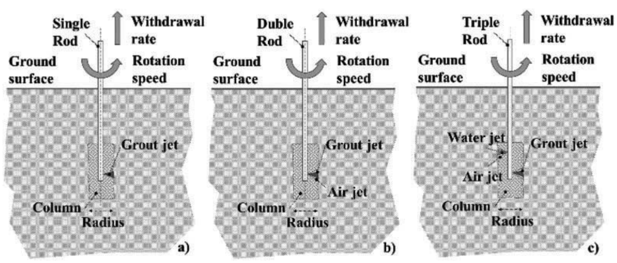


Figure 1. Jet-grouting systems: (a) single fluid; (b) double fluid; (c) triple fluid.

The injection pressure is controlled by pressure gauges; the jet energy and consequently the radius of action mainly depend on pressure. The upper pressure limit is essentially determined by the capacity of the pump used. The number and diameters of nozzles determine the injection capacity: the volume of grout injected into the ground per unit of time and, consequently, the rate of treatment. High flow rates require high power pumps to maintain high pressure. Larger nozzle diameters make more efficient use of the power employed, while large number of nozzles, with the same rates, decreases performance, due to a greater loss of head, so it is preferable to limit the number of nozzles. The water-cement ratio of the grout is the most important parameter regarding the mechanical properties of the treated soil and the initial behaviour of the soil-grout mixture; a low water-cement ratio is extremely important where there is groundwater flow, as this could wash away the cement shortly after injection. The injection time depends on the withdrawal rate and the angular velocity of the drill rod; it is controlled by a timer placed on the drill rig (normally, 1 m every 2–6 minutes and 10–20 rpm). Raising is usually performed in 4–5 cm steps, thus allowing the jet to act on the surrounding ground, for set time intervals. The diameter and the mechanical properties of the ground treated, as well as the time required for treatment, are strongly affected by the withdrawal rate. Table 1 shows the range of jet-grouting parameters commonly adopted for the three conventional jet-grouting systems (Lunardi, 1997a). Typical withdrawal rates, expressed in cm/min, and rotation speed, in rpm, are reported in the table. It is possible to link the flow rate of jetting fluid (Q), the volume (V) and the speed of treatment (v), with the formula $V = Q/v$; the flow rate Q depends on jetting area, i.e. the number and diameters of nozzles, and on the jet speed, in turn related to the injection pressure (P). Thus, the knowledge of these working parameters allows to evaluate a global design parameter: the “linear specific energy”, by the

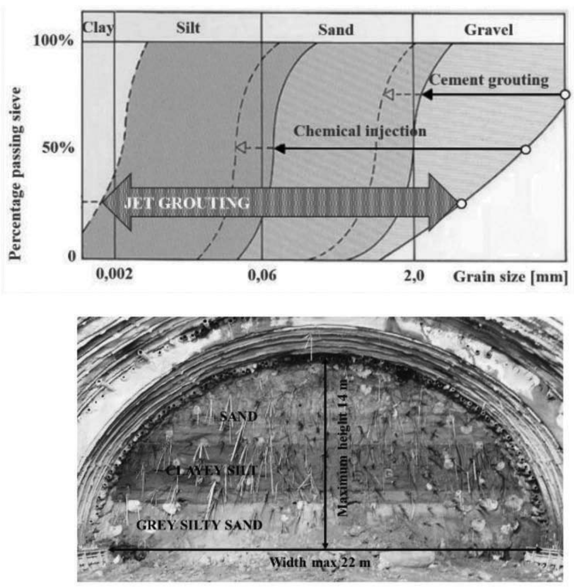
Table 1. Ranges of jet grouting parameters for conventional jet grouting systems.

Parameters	Single fluid system	Double fluid system	Triple fluid system
Water pressure (MPa)	-	-	30~40
Flow rate of water (L/min)	-	-	80~200
Number of nozzle (n°)	-	-	1.5~3.0
Nozzle diameter (mm)	-	-	1~2
Air pressure (MPa)	-	0.7~1.5	0.7~1.5
Flow rate of air (m^3/min)	-	8~30	4~15
Grout pressure, (MPa)	40~70	30~70	7~10
Flow rate of grout (L/min)	100~300	100~600	120~200
Grout density [g/cm^3]	1.25~1.6	1.25~1.8	1.5~2.0
Number of nozzle (n°)	1~6	1~2	1~3
Nozzle diameter (mm)	1.0~4	2~7	5~10
Withdrawal rate (cm/min)	15~100	10~30	6~15
Rotation speed (rpm)	7~20	2~20	7~15
Specific Energy (MJ/m)	10-20	40-80	120-200

formula E = P Q/v, expressed in MJ/m of linear jet-grouting, or the “volume specific energy”, by the formula $E = P\cdot Q/(v\cdot V)$, expressed in MJ/m^3 (according to Tornaghi, 1993). Using these correlations, it is possible to dispose of a rational approach to compare several combinations of working parameters and find the best technical and economical solutions for each application.

2.3 *Context*

From the experiences acquired in several geotechnical works, we can state shot jet-grouting can be successfully performed in any type of soil (Figure 2.a), independently of grain size and permeability, with the exception of very hard cohesive soils whose strength cannot be overcome by the jet (such as stiff silts and clays, with undrained cohesion greater than 0.2–0.5 MPa). This technology has the advantage of being able to treat “stratified soils” too (alternating sands, silts, clays, etc.), providing almost uniform levels of cementation and waterproofing. In fine-grained soils, the outer surface of the columns obtained is normally well defined and fairly regular; in coarse-grained and heterogeneous grounds, this surface is irregular and there is the systematic appearance of “root effect”, i.e. grouting through “claquage” outside the radius of action of the jet. The occurrence of still groundwater does not in any way compromise the results of the treatment. When seepage occurs, special precautions, such as the addition of accelerators to the grout, give good results even at the groundwater speed of the order of 0.1 cm/s. The compressive shear strength of jet-grouted soil generally increases from clays to gravels (see Figure 3). Maximum strengths of about 20–30 MPa could be reached in sands and gravels, while in fine-grained peaty soils, it is hard to attain values ten times lower.



a)

b)

Figure 2. a) Jet-grouting applicability; b) Cassia Tunnel - External track: total length 232 m.

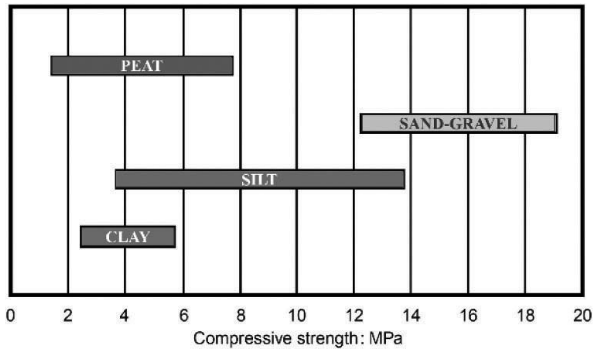


Figure 3. Compressive strength of jet-grouted soils.

2.4 *Design approach and technical specifications*

The design of ground improvement using jet-grouting must involve these main following stages:

a) defining soil investigations and preliminary field tests;
b) choice of grout type and operating parameters,
c) deciding the pattern, shape and size of the grouted volumes,
d) identification of the most appropriate numerical model to study the stress-strain distribution in the soil treated
e) choice of the monitoring and controlling systems.

The most critical aspect is the ones related to the pattern and dimensions of jet-grouting treatments. It is essential to understand that ground volumes treated by jet-grouting are cemented ground and not real structures; there phase to define thickness and required strength, it is necessary to predict the stresses acting on treatments. The treated ground can take compression and shear, and consequently, the application of other types of stresses, i.e. tension, should be avoided. In this case, the insertion of bars and steel sections into improved ground can be achieved, especially for retaining structures, usually before setting takes place, by gravity or using high-frequency vibrators or re-drilling. It must be remembered that the existence of more rigid volumes in the ground may possibly be used to produce a system channelling stresses along a desired direction and these stresses should be carefully considered in dimensioning. The analysis of such problems implies generally the use of the finite element method, since the types of problems connected with jet-grouted ground are clearly non-linear. In addition to this, it is often necessary to analyse structures whose shape changes over time due to excavation or construction operations. This requires starting with the analysis of the natural untreated conditions and passing through an appropriate sequence of stages realistically approximating the actual development of the work. Once the geometry of the treatment is defined and the required strength is fixed, it is necessary to study the correct pattern, considering the column diameters easily achieved in the geotechnical context of intervention and an appropriate overlapping to ensure the continuity of treatment. The working parameters will be set, based on database experiences in similar contexts or according to the specific energy approach discussed in Section 2.2, and they will be confirmed or fine-tuned by a field test. Designer must define in detail, in addition to the executive technical specifications, the prescribed requirements in terms of diameter, strength and permeability of the soil treated, to be checked by tests.

3 TUNNELLING APPLICATION

The authors when designing a tunnel always apply ADECO-RS approach (Analysis of the controlled deformations in rocks and soils) which is related to one only parameter common to all the excavations, that is the tenso-deformative

behaviour of the system "front of the excavation advancement core" and to the introduction of the concept of preconfinament of the cave and of the "conservative systems" (Figure 4).

Particularly, design has been articulated in:

- An investigation phase, during which the designer, has carried out the categorization of the soil crossed by the tunnel in terms of geotechnical parameters. This step is essential to complete the analysis of the existing natural balance, and to correctly work in the following design phase;
- A diagnosis phase, during which have been prepared theoretical forecasts regarding the deformative answers of the soil to the excavation action. The soil behaviour can be intended in terms of genesis, localization, evolution and entity of the probable reaction which, without intervention of soil improvement, would commence at the excavation face and, as a consequence, in the soil ring at the cavity. From the combined analysis of the deformation behaviour of the system excavation front advancement core and of the cavity, one can infer which will be he homogeneous deformative behaviour in the domain of the three fundamental categories of behaviour (category A: stable front, category B: front stable in short terms, category C: unstable front);
- A phase of therapy, during which, following the predictions made in phase of diagnosis, the designer selects the type of action to be exerted (pre-containment or simple containment) and the necessary interventions, among the three behaviour categories (A, B and C) in order to obtain the complete stabilization of the tunnel, and he perfections the choice in terms of systems, cadence and phases of excavation. Then, he defines the composition of the longitudinal standard sections and the cross sections dimensions, assessing their efficacy by using computation tools.

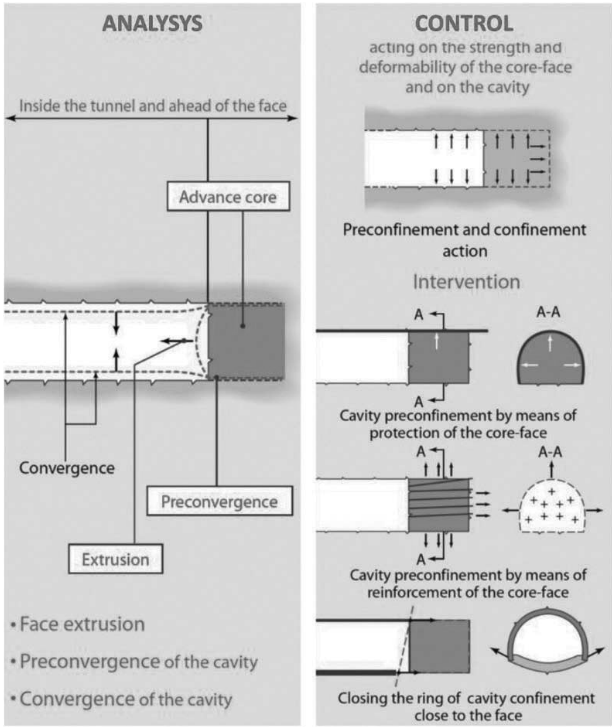


Figure 4. ADECO-RS approach.

3.1 *Portals*

The construction of tunnel portals often involves solving problems that are closely connected with the morphology of the slope to be entered, with the existence of nearby constructions, with the geometry of the structures to be constructed and the type of material involved.

The preparation of a portal site and of the wall to be excavated, very frequently requires substantial cuttings which are of no particular concern when working in rock, but are very problematic when working in soft soils, especially if they are loose. If the decompression caused by excavation in ground with little cohesion is not adequately confined, there is a risk that it will easily and rapidly propagate into the medium with serious effects for the whole

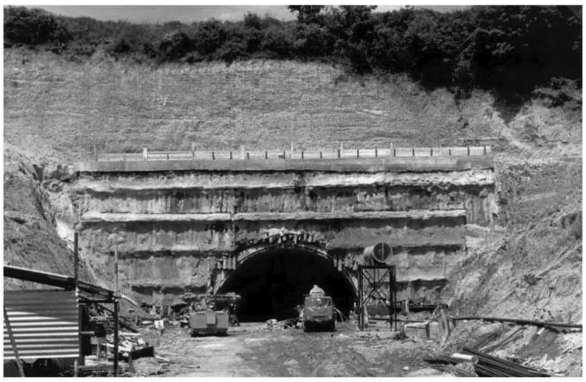
slope. The only way the entrance to the portal of a tunnel can be excavated without decompressing the ground is clearly by creating a structure to confine (or better preconfine) the ground in advance ahead of the future excavation which is capable of conserving the existing natural equilibrium.

The systems available for achieving this goal were to place the following structures at the entrance of the bored tunnel:

- large diameter pile walls, anchored if necessary;
- "Berlin" or soldier pile walls;
- Reinforced Concrete diaphragm walls.

The construction of large diameter piles on slopes tending towards instability is, however, often difficult, if not impossible, because, it is often the case that the morphology of the slopes does not allow the use of the heavy operating machinery required. On the other hand the lability of Berlin type structures themselves, which rely to a large extent on anchors which reach into stable zones of the ground for their effectiveness, mean that these systems are not always sufficiently reliable. Not even r.c. diaphragm walls are sufficient for the most delicate situations: earth removal and the introduction of water have the effect of reducing the shear strength of the ground with consequences for which there is no remedy in some situations.

These problems were then made worse because the lack of adequate techniques to improve the ground in advance and of suitable operating systems, required bored tunnels to be driven with overburdens measurable in terms of tunnel radii. This required huge portions of the ground to be removed with the risk of triggering ground decompression that is very difficult to confine (Figure 5).



a)

b)

Figure 5. a) very deep cut is made into the slope for a tunnel portal in semi-cohesive soils using conventional systems (anchored Berlin wall; overburden: twice the diameter of the tunnel); b) The same portal as the one above, after it had collapsed because of the decompression induced in the slope.

The availability of a jet-grouting systems for improving ground, introduced in Italy around thirty years ago, allowed to invent and experiment an innovative solution to create preconfinement structures in loose or poorly cohesive soils with properties that would overcome the problems that have been described. The idea consists of creating a confinement shell, before excavation for the portal commences, consisting of rows of columns of ground improved by means of jet-grouting, which geometrically enfold the section of artificial tunnel (see Figure 6). The magnitude and distribution of the treatment are decided on the basis of each specific operating and geotechnical context. A top beam in r.c. joins the tops of the columns to help make it a single rigid structure. Once the earth has been removed for the entrance to the portal, the work is completed with:

– a layer of shotcrete sprayed on the whole surface of the exposed wall;
– drainage pipes placed sub-horizontally through the improved ground to prevent the formation of heads of water behind it.

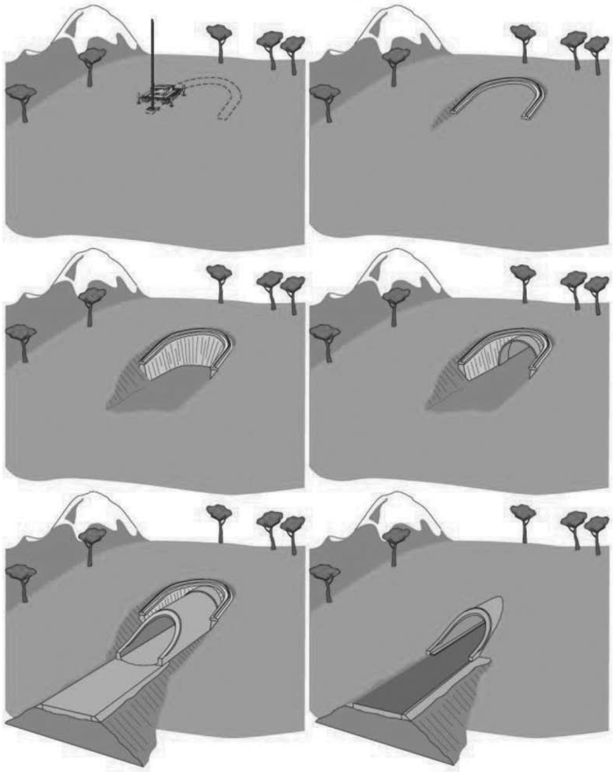


Figure 6. Tunnel portals with shell of improved ground by means of vertical jet-grouting (Lunardi, 2008).

The structure thus built functions by means of the sub-horizontal arches and is subject mainly to compressive and shear stress. The creation of shells of this type is strictly dependent on the subsequent tunnel being driven using horizontal jet-grouting methods. Thanks to the characteristics of this ground preconfinement technology, which requires only minimum overburdens, bored tunnels can be driven with extremely low cover, with many important advantages, including the way it fits unobtrusively into the environment.

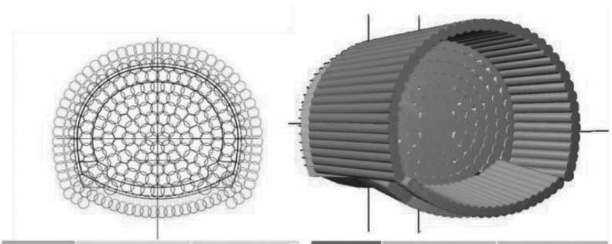
3.2 *Sub horizontal jet-grouting columns*

The use of sub-horizontal jet-grouting column inside a tunnel could be performed mainly by two way: around the cavity or at the face and together also (see Figure 7).

Truncated cone 'umbrellas' realized by sub-horizontal columns of jet-grouting as a conservative protective intervention. It creates ahead of the face around the cavity a protective shell. It channels stresses around the outside of the face performing, as the term says, a protective action which conserves the natural strength and deformation characteristics of the ground.

Sub-horizontal jet-grouting is used to create a series of columns of improved ground, side by side ahead of the face around the profile of the extrados of the tunnel to be excavated. An arch of improved ground with considerable strength is created to provide protection to the ground inside the advance core along the longitudinal direction, lightening the load on it and giving it stability; this arch produces cavity confinemnt action occurring along the transverse direction, sufficient to prevent the ground around it from decompressing and consequent deformation from occurring. It therefore allows subsequent tunnelling operations to proceed under the protection of an arch effect already operational and therefore in complete safety.

Reinforcement of the core-face by means of sub-horizontal jet grouting column is a conservative reinforcement intervention. It acts directly on the consistency of the advance core, improving its natural strength and deformation characteristics by means of the reinforcement techniques.



FACE		
N°	161	
Diameter [mm]	1350	1400
L_{PER} [m]	11,33	
L_{GROUT} [m]	2,5	0,5
$V_{THEORETICAL}$ [m]	575,84	123,86
V_{TOTAL} [m]	699,70	
$L_{PER-TOTAL}$ [m]	1824,13	

CROWN	
N°	43
Diameter [mm]	1100
L_{PER} [m]	19,33
L_{GROUT} [m]	16,33
$V_{THEORETICAL}$ [m]	535,36
V_{TOTAL} [m]	666,98
$L_{PER-TOTAL}$ [m]	831,19

INVERT 1	
N°	22
Diameter [mm]	1100
L_{PER} [m]	20,00
L_{GROUT} [m]	10,50
$V_{THEORETICAL}$ [m]	219,42
V_{TOTAL} [m]	219,42
$L_{PER-TOTAL}$ [m]	440

INVERT 2		
N°	17	6
Diameter [mm]	1100	1100
L_{PER} [m]	15,83	17,83
L_{GROUT} [m]	8,50	10,50
$V_{THEORETICAL}$ [m]	137,25	59,84
V_{TOTAL} [m]	197,09	
$L_{PER-TOTAL}$ [m]	269,11	106,98

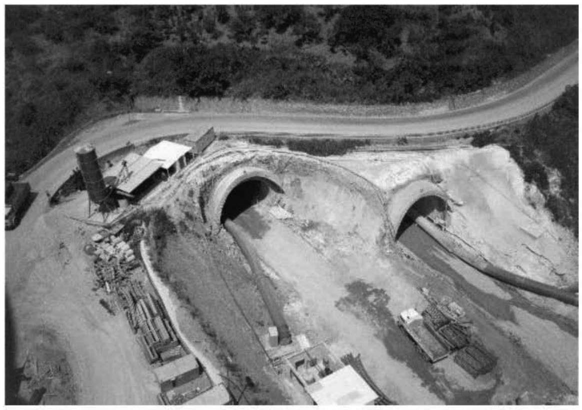
Figure 7. Sub-Horizontal jet grouting: intervention map, assessment though 3D analysis and parameters.

4 CASE HISTORY

The solutions described in section 3 have been developed by Prof. Lunardi and his teams more than 30 years ago and from that time applied in a lot of cases. In this section the authors just mention the tunnelling applications of sub-vertical and sub-horizontal jet-grouting columns and they will give more details about one face reinforcement application more recently designed.

The first time that sub-vertical jet-grouting to pre-confine excavation was experimented in 1980 at Sesto San Giovanni (Milan), in an area destined to contain a ventilation chamber 9.80 m deep on a section of the Milan metro line 1 under construction. The first application for the construction of tunnel portals occurred five years later for the T1 portal on the Pontebba side of the S. Leopoldo tunnel on the Pontebba-Tarvisio. railway line. This application was suddenly followed by several application (Lunardi, 2008):

- S. Elia Tunnel (Messina-Palermo motorway): portal on the Messina side under construction, 1986 (Figure 8a).
- Pianoro Tunnel (new high speed/capacity railway line between Bologna and Florence), 1996.
- Gran Sasso Tunnel, Assergi side Portal, xxxx.
- Tunnel No. 2 (Sibari-Cosenza railway line): the use of jet-grouting technology enables tunnel portals to be built in difficult grounds with full respect for natural equilibriums and for the landscape, 1992 (Figure 8b).



a)

b)

Figure 8. Examples of portal of tunnels by jet-grouting shells. (a) S.Elia Tunnel, Messina-Palermo Motorway and (b) Tunnel N2, Sibari-Cosenza Railway Line (Lunardi, 2008).

Horizontal jet-grouting made possible to overcome all the difficulties connected with excavation in cohesionless soils. In this case also a statics design that is congruent with the features of the treated ground was fundamental, namely, a design in which the material is mainly subjected to compressive and shear stresses.

This is the famous 'umbrella' treatment which, by penetrating beyond the face of a tunnel, develops arching in the ground ahead of the excavation. The first application of this technique, which was developed in 1983, was during the construction of the 'Campiolo' tunnel, along the Udine Tarvisio railway line (Figure 9).

The first case was followed by several application:

- Underpass of the Campinas railway yard in Brazil (1987)
- Milan-Chiasso railway line, Monte Olimpino 2 tunnel, (1984)
- The Rome Greater Ring Road: Appia Antica Underpass (Lunardi 2000a), Cassia and Trionfale Tunnels
- Firenzuola tunnel, high speed/high capacity railway line Bologna-Florence (Lunardi, 2000b)
- Road underpass of the Ravone Railway Yard (Bologna, Lunardi & Cassani, 2001)

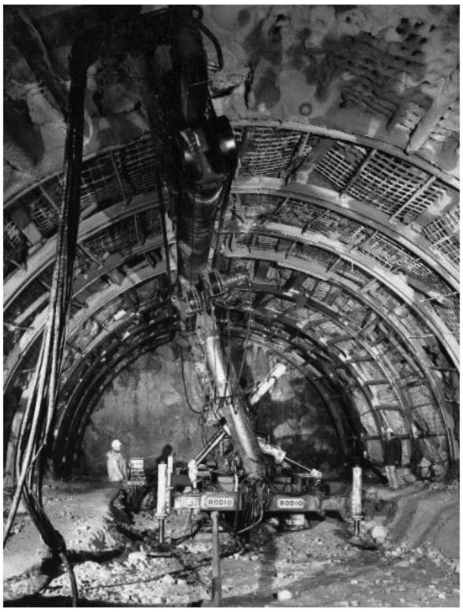


Figure 9. Campiolo Tunnel, Udine-Tarvisio railway line (Lunardi, 2008).

The most recent and challenging application is the one of the Isarco River Underpass. The southernmost construction lot of the Brenner Base Tunnel is the construction lot know as Isarco River Underpass. This lot links the Brenner Base Tunnel with the existing Brenner line and the railway station in Fortezza. The work has been completed in 2023.Since in this section the tunnel tubes are just a few meters below the surface, a portion of the activities pertaining to this construction lot has been carried out building artificial tunnels. Furthermore, as loose fluvioglacial materials and the groundwater layer crossed, it has been necessary to adopt specific ground consolidation procedures including ground freezing and the so-called jet grouting.

The Isarco River Underpass passes through the alluvial deposit of the valley bottom and through the dejection conoids of the tributary rivers. These loose deposits, heterogeneous both in composition and in granulometry, consist of gravels and rounded sand, with frequent boulders and thick layers of sandy silt. The flanks of the valley are covered by coarse particle size material, composed by slope debris, alluvial sediments and weather material. Figure 10. Shows the geological profile and Table 2 summarizes the geotechnical parameters.

Excavation section C1 (Figure 11 reported a general scheme) has been applied in case of loose soils of quaternary origin. Particularly in the Northern sector, in correspondence of the Debris Flow with unstable behaviour, to underpass the motorway A22 and the SS12; the overburden is ranging between 25 to 30 m. It is applied in the Southern sector too, in correspondence of the detritus conoids where unstable core-face behaviour is expected. This section type considers pre-consolidation intervention around the cavity (blue mark in Figure 11 and at the core-face (red marks in Figure 11), aimed creating the conditions of stability and waterproofing of the natural soil.

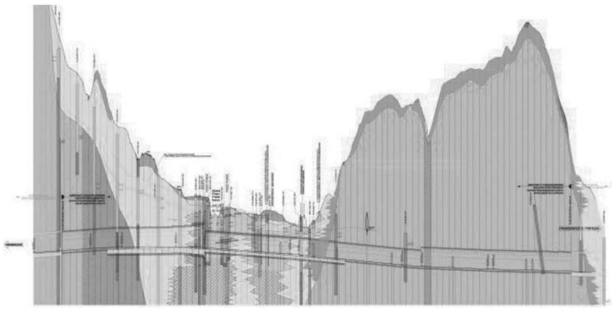


Figure 10. Isarco River Underpass Geological Profile (Lunardi et al. 2018, Lunardi et al. 2019).

Table 2. Soil mass geotechnical parameters.

SOIL TYPE	γ (kN/m^3)	φ (°)	c' (kN/m^2)	E_s (MN/m)
Debris Flow	21,0	30	10	60
Slope Debris	21,0	35	0	60
Alluvional sediments	20,5	36	2	60
Weathered material	21	30	0	30

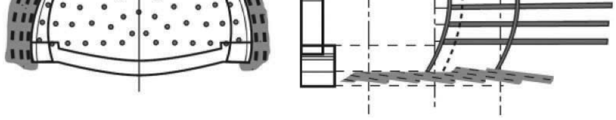


Figure 11. Reinforcements sketch made by jet grouting sub-horizontal columns.

Figure 12. Section C1: Blue marks truncated cone 'umbrellas', red marks core face reinforcements.

The design requires that excavation is performed without reducing the groundwater level, in hydrostatic conditions. For this reason it is necessary to create a grouted arch around the cavity and a plug at the face, so that the advance core is waterproofed. The last requirement has been satisfied tanks to the application of a special jet-grouting technology: Quick set jet grouting - QSJG - based on a "triple-fluid" system. The fluid added to the most common "double-fluid" system is a silicate and its accelerating characteristic was fundamental for "the quick" development of the ground column resistance and waterproofing. Despite to the not ideal conditions for jet grouting application, the adoption of QSJG solve the most critical issues related to this technology (Figure 13). The truncated cone 'umbrellas' realized by sub-horizontal columns create a pre-containment structure in the ground before its excavation, with the creation of "arch effect" which minimizes the deformations. The reinforcement of the core-face by means of sub-horizontal jet grouting column acts directly on the consistency of the advance core, improving its natural strength and deformation characteristics.

Figure 13. Section C1: detail of sub-horizontal jet-grouting column and detail of the excavated ground.

The performed interventions made the cavity and the advance core waterproofed allowing to perform the excavation in hydrostatic condition with a hydraulic head of 25m on the crown key.

The work phases related to this kind of intervention can be summarize as follow:

1) reinforcement of the core-face with sub horizontal columns of ground improved by means of jet-grouting (Figure 14);
2) creation of columns of sub-horizontal jet-grouting in advance in the crown;
3) creation of sub horizontal columns of improved ground under the tunnel floor (Figure 15);
4) full face excavation with steel ribs and shotcrete placed (Figure 16);
5) the face is given a concave shape and is sprayed with shotcrete;
6) the kickers and the tunnel invert are excavated and cast at a distance from the face of ≤ 1 diameter;
7) water-proofing is placed and the final lining is cast at a distance from the face of ≤ 2 ÷ 3 diameters.

5 CONCLUSIONS

Jet-grouting has a fundamental role in the progress that has been achieved over the last thirty years in tunnel construction. Jet-grouting treatments can be executed by surface, where space is available and overburden is limited, or directly at the tunnel face. In the paper, the authors rendered a general overview of the technology, together with the design criteria for tunnelling applications such as portals, cavity and excavation face reinforcements.

Figure 14. Reinforcement of the core-face with sub horizontal columns of ground improved by means of jet-grouting.

Tunnelling can be performed with a very low overburden, by jet-grouting shell, arch shaped, thus minimizing the risk of slope instability and providing outstanding results from an environmental and landscape point of view.

Horizontal jet-grouting made possible to overcome all the difficulties connected with excavation in cohesionless soils. Sub horizontal jet-grouting is used to create a series of columns of improved ground, side by side ahead of the face around the profile of the extrados of the tunnel to be excavated. The authors listed a series of application performed during the latest 30 years and described the most recent and challenging application related to one section of the Isarco River Underpass.

Figure 15. Creation of sub horizontal columns of improved ground under the tunnel floor.

Figure 16. Full face excavation with steel ribs and shotcrete placed.

ACKNOWLEDGMENTS

A short acknowledgement section can be written between the conclusion and the references

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