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Soil Improvement Technologies for Tunnelling: Selected Case Histories

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SOIL IMPROVEMENT TECHNOLOGIES FOR TUNNELLING: SELECTED CASE HISTORIES

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ABSTRACT

Soil improvement technologies have been widely employed over the recent decades to overcome tunnelling problems in difficult grounds, their range of application growing proportionally to the technological development. The constant advancement in the different mechanical (*flexible and more powerful equipment*) and electronic (*enhanced reliability and direct quality control*) aspects of these technologies, fostered the confidence of engineers and tunnellers and, ultimately, allowed the entire tunnel industry to approach complex excavations in a safe and cost effective fashion.

This paper outlines the main features of commercially available soil improvement techniques, with particular emphasis on permeation grouting and jet grouting. These two technologies, developed concurrently in Europe and Japan, and there customarily adopted in the design of underground structures, have known extensive and extreme applications worldwide in recent years. Case histories of soil improvement techniques, as they apply to tunnelling, are also rendered.

1. BACKGROUND

Grouting technologies for improving the mechanical and hydraulic conductivity properties of soils have been used for decades in diverse civil engineering applications. The first reported applications in the underground industry are mainly related to groundwater control. Tunnellers have quickly perceived the tremendous potential applications of grouting technologies to underground excavation in poor ground conditions. As a result, the underground construction industry has, with the hydroelectric one, arguably fostered considerable improvement to soil treatment reliability and quality.

Four soil grouting processes are typically identified:

1. Permeation grouting
2. Jet grouting
3. Hydrofracturing (or *claquage*)
4. Compaction grouting

Permeation Grouting: The core principle of permeation is to fill the voids naturally present in the soil with grout, without changing the original soil structure and volumetry. This is probably the oldest grouting technique, the first documented applications dating back to the early 1800's, and also the most experimented and researched. Recent developments and notable tunnelling case histories are provided in the following sections.

Jet Grouting: As one of the youngest grouting techniques, jet grouting overcomes the limitations related to the soil grain size

distribution, typical of the traditional grouting techniques. The soil structure is virtually obliterated by high pressure - high velocity jets. Ultimately, the remaining soil is mixed *in situ* with cement based grouts.

Hydrofracturing: This typically French grouting application aims at injecting grout in the ground at relatively high pressure, thus fracturing the ground itself and creating lenses of grout, mainly along horizontal planes. Hydrofracturing (or *claquage*) can be used in association with permeation grouting, or can be a dangerous and undesirable by-product of it. Because of the potentially uncontrollable deformations associated with its use, this grouting category is not widely used in the tunnelling industry.

Compaction Grouting: High cohesion and rigidity grouts, often containing diverse granulometries of aggregates, are injected to form bulbs around the injection pipe, inducing densification in the surrounding soil. Compaction grouting is not typically used for excavation support; however, compensation grouting, a variant of this grouting concept, is increasingly used for control of tunnelling induced settlement. Remarkable accomplishments have been recently achieved in major tunnelling projects in Europe, Canada, and USA.

2. APPLICATIONS

2.1 *Permeation grouting*

Permeation grouting is widely used in the tunnel industry for excavation support, groundwater control, and can be applied to a variety of subsurface conditions, ranging from rock to soil. The current state of the technology permits the installation of grout from the ground surface, as well as from the tunnel section itself, ahead of the excavation face, or from dedicated grouting / pilot galleries.

Diversified grouting techniques are available according to different subsurface conditions. In particular:

In rock:

- ascending or descending stage methods
- multi-packer sleeved pipe method (MPSP)

In soil:

- sleeved pipe (tube à manchette, or TAM)

The ascending method is the simplest and most economical; it consists in drilling the grouting holes in the formation to the required depth, placing the packer and injecting the grout from the bottom up, withdrawing the packer in stages (typically 3 m long).

When the quality of the rock mass is such that the uncased grouting holes have the tendency to collapse, thus hindering the translation of the packer to the following stage, the descending method can be used. In this case the grouting hole is drilled in stages of the order of 5 m in length, and grouted accordingly.

The MPSP method can represent a viable option in case of extremely poor quality rock formations, where even the downstage method can not prevent grout escapes around the packer, and subsequent loss of control of the grouting operation. This technique entails the installation of a grouting pipe (steel or plastic), fitted with one-way rubber grouting sleeves. Bag packers are also fastened to the pipe at regular intervals (commonly 3 to 5 meters) that are inflated with grout, thus isolating the hole section. Subsequently the upstage grouting phase takes place by inserting a single or double packer in the grouting pipe.

The sleeved pipe method is a multiple phase process that allows several injections of the same hole in different times and with different grouts. It presupposes the permanent installation of the sleeved pipe, which is sealed into the ground by a weak "sleeve" grout, generally composed of water-cement-bentonite mixture, as shown in figure 1. The pipe is fitted with one-way valves, small holes covered by rubber sleeves, at regular intervals. The grout is placed at pressure in order to break the sleeve grout at the injection

point, and then penetrate the soil radially around the pipe. Double packers are used in order to create an enclosed chamber within the pipe with one-way openings.

Undoubtedly, this method presents many advantages for its adaptability to different treatment geometry (grout holes can be drilled and grouted at 360 degrees) and different grout products. The grouting can be staged in different phases, allowing the use of different mixes with decreasing viscosity to ensure the penetration of the grout in the fine voids, after the larger ones have been previously grouted. Without entering into the details of grouting design, it is worth to mention some of the recent developments in the field of the grouting materials. New classes of cement and chemical mixes have been developed in the recent years, principally by the R&D department of the principal specialty contractors worldwide (De Paoli et al, 1992a). Researches and experiments have been performed to improve the stability and reduce the internal cohesion of cement based grout, thus increasing their penetrability. A typical example is represented by the MISTRA grouts, developed by Rodio: these are stable, low-viscosity suspensions, which can penetrate fine soils that are not permeable by ordinary cement mixes.

Remarkable improvements have been recently seen in the field of microfine cements. Various types of microfine cements are commercially available nowadays. Yet, for various reasons associated with their geographical availability, delicate handling and high cost, they are seldom used. These obstacles are overcome by the CEMILL system: this is an on-site manufacturing process, which grinds ordinary raw cement and produces stable grout mixes, characterized by remarkably fine grain size (De Paoli et al, 1992b). These mixes are capable to penetrate into medium-fine sands with a permeability coefficient k as low as 10^{-4} m/s, thus approaching the penetrability limits of chemical grouts (figure 2).

Increasing environmental concerns, especially in urban areas and below the water table, have

led to the development of a new family of grouts, composed of silica liquor and an inorganic reagent. Commercially known as SILACSOL, these mixes have groutability characteristics similar to the traditional silica gels, but are remarkably more stable and less aggressive to the environment. In addition, they do not produce the disagreeable odour associated to silica gels, particularly noticeable in tunnelling works. In fact, the reaction in the ground of the two components, results in insoluble calcium silicate crystals with a structure very similar to hydrated cement. As a consequence, these are not only low viscosity, highly penetrating mixes, but also result in a material with concrete like behaviour, minimally subject to creep and permanent load deformation.

In the last decade, the grouting equipment has been dramatically improved, to the extent of fully automated grouting stations, capable to produce variable grouts and control several injectors simultaneously, and to record and display in real time the relevant grouting parameters. These grouting stations can also be connected to a network of sensors detecting ground surface or structure deformations, thus reducing the risk of damages induced by grout injection to surrounding infrastructures.

2.1.1 Case histories

Turin Railway Interchange, Italy. The new Turin (Italy) railway interchange, currently under final phase of construction, intersects underground the city centre, along the north-south alignment, through a series of tunnels and cut-and-cover sections. A critical segment of the tunnel, was to be mined underneath the double track high traffic Turin-Milan railway line at shallow depth. The soil profile comprises the alluvial formations characteristic of the Po River valley, ranging from gravel to fine sand, finely interbedded. The tunnel excavation, carried out in several sequences, was preceded by intense use of soil improvement

techniques. A grouting gallery (or pilot tunnel) of 3.6 m in diameter was mined in 6 m increments, at a safe distance underneath the railroad tracks, and protected by a canopy of sub-horizontal 0.6 m diameter jet grouting columns (figure 3, after Manassero, 1993). From within the grouting gallery fans of sleeved PVC pipes were installed radially. An initial phase of permeation grouting, aimed at filling the most pervious gravelly layers, took place by using stable MISTRA mixes. A second phase of silica based mixes (SILACSOL) was necessary to permeate the fine layers and ensure the formation of a continuous 4.0 m thick arch of consolidated soil around the main bore.

A canopy of driven steel reinforcements was then installed ahead of the excavation of the 12.5 m wide main section arch (figure 4, after Manassero, 1993): the steel poles were 12.5 m long and the excavation was done in 9.0 m increments. The soil reinforcement ahead of the tunnel face was made possible by the use of dedicated drilling equipment, specifically designed for this type of tunnelling applications (figure 5). Before the final excavation of the bench section, sub-vertical jet grouting columns were also used to consolidate the side walls of the tunnel.

A dense array of tilt-meters and laser targets was used to constantly monitor the rail tracks, both during the grouting and the mining phases.

In spite of less than 2.0 m coverage between the top of rail and the tunnel extrados, and the unfavorable soil conditions, the excavation was carried out safely, and without disruption to the railroad traffic. Surface settlements were kept within 15 mm.

Park Road Tunnels, Washington, USA. The 3.6 km expansion of the Washington DC metro, included the construction of two stacked tunnels. The tunnels, 6.4 m in diameter and 1 km each in length were driven by two open face shields in very variable soil conditions, ranging from coarse grained terrace deposits, to silty sands. The water table was at a depth of approximately 9 m,

well above the tunnels invert, which were ranging from 11 to 22 m depth. The initial design entailed extensive dewatering, as primary method of ground control, and chemical grouting, to provide localized crown stability. Notwithstanding the tight spacing of the wells (approximately 15 m), the dewatering technique proved to be extremely slow and inefficient in the fine grained layers. In fact, the excavation stopped after only 75 m from the portal, due to significant face instability, loss of ground, and surface settlement. Greater emphasis was then placed on the chemical grouting from ground surface as the primary ground treatment method, by extending the treatment zone 3 m above the crown and 1.5 m externally at the spring line, including zones within the silty sand layers intersected by the tunnel profile. Minimum compressive strength allowable was 0.7 MPa. A total of 42 million liters of sodium silicate and organic reactants were injected through tubes à manchette around the tunnels, at a rate often exceeding 95 000 liters per day.

2.2 Jet Grouting

The fundamental principle of the jet grouting technique is a high speed erosional jet, acting under a nozzle pressure of up to 50 MPa. The soil is fractured, eroded, and mixed in situ with cement based grouts. Different jet grouting categories are commercially available, depending on the type and number of fluid injected simultaneously.

The most common method employs a grout jet to fracture and mix the soil *in situ*. The erosional efficacy of the jet can be enhanced by shrouding the grout jet with compressed air, in the so called double fluid jet grouting. The triple fluid system separates the erosional (air and water) from the stabilizing (grout) function.

In all the three procedures described above, the nozzle(s) injecting the various fluids are located onto a special jetting device, called monitor. The monitor is generally attached at the bottom of a specific string of drill rods and advanced in the ground to the required

depth. The monitor is then rotated and extracted in a controlled fashion, while the injection at high pressure of the fluids takes place. The dimension and mechanical properties of the treated body depend on the combined effect of the type of soil and composition of the grout, grout pressure and flow, rotational and withdrawal speed. The diameter of single fluid columns, typically in the range of 0.5 to 0.9 m, can be increased to over 4 m by using double or triple fluid techniques.

The detail design of jet grouting works is generally the prerogative of the specialty contractor, and it is based on empirical considerations, taking into account the specific subsurface conditions, equipment characteristics, and the specification requirements. Being the jet grouting technique virtually independent from the soil texture and structure, it can be applied to a variety of conditions. The grout mix is, in the majority of the applications, a straight water-cement mixture, with initial rheological properties typically characterized by low viscosity and rigidity. Grout additives can be utilized in particular applications: for instance, bentonite can be added to contain strength of the treated soil; mild initial set accelerators can be used in case of high-velocity flowing water. Anti-flocculant and dispersant are at times used in cohesive soils. In jet grouting particular emphasis is given to the equipment aspects of the technology, such as the high-pressure grouting pumps, the air-water-grout nozzles and jetting monitor. Another aspect of the technology which has seen a rapid development in the recent years, is related to the monitoring and quality control of the process (Jameson, Pellegrino and Shea, 1998). Rig mounted systems are capable to record and display in real time the most significant installation parameters, allowing to:

- identify depth intervals requiring treatment;
- monitor and document the drilling and grout process;

- verify the grouting performance through quantification and comparison of pre- and post-treatment subsurface conditions.

Due to its great flexibility, the jet grouting has rapidly gained popularity in the solution of difficult tunnelling and foundation problems. In fact, this technique is applicable to the entire spectrum of soil types and is adjustable to diverse treatment geometry. Moreover, allowing the treatment of large volumes of ground by virtue of small diameter holes, it can be applied to diverse tunnelling situations:

- temporary arch stabilization/support ahead of the face of excavation by sub-horizontal elements (reinforced or not) from within the tunnel
- temporary tunnel face stabilization/support by sub-vertical (overlapping or not) elements
- continuous linear soil treatment to create a water cut-off.

2.2.1 *Sub-horizontal Treatment*

An example of application of sub-horizontal treatment ahead of the excavation face is provided in the above section dedicated to permeation grouting. However, it is worthwhile to expand on this tunnel support scheme which has seen growing popularity in NATM tunnelling in Europe, Asia, and South America over the last 15 years, and yet, very limited applications are recorded in North America. The scheme was first used in 1983 to overcome morainic soils at the Campiolo railway tunnel, along the Udine-Tarvisio line in northern Italy (Tornaghi and Perelli Cippo, 1985). This scheme for temporary support system entails the installation of a series of sub-horizontal jet grouting columns in a conical pattern such as to create a "canopy" of grouted soil beyond the tunnel face. The grouted soil is subject to compressive and shear stresses, as it develops arching in the ground ahead of the excavation; for this reason, the continuity of the grouted ground is paramount. In order transfer the stresses

induced by the arch deep below the invert, the "canopy" is generally deepened by means of sub-vertical jet grouting columns prior to the bench excavation. This scheme has proven extremely effective in minimizing surface settlement and convergence of the excavation prior to the completion of the final lining, even in very shallow conditions.

Among the increasing number of applications, one well documented case history of German experience is noteworthy for its shallow and urban characteristics.

Bad-Godesberg Tunnel, Bonn, Germany. An 85 m² section tunnel segment for the Bonn light-rail had to be excavated at shallow depth (3.5 to 6.8 m to the crown) in quaternary alluvial soils. The typical stratigraphic sequence reveals highly pervious sandy-gravel body ($k = 10^{-2}$ m/s) underlying a 4.5 m thick sandy-silt layer (see figure XX). The 500 m long tunnel had to cross underneath a 30,000 vehicle/hour freeway, several utilities, and in close proximity to the high-speed Köln-Frankfurt railway. The NATM scheme adopted for the excavation entailed extensive use of single fluid jet grouting elements to consolidate the arch in granular soils. Where the sandy-silt layer intersects the excavation face, the crown soil-stabilization is replaced by 28 mm diameter steel spiling. A full scale soil-stabilization test section was completed before the beginning of the jet grouting works, in order to define the grouting parameters. The typical jet grouting column diameter identified during the test section was 60 cm average; accordingly, the spacing at the tunnel face was set at 47 cm, so that at the end of the 12 m long treatment, the columns were theoretically tangent. The excavation proceeded in 9 m increments.

During the installation of the first columns, some surface was noticed. The phenomenon was related to the very limited ground coverage above the jet grouting (as little as 3 m), and to the momentary loss of spoil return from the borehole: this was believed to cause a transitory status of overpressurization in the soil, causing its volumetric expansion. This

phenomenon was mitigated by reducing the grout volume and injection pressure, and by drilling pressure relief holes immediately above the jet grouting boreholes. Subsequent to the implementation of these revised procedures, the installation of the jet grouting elements was completed with a total recorded ground heave of below 10 mm, with less than 3 m of ground coverage. The jet grouting treatment quality control entailed the verification of mechanical properties of the jet grouting spoil collected at the borehole. The average 28-day compressive strength recorded was 22 ± 10 MN/m², while the average total unit weight was 16.5 ± 2.5 KN/m³.

Also the excavation phase was cautiously sequenced in order to minimize disturbance and surface settlement: 10 m² sections were excavated and immediately covered with 3-4 cm of spritz beton. The steel rib spacing was set a 1 m, with every third rib closed through the invert. The temporary support was completed by applying 25 cm of spritz beton, reinforced with double steel wire mesh, and extended to protect the tunnel face. The work progressed from both headings, with the same excavation and grouting crews alternating from one front to the other. The jet grouting spoil, typically consisting of a variable admixture of grout and soil, was evacuated from the tunnel face and collected at the portals, for future disposal after the initial set. The jet grouting treatment performed satisfactorily overall, allowing the safe completion of the tunnel excavation. It must be noted however, that in the section where the jet grouting treatment at the crown was interrupted (silty-sand lenses) the largest settlement occurred (see figure XX). Conversely, the continuous arch of jet grouted soil allowed the containment of surface settlements within 10 mm. The total work quantity for the soil-stabilization by jet grouting included 20,000 lineal m of jet grouting columns.

Globally, the installation of 55 jet grouting treatment sections and excavation of the tunnel were completed in a 7-month time,

averaging 18 m (or 2 complete sections) of excavation and completed temporary support per week. The work schedule was on 2 8-hour shift per day, 6 days per week.

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A large number of applications are recorded in the literature.

Two case histories of full-face treatment are provided hereafter.

2.2.1 Case histories

Islais Creek, San Francisco, USA. A groundbreaking application of jet grouting to tunnelling in soft clays was done at the Islais Creek Transport/Storage Project in San Francisco, and is described in detail by various authors (Bruce and Pellegrino, 1996; Pellegrino and Adams, 1996). The original design for the 232 m of combined sewage tunnels, 4.5 m in diameter, contemplated the use of compartmentalized breast boarding shield under compressed air to overcome squeezing ground conditions. The Contractor proposed the use of jet grouting to pre-treat from ground surface the soft clay along the tunnel alignment, excavate the jet grouted soils with an open face road header, and install steel ribs and wood lagging as the primary tunnel lining. The revised design, based on 2-D and 3-D F.E.M. analysis, required full face treatment, extended 1.2 m around the bore, with a minimum unconfined compressive strength of 830 kPa. Predicted surface settlements were in the order of 10 mm.

The pre-treatment of the clay started in advance of the tunnelling operation, by installing close to 1000 overlapping jet grouting columns, for a total of 7500 linear meters of jet grouting. A section of the tunnel had to be mined under three highway viaducts, a double-track commuter railroad

embankment, and several underground utilities. Angled jet grouting columns up to 25 m deep were necessary to ensure complete coverage of the tunnel alignment, as shown in figure 6 (after Pellegrino and Adams, 1996).

The tunnel excavation took place over approximately 4 months, with excavation rates in the order of 6 meters per 10 hour shift. Tunnel muck consisted of chips of hard jet grouted clay, easy to handle and dispose. The surface settlements recorded were in conformity with the design prediction, and no disruption to the highway and railroad traffic or adjacent utilities was caused by the mining operation.

Although the use of jet grouting to overcome squeezing ground conditions was not unheard of in the industry, especially in the Far East (Mongilardi and Tornaghi, 1986; Fang and Yu, 1998), this Project represents the first recorded application of full-face treatment.

Utility Relocation, Boston, USA. The Central Artery/Third Harbour Tunnel Project in Boston USA, is one of the largest and most complex urban infrastructure project currently in construction in North America. Jet grouting has been extensively used project wide as support of excavation, mass soil stabilization, and deep water cut-off (Lambrechts and Roy, 1997; Bruce and Pellegrino, 1996). As part of a major utility relocation contract in the South Boston area, two tunnels were to be excavated, for a combined length of 250 m in diameter, and diameter ranging from 2.1 m to 2.5 m. Tunnels invert lay at a depth of approximately 8 m, in a highly congested metropolitan area, as indicated in figure 7. The subsurface profile includes very soft organic silts underlying granular fill and miscellaneous urban debris at depth varying from 7 m to 8 m. The organic silts rest over marine clays, part of the well known Boston Blue Clay formation. Water table is found in close proximity to the ground surface, as the tunnel alignment is only 30 m distant from the inner Boston harbour.

Jet grouting was designed to support the final pipeline, and extended from tunnel invert to the deeper marine clay bearing stratum. The Contractor elected to extend the jet grouting through the tunnel elevation, to overcome otherwise problematic mixed face conditions. However, the two different formations required the tailoring of the jet grouting work in to a 2-phase operation, to avoid the development of excessive strength in the granular fill present through the tunnel profile. The deep foundation of the pipeline was created by injecting 1.2 m diameter columns from the bearing stratum up to 0.5 m above the tunnel invert, developing unconfined compressive strength in the organic silts in excess of the minimum specified of 480 kPa, thus providing adequate support to the future pipeline.

In a subsequent phase, the tunnel face was consolidated by means of 1.8 m diameter columns, injected with a cement-bentonite grout mix to maintain the unconfined compressive strength of the jet grouted soil under 400 kPa, as shown in figure 8. The weak treatment of the granular fill allowed sufficient stand-up time to the otherwise raveling sands at the tunnel face, without impeding the hand mining operation. Pipe jacking and hand mining were performed in safe conditions under an intersection of major thoroughfares, and water inflows in the tunnel were kept to a minimum.

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