Use of special jet grouting technologies for tunnel’s crown and core advance consolidation – technical aspects and case studies

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ABSTRACT: From the early nineties of last century-ADECO-RS tunnel design approach, devised by Rocksoil, has been widely used in Europe, mainly in Italy, for tunnelling in difficult soils. ADECO-RS is based on the analysis and control of the deformations both of the tunnel’s surroundings and core. The jet grouting technology is very often applied in the ADECO design for the formation of a series of concentric truncated cone-shaped crowns of reinforced consolidated soil on the border. The advance core can be treated, when necessary, with fibreglass elements or yet with jet grouting columns.

Applying jet grouting in sub horizontal assuring the formation of a continuous arch of consolidated soil in unstable soil conditions or in the presence of cohesive soil and without causing upheaval on the above structures and ground is not an easy task. To these purposes, very often equipment and jet grouting techniques to be used must be completely different from the ones used in conventional vertical application.

The present paper presents two special applications of said technologies finalized by Trevi Group and applied with very good results. The first one is named “roto-injection technology” and is a patented technique that allows both to create columns and to install reinforcing steel pipes with large diameter and thickness, and it also minimizes the risks of upheaval on the surface.

The second one concerns the use of ETJ (Enhanced Trevi Jet) system to substantially improve the efficiency of the jetting in particular soil conditions using special components to increase the disruption power of the jet. ETJ is often used together with roto-injection.

Besides a technical explanation of the two technologies, some application case studies are briefly reported. In particular Cassia Tunnel (located in a succession within the works for the renovation of the three lanes of the Great Ring Road in Rome) and Cavallo tunnel for the A14 Highway between Bologna and Ancona.

1 INTRODUCTION

The transportation infrastructures efficiency is a today business key factor, especially in a country like Italy, in which the elongated geographical structure has compelled the construction of long and narrow highway sections.

Trevi spa has been involved in two critical projects to enlarge the existing highway from two to three lanes in order to streamline the communication in two of the most congested infrastructures in Italy.

For the first one, among the widest projects of the A14 (Adriatic highway) enlargement, Trevi was requested to execute the Cavallo tunnels with a radius of up to 9 m, an average of 200 sq.m section and extending for an overall length of 510 m. Jet grouting in advance has been proposed by Trevi, taking special care to avoid surface settlements or heaves due the presence of buildings and infrastructures (Figure 1 and 2).

The second one is relevant to the two Cassia tunnels construction as part of the works for the introduction of the third lane and emergency lane into the Great Ring Road (so called G.R.A.) in Rome.

The Cassia Tunnel, in its external track, has a total length of 232 m and its internal track is 124 m long. The tunnels have a large cross of about 260 sq.m (22 m
Figure 2. Existing buildings in a “type” profile.

Figure 3. Cassia Tunnels – cross section.

Figure 4. Cassia Tunnels. On the right the old tunnels of the Great Ring Road.

Figure 5. Cassia; tunnel front covered with shotcrete after excavation.

2 THE NEW APPROACH

The great dimensions of the excavation front (see Figure 5), the poor mechanical characteristics of the encountered soils and the importance of overlying structures, would have prudently suggested the excavation be carried out via a series of partial excavations.

Approaching the problem with the ADECO-RS design method and using the state-of-the-art innovative systems of soil improvement, allowed the full face excavation.

This was possible thanks to a final structural shell (made up of the combination of shotcrete and steel ribs on the vault and invert), constructed at a short distance and in advance of the excavation front. This reduced the deformations outside the excavation and reduced the settlements at the surface by limiting ground relaxation.

Moreover it was possible:

- to increase the safety of the workers
- to improve the schedule and reduce costs

Obviously, simplifying the operations to be carried out for a full face excavation (including the benefits obtained in terms of safety) is more controllable and effective than having to employ stepped excavation techniques.

3 DESIGN OF THE TUNNELS

The tunnels have been designed using the ADECO-RS approach (i.e. Analisi delle DEformazioni COntrrollo nelle Rocce e nei Suoli, that is Analysis of the controlled deformations in rocks and soils) which is related to only one parameter common to all excavations, that is the tenso-deformative behaviour of the system in “front of the excavation-advancement core” and to the introduction of the concept of pre-containment of the cave and of “conservative systems”.

wide and 14 m high). In this project, the under crossing of both old tunnels and an ancient Roman villa (Figure 3) in the Cassia road, was necessary, with a relative low distance of separation. For this reasons, severe precautions to avoid surface disturbance were taken.

In both projects, tunnels have been excavated in loose soils, with little cohesiveness at places.

The external Cassia Tunnel passes below the Cassia roadway and an ancient Roman villa (Figure 2), while the internal Tunnel (Figure 3) passes below the SS Cassia roadway and the old tunnels of the Great Ring Road.
The design consists of:

1) An investigation phase, during which the designer has carried out categorization of the soil exposed by the tunnel in terms of geotechnical parameters. This step is essential to complete the analysis of the existing equilibrium condition, and to correctly work in the following design phase;

2) A diagnosis phase, during which theoretical forecasts have been prepared regarding the deformative behaviour of the soil to the excavation action. The soil behaviour can be assessed in terms of genesis, localization, evolution and probable reaction to the works without intervention of soil improvement at the excavation face and, as a consequence, in the soil ring at the cavity. From the combined analysis of the deformations of the system “front-advancement, core and cavity”, one can infer the deformation behaviour in the domain in terms of three fundamental categories of behaviour (category A: stable front, category B: front stable in short terms, category C: unstable front).

3) A phase of therapy, during which (following the predictions made in the diagnosis phase) the designer selects the type of action to be provided (pre-containment or simple containment) and the necessary interventions for the three behaviour categories (A, B and C), in order to obtain stabilization of the tunnel. The appropriate composition of the longitudinal standard sections and the cross sections dimensions are assessed using computation tools.

The analysis in diagnosis phases led to the conclusion that it was necessary to stabilise the excavation front and, by means of proper soil improvement (installed in advance), to artificially produce the arch effect at the outline of the excavation.

4) TECHNOLOGICAL ASPECTS (EXECUTION OF THE CONSOLIDATED ARCH)

The clayey-silt formation in which the bearing arch of the tunnels (in both projects) is located was characterized by a high plasticity and resistance to static penetration ranging between 15 to 20 MPa and values of pocket penetrometer between 0.2 and 0.5 MPa.

Figure illustrates the consistency of this material and shows the difficulty of achieving sub-horizontal columns with an average diameter of 600 mm in this type of soil. Adopting a “conventional” jet (single fluid with grout, disaggregating treatment during lifting phase) would have caused the risk of up heave of the above soils. Such risk is not well-suited for the overlying existing structures (Roman villa and roads).

Moreover, time and costs of the operation would increase dramatically due to the high consumption of cement and the volume of the spoil produced.

Even using a phase of pre-cutting in advance (using water), to produce a constant outflow of spoil during treatment, would still require pre-washing of most
part of the soil. The result would not be the formation of a column of consolidated soil, but a cylindrical cavity full of cementitious sludge having a low density which (because of the sub-horizontal inclination) would inevitably be likely to drain. Moreover it would be subject to a shrinking effect during the hardening phase.

TREVI patented rotoinjection technique was proposed to resolve the problem. In this technique, the jetting phase is performed concurrently with the drilling phase, using a steel casing which is left in place.

The method uses a drill-jetting string made of two coaxial pipes (rods and casing) rotating in opposite direction. The inner battery is made up of the jetting rods and of the self-drilling monitor, and the external one is made up of a steel pipe which acts as a protective casing during the drilling phase. The pipe is left in place as a final reinforcement at the end of the treatment.

The two strings are simultaneously driven by two coaxial power swivels (double rotary). The lower rotary (placed in front) moves the casing and has a hollow passage which allows the insertion of the jetting string moved by the upper rotary. The reciprocal position of the two power swivels can be continuously adjusted and it is generally adapted to constantly maintain the monitor (positioned at the tip of the inner jetting string) slightly in advance on the casing shoe.

By using this system, the spoil generated during the jet treatment is conveyed into the annulus between jet rods and the casing. In this way, continuity of the spoil flow can be assured and controlled. This avoids formation of those dangerous overpressures which are at the basis of the well-known heave phenomena experienced when performing jet grouting in cohesive soils. The casing is inserted into the untreated soil at the mouth of the hole, and prevents the draining of the column during and at the end of consolidation.

The inner diameter of the casing is selected considering the soil conditions, the geometries and the jetting parameters.

As illustrated in the paragraphs above, resuming the main issues related to the injection in advance, we can identify basically 3 main points.

Avoiding or minimizing surface “lifting” phenomena (due to jet grouting over pressure), in order not to cause damages to the existing buildings situated above the tunnel. During the trial test field, in fact, control of the slurry pressure was not easily permitted without adopting special precautions. As we know, the slurry produced by a single fluid jet grouting in cohesive soils has a high viscosity and this turns out to be very difficult to evacuate through the annular space between the hole wall and the drill string, especially if the same has an irregular profile.

The Solution: using the “Horizontal Rotoinjection Technology” while advancing, by which the spoil is conveyed through an annular space always guaranteed by the presence of a steel casing. In addition, special injection parameters have to be observed.

Cavities formation in the soil after treatment; it is well known that the in-situ material generated by jet grouting has a very low density & viscosity. In a horizontal treatment, the drainage of such a liquid material outward can lead to cavities formation in the upper part of the treated soil volume.

The Solution: using the “Horizontal Rotoinjection Technology” while advancing, with steel casing left in place. The same casing can act as reinforcement pipe.

Difficulty in reaching 60 cm columns in very cohesive soils, and with high UCS values required by the project. This was fundamental to achieve the “arch effect” at the tunnel excavation boundary. The sub horizontal geometry requires that treatment times are not too long. It is well known that the longer are treatment times, the higher is the substitution of the soil by the grout mix.

In this specific case, the casing had a diameter of 150 mm.

By using “standard monitors” (with low efficiency, hence with a lower disruption power) and “standard” withdrawal time, columns with an insufficient diameter (30–40 cm) would have been obtained, as verified in the test field. On the contrary, by increasing the withdrawal time, not only the expected diameter wouldn’t have been achieved, but the in situ soil’s substituted fraction would have been greater than the mixed one, thus generating an uncontrollable formation of cavities. The solution: resorting to TREVI ETJM (Enhanced Trevi Jet Single Fluid) which, thanks to the use of higher efficiency components, allows the formation of the pre-set diameter without changing the ratio between the substituted in-situ soil and the mixed one.

In short, the key technique for carrying out a consolidation such as to meet design requirements, avoid treatments from the surface near buildings, and simultaneously ensure excavation’s stability with low heart covering as well as a faster and safer dig advancing, consisted in the adoption of the jet grouting method with the employment of high efficiency ETJ monitors.

5 JET GROUTING IN ADVANCE

This technique involves the use of a drill rig fitted with a mast with a double rotary operating a double counter-rotating drilling battery (jet rods/casing). Internal drill strings are made up of the jetting battery equipped (in this specific case) with an ETJ high-efficiency self-drilling monitor. At the end of the treatment, the casing pipe is left in place thus serving as a definitive reinforcement, and it must be dimensioned according to the jet rods’ diameter.

Position of the inner strings (jet rods) may be adjusted in such a way as to have it come out or not from the external casing. During the treatment, the spoil material is conveyed into the annular space between the rods and the casing pipe, so as to check flow's
continuity and prevent the grout mix from leaking out at the end of the treatment.

Among the advantages of said method, it is worth mentioning the possibility of effectively control spoil back flow.

The latter, indeed, by flowing within the annular space between rods and casing is no longer subjected to interruptions and blockages, since it can always flow into an open flowing channel and the rods’ counter-rotation does not hamper its movement. On the contrary, in traditional jetting, discharge takes place between the injection rods and the uncased drilling surface, so that this channel becomes frequently obstructed, thus easily generating upheaval of the soil and of the surface structures.

In the case of Cavallo tunnel, it was absolutely necessary to preserve the important pre-existing structures on the surface. On the whole, the in advance jet grouting method with ETJ technology can be split up into the following operational phases:

- Phase 1: drilling down to the design depth and simultaneous high-pressure water injection through the nozzles located on the “monitor” (“pre-cutting” phase). It is important to leave a not treated zone of about 1 meter at the beginning of drilling operations as a “retaining” structure of the front-side treated soil. Moving-back from the bottom of the hole, up to the drilling front side.
- Phase 2: Shifting from water to grout mix and penetration into the hole down to the bottom at a controlled speed and rotation; the result is a simultaneous high-pressure injection with the insertion of the reinforcement pipe;
- Phase 3: once the project depth is reached, the jet battery is moved back, the casing is pushed into the not treated soil so as to form a plug and avoid grout leakages to the hole mouth; detachment of the reinforcement pipe from its rotation head (it is used as reinforcement of the jet column) – and retrieval of the jet rods’ batteries.

6 JET-GROUTING TECHNOLOGY WITH ETJ SYSTEM ACCORDING TO THE LITHOLOGY OF THE AFFECTED SOILS

As previously said, the geology characterizing the two projects is made up of mainly clayey and silty soils, with highly-cohesive sandy layers. Surveys carried out from the surface allowed to establish that these cohesive soils are characterized by high shear strength values, in undrained conditions, which increase as the tunnel depth become greater, with Cu values ranging from 200 and 350 kPa. Considering the high consistency of the soil to be treated, an energetically “optimized” single-fluid jet grouting system named ETJ (Enhanced Trevi Jet) was employed. This technology uses a range of devices (feeding heads, ducts, monitors, nozzles) especially devised for preserving the energy of the fluid injected at high speed allowing a higher “coherence” of the jet itself after its flowing out of the nozzle. In this way, it is possible to increase its cutting power, the energy employed being equal. Such technology is derived from Japanese and French experiences and it was further designed by Trevi after a long period of tests carried out in co-operation with Bologna University in order to define the best geometries. At the heart of the system is the Monitor: the “traditional” ones are nothing but hollow cylinders with one or more openings that serve to allow high pressure grouting exit with high turbulence phenomena.

On the contrary, the ETJ Monitor allows to “accompany” the flow towards nozzles having optimal sizes. The positive result, in terms of disruption capability and jetting coherence, is shown in Figures 21 and 22, which illustrate jets’ conformation in both cases (traditional monitor and ETJ). It is also confirmed by the outcome of the erosion tests on the prefab concrete samples.

The single-fluid system (ETJM) allows to improve performances by 60% up to 100% and more in terms of treated volume, the specific energy employed being equal.

The average increase in terms of achievable diameter – compared to the traditional one – is equal to about 33%.

The construction phases are reversed compared to conventional jet, and they can be summarized as follows: disruption of the soil by means of pre-cutting in advancement using the double string, leaving a plug of un-treated soil at the front of at least 2 m which, due to the containment of the outer casing, has the function of blocking the spoil. The pre-cutting is carried out by pumping water and special disaggregating admixtures at high pressure.

After completion of pre-cutting, extraction of the string is carried out until the nozzles of the monitor are at the edge of the un-treated soil plug.

Further advancement of the string, and simultaneous jetting treatment using grout with a single fluid technology.

At the end of the jetting phase, the casing is advanced at least one metre without pumping, to embed the casing shoe into the un-treated soil. In this way, the draining of the columns, still semi-liquid, takes place through the external casing.

Eventually, the casing is unlocked and left in place as a steel reinforcement, and the jetting string is withdrawn.

7 EQUIPMENT FOR DRILLING AND JETTING

All the equipment deployed for consolidation activities has been produced by SOILMEC, the manufacturing division of TREVI Group. Given the unique characteristics of the tunnel, top range has been used, particularly:

Mixing plants GM20
High pressure pumps SOILMEC 7T-450
Tunnelling rig double boom SOILMEC SM605 DT
Besides the introduction of the rotoinjection technology, other innovations and improvements have been launched in the two tunnels, among which: Use of "special" working parameters for the jetting, to generate a continuous spoiling, avoiding the formation of aggregated chips which could have caused chocking of the back-flowing material.

Use of the ETJ monitor (Enhanced Trevi Jet). A monitor specially conceived to focus and thus to increase the disruption of the jetting, at equal specific energy, illustrates the area of the test field which has been carried out on the east portal, in which both conventional monitors and ETJ monitors have been used. The increase of treated volume at equal specific energy has been about 40% on average.

Use of a system specially designed and built in strict cooperation with SOILMEC to collect and convey the spoil material from the swivel to the temporary pond excavated in front of the tunnel rig close to the tunnel face. In this way the working floor has been kept in clean state, with obvious advantages to the safety issues.

The major aspects of the construction are:

An operative phase, during which the advancement of the tunnel has been carried out including the setting of (the design) reinforcing measures and adaptation of the containment and pre-containment to the actual deformative behaviour of the soil.

A checking phase in which, by means of the reading and interpretation of deformations arising during construction, actual and expected deformations have been compared.

This observational technique offered an effective but simple guide to the provision of works.

The entire monitoring system is based on the installation at sections placed perpendicular to the tunnel axis and equipped with instruments outside, on the surface, and inside the tunnel (Figure 20 and 21).

The standard monitoring was planned to have the following features available:

- Systematic convergence stations for the entire length of the tunnel, based on the recorded tenso-deformative behaviour;
- Extrusion measurements, by means of extrusion-meter up to 40 metres long;
- Altimetric topographic measures (survey on monuments placed on the surface).

Moreover, for each tunnel there were special monitoring stations and each one was generally equipped as follows:

**Outside:**
- altimetric topographic measures (survey on monuments placed on the surface);
- T-REX incremental extensometer;
- Piezometer;
- Inclinometer;

**Inside:**
- Measures of convergence and extrusion;
- Vibrating wire placed on the steel ribs and on the final lining (where prescribed);
- Load cells (where prescribed) under the steel ribs footings;
- Electrical wire crackmeters (where prescribed).

Additional: geotechnical and topographical instruments were installed in the old tunnels of the Great Ring Road, in order to check the stability of the phases during construction of the internal Cassia tunnel.

Monitoring (self-performed by the design firm) allowed the carrying out the works by customizing the level of soil improvement and reinforcement, and thus excavating the tunnel in safe conditions.

In this paper we have illustrated the crucial aspects related to design, and the technological aspects related to production for the construction of the tunnels Cassia, which are part of the works for the extension to three lanes of the Great Ring Road in Rome.

The dimensions of the excavation front, the poor geo-mechanical characteristics of the crossed soils and the undercrossed valuable structures, would suggest tackling the execution by means of a series of partial excavations.

The approach to the problem by means of the ADECO-RS design method and the self-performed monitoring, in combination with the support supplied by TREVI Group both in terms of technological innovation and of customization of special equipment, have made it possible to complete a totally safe project, with full face excavation. This method, not only allowed to considerably reduce the duration and the costs, as compared to the conventional approach, but it minimized the effects induced in the soil outside the tunnel, and therefore the settlements at the surface and on the existing structures.