Chapter 51

NEW DEVELOPMENTS IN GROUND REINFORCEMENT AND TREATMENT FOR TUNNELLING

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ABSTRACT

The authors describe novel aspects of ground reinforcement and treatment as related to soft ground excavation for tunnels throughout the world. Insitu reinforcement for cut slopes (soil nailing), as underpinning (reticulated micropiles), and as direct tunnel support (infilaggi) is introduced. Ground treatment focuses on new aspects of permeation grouting (by the tube`a manchette system), and on jet grouting--a very powerful and positive new technique. Recent developments in equipment, materials, methods and instrumentation are reviewed, with special reference to major tunnelling projects in Italy and Singapore.

1. INTRODUCTION

The construction of open cut excavations or tunnels through soils invariably requires some degree of reinforcement or treatment of the surrounding ground. Such action is necessary to secure the safety of the structure being formed, and to minimize the construction influence on adjacent existing structures. In addition, the imaginative application of such ground improvement techniques will give the tunnelling contractor a financial edge, for example, by permitting the construction period to be reduced through the resulting higher rates of progress.

A characteristic feature of world construction activity in the last decade has been the execution of major tunnelling projects associated with infrastructure development or rehabilitation. One can refer readily to the newer Metro projects in major cities worldwide--Washington, Milano, London, Singapore, Hong Kong and Los Angeles--while Cairo, Chicago and Milwaukee are the sites of massive sewerage upgrading programs.

In each of these areas, tunnelling engineers have been faced with similar combinations of problems involving soft ground conditions and intense urbanization, as well as restrictive time and financial parameters. Their response has been positive and innovative, a fact reflected in the wealth of technical publications and conferences held in the last few years alone to share experiences.

This explosion of ideas and publications has, of course, resulted in the reality that it has become increasingly difficult to keep abreast of these "new technologies" described, as they are, across the spectrum of the construction process ranging from structures to soil mechanics. The purpose of this paper, therefore, is to highlight major new developments which the authors believe may not necessarily be common knowledge, but which certainly have major significance for the soft ground tunnelling fraternity in the United States.

For reasons of space, the authors have not described equally valuable innovations in ground retention systems. In this regard, the increasing power and accuracy of slurry trench excavation equipment based on the hydraulic mill method (e.g., Hydrofraise) is permitting fast and deep construction even through boulders and bedrock. In addition, new developments in ground anchorage technology (e.g., the use of the Duplex drilling method (Bruce 1984) for difficult ground penetration, and the exploitation of postgrouting systems to enhance anchorage capacity in poor soils) are also particularly exciting. Rather, the paper focuses on aspects of insitu soil reinforcement (by the introduction of rigid inclusions), and soil treatment (by injecting foreign materials) of special significance. The descriptions are not fundamental and comprehensive: they presume a working knowledge of the principles of ground reinforcement and treatment. Given the close links both topics have with tunnelling technology, this is felt to be a safe basis from which to proceed.

2. OUTLINE OF NEW TECHNIQUES

2.1 Ground Reinforcement

Three basic categories of insitu reinforcement for stabilizing excavations and slopes in soils may be identified (Figure 1):

(i) Soil Nailing, (ii) Reticulated Micropiles, (iii) Soil Dowelling

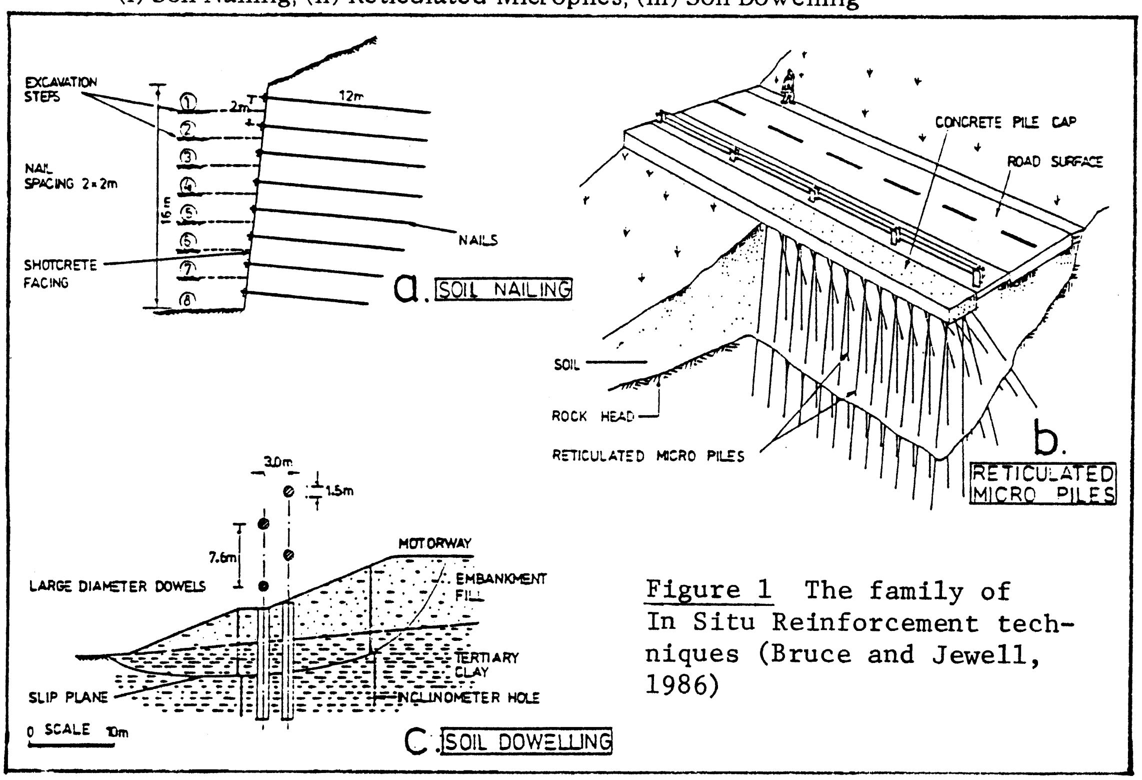

Figure 1 The family of In Situ Reinforcement techniques (Bruce and Jewell, 1986)

(i) Soil Nailing - Short, fully bonded steel bars are grouted into the soil, approximately perpendicular to the cut face, as excavation descends in stages. When performed properly, the reinforced mass acts like a conventional gravity structure which will minimize structural movements (deflections at head 0-0.3% of the slope height), and resist externally applied static and dynamic loadings. The origins of the system lie in the New Austrian Tunnelling Method, and the principle of operation is the same: reinforcement is provided to the ground before it moves and thereby loses its at-rest strength.

Since 1972, soil nailing has been executed in Western Europe in a wide range of soil conditions for slopes and deep excavations, many associated with Metro construction; e.g., Lyon, Paris and Charleroi. Since it does not need massive structural face membranes (0.1m-0.2m sprayed concrete suffices) and because it offers a flexible fully integrated solution to the excavation contractor, cost savings of up to 30% can be generated relative to conventional excavation support methods.

Soil nailing has been used in the States sporadically, and on a very localized basis, since the mid 1970's. However, it is only in the last 5 years that its potential has approached national recognition (Nicholson 1986). Its great value as a technique has recently been demonstrated in the States by the researching of numerous Government sponsored studies, such as that by NCHRP 24/2, to be published in late 1987.

Soil nailing constitutes an excellent option for rapid and safe excavation stability in excavations up to 20m high in all conditions, except soft plastic clays. To illustrate its popularity, in France an estimated 50 projects are executed per year, of which perhaps 5 are permanent applications. Typical job sizes are 1-2000m^2, but projects up to 24,000m^2, have been conducted. In both France and Germany, major field and laboratory studies have been carried out by collaborations of contractors, universities and governmental agencies. There is no doubt that a similar upsurge on all fronts is about to occur in the States also.

(ii) Reticulated micropiles are steeply inclined in the soil at various angles both perpendicular and parallel to the face (Figure 1b). The overall aim is similar to soil nailing, namely to provide a stable block of reinforced soil which supports the unreinforced soil by acting like a gravity retaining structure. The soil is held together by the multiplicity of reinforcing members acting to resist bending and shearing forces.

Arrays of reticulated micropiles may also be used to directly support vertical loads, to conduct them away from adjacent tunnelling activities (Figure 2), and to form retaining walls to protect surface structures (Figure 3). Bearing in mind that micropiles sustain load at very small settlements (or may be preloaded to avoid any settlement in service) such systems are excellent methods of underpinning sensitive buildings potentially subjected to tunnel induced settlements.

(iii) Soil dowelling is applied to reduce or halt downslope movements on well defined shear surfaces (Figure 1c). The slopes treated by dowelling are typically much flatter than those in soil nailing or reticulated micropile applications. Gudehus (1983) has shown that the most efficient way to improve mechanically the shearing resistance on a weakened shear surface through the soil is to use relatively large diameter piles which combine a large surface area with high bending stiffness. Thus the diameter of a soil dowell is generally far greater than that of a soil nail or micropile.

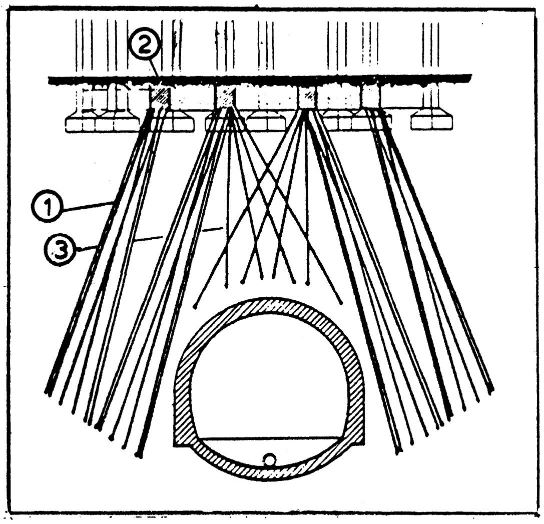

Figure 2 Reticulated Micropiles for underpinning structures over tunnels (After FHA 1976)
Legend (1) Micropiles for underpinning, (2) New r.c. pile cap (3) Micropiles as in situ reinforcement to ground over tunnel crown

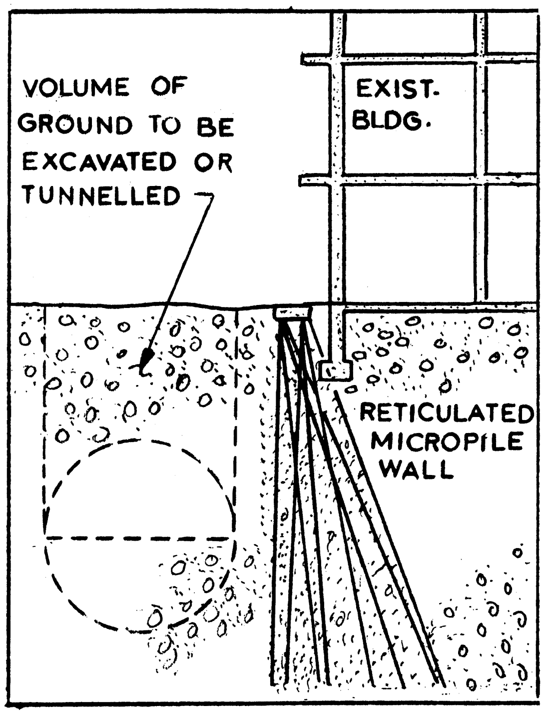

Figure 3 Reticulated Micropile Wall to protect existing structures adjacent to cut and cover, or tunnelling, activities

It is difficult, however, to imagine particular applications in tunnelling, and in any case, the technology of installing large diameter piles or caissons is already well developed.

There is in addition a fourth technique, not referred to in the Bruce and Jewell (1986) classification, as it is not insitu reinforcement sensu stricto:

Horizontal micropiling: Clough (1981) describes the use of "Spiling" for tunnel support by an array of steel rebars driven ahead of the excavation to form a reinforced zone around the subsequent excavation. However, in recent years, advances in specialized drilling equipment (e.g., the RODIO SR 500 diesel hydraulic drilling rig with a 19.2m long mast - Figure 4) have allowed the full operational potential of these horizontal reinforcements ("infilaggi") to be realized as a routine and cost effective method of tunnelling in soft and shattered ground. Basically steel tubes, 76mm OD and 56mm ID, are drilled at close centers from the face around the profile of the tunnel to be excavated (Figure 5). Excavation then proceeds under this "umbrella," steel arches being placed directly against the horizontal tubes, and the primary lining completed by spraying with shotcrete. Depending on ground conditions, each phase of horizontal micropiling (infilaggi) may be up to 19m long (uniform morrainic soils) or reduced to 5m or less in especially variable, shattered rock and wet conditions. The steel tubes may be equipped to permit cement or chemical post grouting (to provide ground treatment and so enhance the effect of the insitu reinforcement), or can be wrapped in a cement inflatable geotextile tube to ease primary grouting in instances where the holes are upwards inclined. In addition, such insitu reinforcement can be used to supplement the effect of other ground treatment techniques (i.e., horizontal jet grouting) to protect tunnels passing close under existing structures exerting high loadings.

The technique can be employed at portals to enable construction of initial tunnel drives through incompetent/weakened materials prior to their transition into harder rock conditions, or it can be used, as above, as a standard tunnelling method closely phased with the main contractor's program.

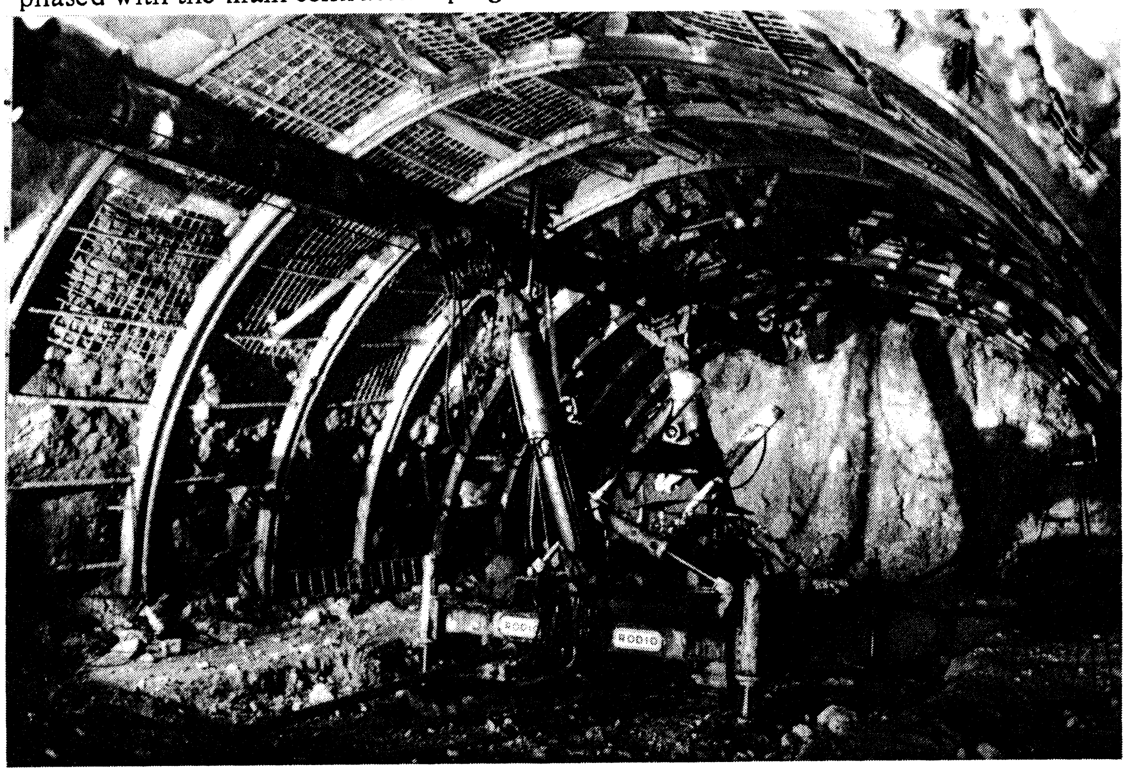

Figure 4 RODIO SR500 tunnel rig with long mast for drilling horizontal micropiles, or jet grouting

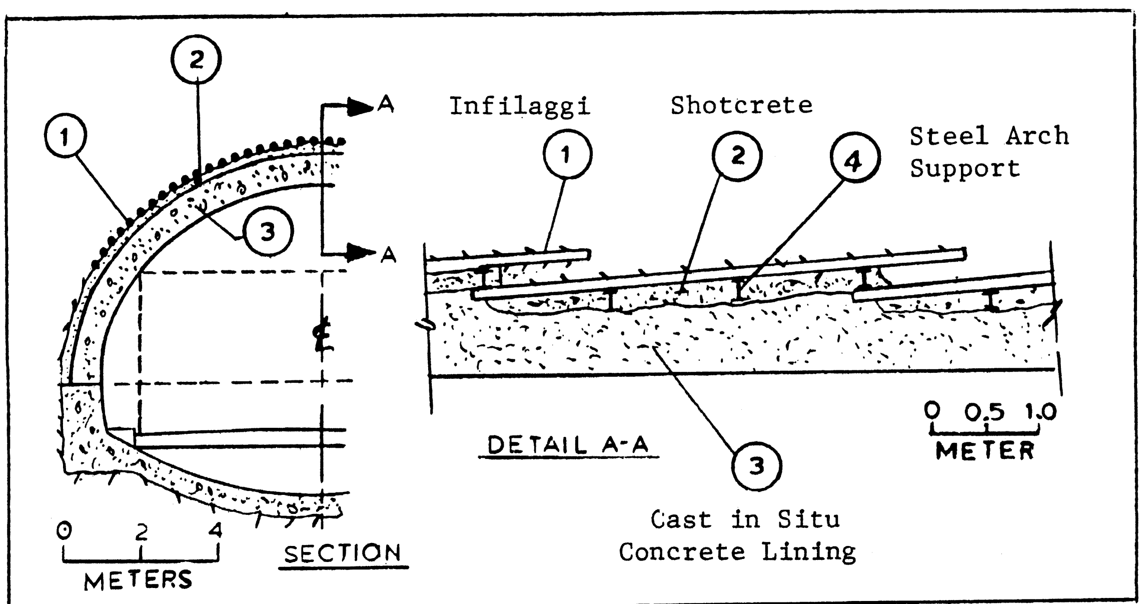

Figure 5 Details of typical (short) infilaggi application. Mammola Tunnel, Italy

2.2 Ground Treatment

Ground treatment refers to the injection of foreign materials into the ground to change one or more of its natural properties. For example, some grouting methods may concentrate on providing "cohesion" to clean sands, thus improving their mechanical resistance, while others will attempt to reduce natural porosities thus dropping the insitu permeability. Often a combination of both purposes is sought, or provided incidentally. This definition excludes stabilization by ground freezing, which is well described by Gallavresi (1982), and Deix and Braun elsewhere in this conference (1987).

Most tunnelling engineers have some form of experience with grouting for ground treatment, as defined above. However, in many cases, it may be guessed that the experience has not been successful. Reasons--and excuses--range from unsuitability of the method or materials, to poor workmanship and control by the grouting contractor. In addition, it must be acknowledged that grouting has often been selected as a final remedial option in difficult situations where "conventional" techniques have also failed, instead of being regarded as the "design tool, as it should be" from the onset (Clough, 1981).

The modern trends in ground treatment described in this paper have been selected with such potential criticisms in mind. They emphasize (i) the wider range of grouting materials which are now available, (ii) the newer techniques and systems which have been developed to combat the problems of soft ground tunnelling, (iii) the advantages of integrating such techniques as routine construction methods, and (iv) the high degree of operational control which can now be exercised, and demonstrated, by an experienced and efficient grouting contractor.

2.2.1 Basis for Selecting Innovative Aspects - Four categories of grouting to treat soils are usually recognized (Mongilardi and Tornaghi, 1986):

(i) Hydrofracture
(ii) Compaction
(iii) Permeation
(iv) Replacement

(i) In hydrofracture grouting, the ground is deliberately split by injecting stable cement based grouts at high pressures. The lenses and sheets of grout so formed increase total stresses, fill unconnected voids, possibly consolidate the soil under injection pressure, and conceptually constitute impermeable barriers, mainly horizontal. However, it is very difficult to control, and the danger of damaging adjacent structures by the use of high pressures often proves prohibitive. Alone it is not a technique which would seem to be attractive to the US market, although as noted below, some hydrofracture phenomena are usually found in permeation grouting works.

(ii) For different reasons, compaction grouting is also not pursued further in this paper. It features the injection of thick mortar-like mixes at discrete locations. These cannot permeate or fracture the ground (if correctly designed) but instead act as radial hydraulic jacks which compress and/or densify the soil. This American technique has had success--and a great deal of publicity--in many major projects throughout the country. For example, it was used in the Baltimore Metro (Baker et al., 1983) and is foreseen for the LA Metro. The authors are aware of no new fundamental developments in this field. The interested reader is referred to a definitive presentation given by Warner (1982) and to Stokes and Wardwell's paper in this conference (1987).

(iii) In certain ways, the techniques involved in permeation grouting are the oldest and best researched. The aim is to introduce grout into soil pores without any essential change in the original soil volume and structure. The properties of the soil, and principally the geometry of the pores, is clearly a major determinant of the method of grouting and the materials which may be used (Figure 6). This paper details new developments in materials, procedures, and monitoring as related to injection exclusively by the tube'a manchette (sleeved pipe) system already well known throughout the industry (Bruce 1982).

(iv) Replacement grouting is the newest concept in ground treatment and has extreme potential. According to Miki and Nakanishi (1984) the initial idea was proposed in Japan in 1965, but even there it is only within the last 10 years that the various derivatives have been widely and routinely used. Its development was fostered by the need to treat soils from gravels to clays in areas where major environmental controls were strongly exercised over the use of chemical (permeation) grouts and allowable ground movements. In its most sophisticated form (Figure 7), the ground around the drill string is cavitated by very high pressure horizontally directed water jetting, and expelled from the hole by the aid of compressed air. The cavity so formed is then simultaneously filled with a cement based grout, which does, of course, incorporate some of the native ground. A simpler variant eliminates the air/water cavitation and instead uses only the high pressure grout jet to cavitate and eject, as well as inject, during withdrawal and rotation of the drill string. Popularly, the technique is called jet grouting, while the grouted product is appropriately referred to as "soilcrete" by the GKN group of companies. Further reference to the technique is made by Mussger et al. in this conference (1987).

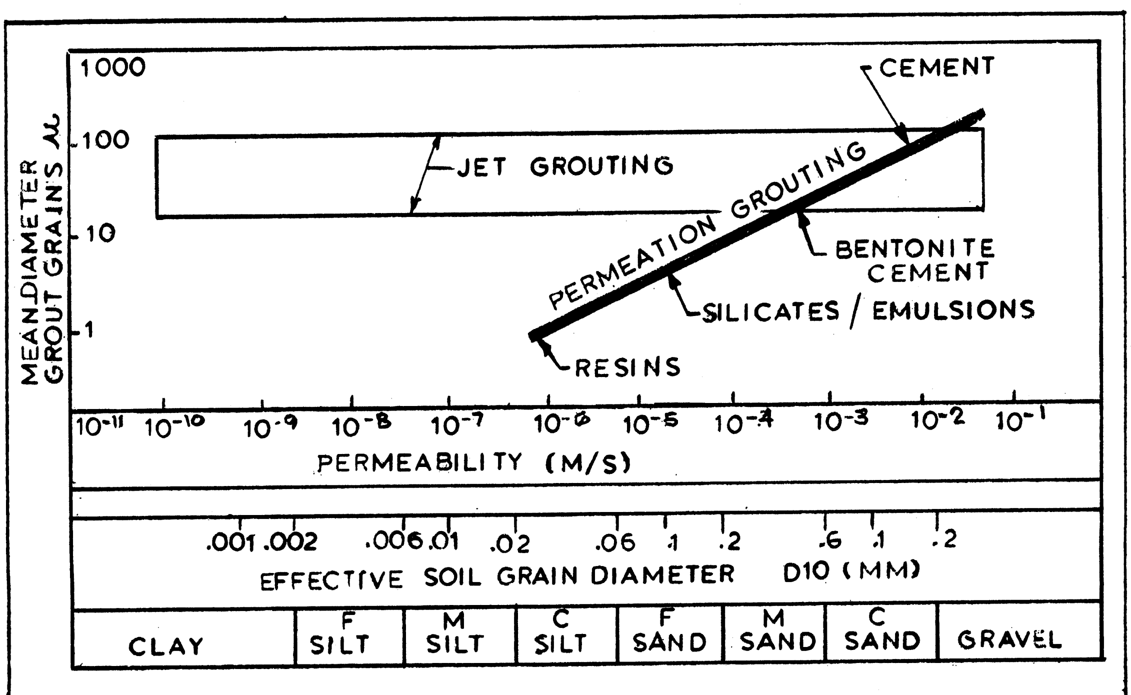

Figure 6 Groutability of soils in relation to grout and soil properties (After Coomber, 1985)

2.2.2 Innovations in Permeation Grouting

2.2.2.1 Equipment - Each contractor has his own specialities in terms of installing the tubes and executing the grouting. However, the following trends are evident on a worldwide basis:

- use of long mast "one stroke" drilling rigs, permitting fast installation programs and usually operating with bentonite flush or a self hardening drilling mud, further reducing operating costs.
- use of more flexible plastic tubes, delivered in one piece, to ease installation from within restricted tunnel access conditions, and to reduce risk or malfunction due to leakage at joints. Alternatively steel tubes are being used for surface installations; these provide the additional service of reinforcing the ground mechanically. (See Figure 18)
- use of hydraulically or pneumatically inflatable double packers for grouting, thus reducing labor effort, ensuring efficient sealing, and then permitting any deviated or damaged hole to be "rescued" and still used for grouting.

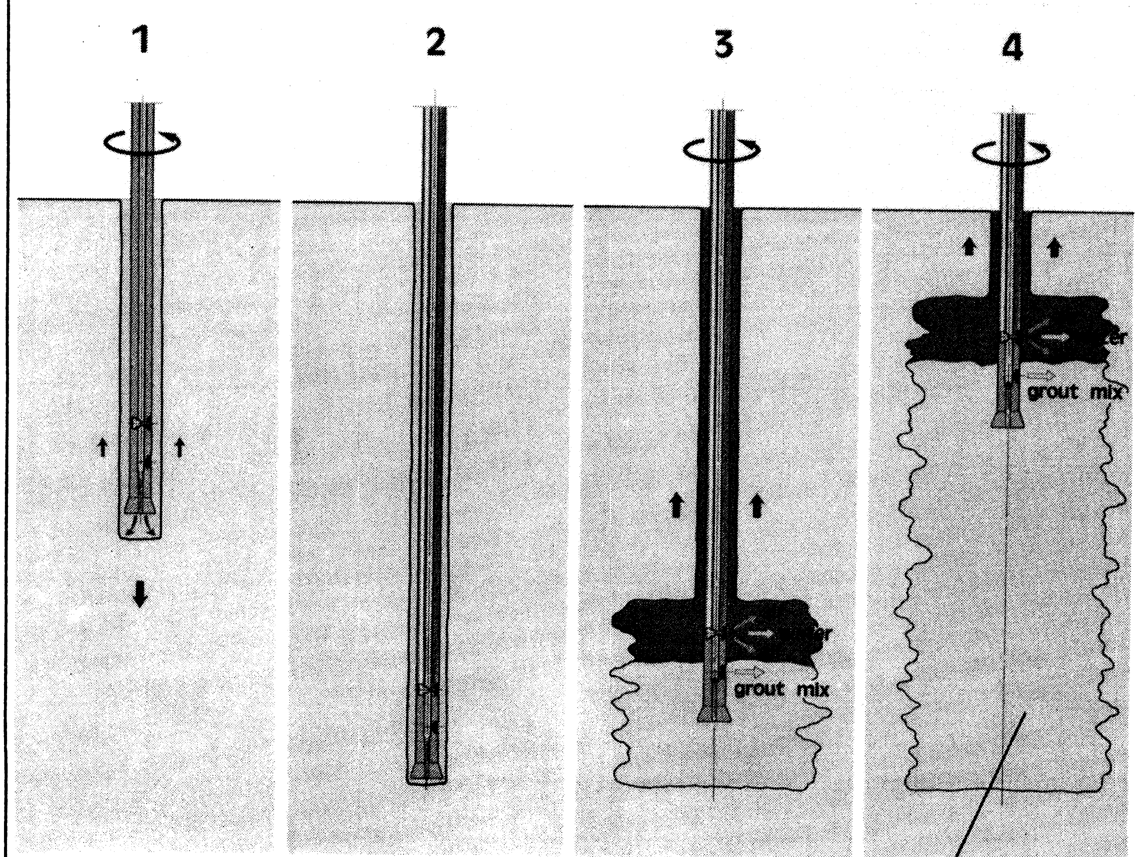

Figure 7 Sequence of construction of jet grout columns by Rodinjet 3 method (uncased borehole)

2.2.2.2 Grouting Materials - The description of grout classifications on the basis of rheological performance is long, complex and beyond the scope of this paper. The interested reader is referred to recent summaries by Karol (1985) and Mongilardi and Tornaghi (1986). Regarding particulate (cement based) grouts, the main obstacles to penetrability (Figure 6) are related to (i) the maximum particle size of the solid components in the grout, v.v., the pore sizes in the soil and (ii) the rate of pressure filtration which may induce rapid clogging even under low pressures.

The first problem is being tackled by generally introducing finer cements, for example, MC500 (Karol 1985) in which the average particle size is claimed to be 4 microns, and by minimizing grain agglomeration or flocculation by the improvement of mixing plants and addition of dispersing agents. In contrast, the filtration problem has represented the main obstacle in the past, since in conventional "stable" grouts a reduction of water loss rate can be obtained only at the cost of increasing viscosity, by an additional content of active colloidal particles, such as bentonite.

However, this problem has very recently been resolved by RODIO, which has developed an entirely new class of cement-bentonite grouts exhibiting extremely important and advantageous properties:

- very low filtration rates (considering a relative scale with bentonite mud being 1, then these new grouts are 2.5, compared with 10 for conventional cement-bentonite grouts, and 20-30 for cement grouts).
- no bleeding
- low values of yield point and plastic cohesion over an adjustable period time
- higher long-term strength and lower permeability in comparison with conventional grouts having similar contents of cement and bentonite.

The practical advantages of this new class of grouts to the tunnelling engineer can be summarized as follows:

- improved penetrability under a lower pressure in sandy-gravelly soils
- a lower water loss and therefore a greater volume of voids filled with the same volume of grout
- the possibility to fill all the voids consistent with the size of individual cement particles, and therefore, to treat medium-coarse sands with refined products, minimizing hydrofracturing effects.

Chemical grouts based on sodium silicate solutions and inorganic reagents (e.g., sodium aluminate, sodium bicarbonate) have long been used to provide soft gels for waterproofing sands. In order to increase strength, silicate concentrations must be raised, but this ensures almost instantaneous gelling. Thus, early higher strength requirements (say up to 0.5-1.0M_{pa}; i.e., 70-140psi)could only be satisfied by a two shot system such as the Joosten process. Most recently the Japanese have developed specialized drill and grout systems such as LAG (Tokoro et al. 1982) and DDS (Bruce 1984) which can handle the problems of injecting flash setting grouts of this type, but these systems are only practical in the softer uniform deposits.

The use of organic reagents (e.g., Rhone Poulenc 600) capable of matching these higher strength requirements, but still offering long gel times has grown over the last 20 years. However, in certain areas including Japan and Germany, such organically based reagents are not environmentally acceptable. In addition, creep effects may be a significant problem for silicate gel stabilized soils if the design involves a high and permanent loading (Tan and Clough 1980), while questions of durability under certain conditions may be valid. (The authors, however, support the view of Mongilardi and Tornaghi (1986) that there are certainly "overconservative prejudices against organic materials in some important urban areas and below the water table .")

In light of these problems, potential and real, the newest developments have led to the evolution of a new type of chemical grout, composed of (a) a silica liquor, and (b) an inorganic reagent. As opposed to commercial alkaline sodium silicates, which are aqueous solutions of colloidal silica particles dispersed in soda, the liquor is a true solution of activated silica. The activated dissolved silica when mixed with the reagent produces calcium hydrosilicates with a crystalline structure quite similar to that obtained by hydration and setting of cement. The resulting product is a complex of permanently stable crystals. Hence the reaction is no more an evolutive "gelation" as in the case of silica gels, involving the formation of macromolecular aggregates and possible loss of silicized water (syneresis). On the contrary, it is a direct reaction on a molecular scale.

This type of mix (Silacsol), recently developed in France and successfully used by RODIO in Italy, presents the same groutability range as common silica gels: medium to fine sands can be effectively treated. Even if larger voids or fissures are accidentally created by hydrofracturing, a permanent filling is assured without any syneresis risk. In fact, the activated silica mix has the stablity of a cement grout owing to the nature of resulting products (insoluble crystals of calcium silicate) and to the absence of aggressive by-products, thus involving full safety against pollution.

2.2.2.3 Instrumentation - Throughout the grouting industry there is an increasing employment of computer-aided technologies as monitors and controls over grouting operations in the field. This is reflected in several of the papers presented at the "Issues in Dam Grouting," session at the ASCE Convention, Denver 1985. The most effective of these, as far as injections are concerned, will be similar to the RODIO PAGURO System of remote centralized monitoring. This monitors numerically and graphically the full injection characteristics of each pump (the setting of which is incidentally still under manual control) in real time. It thereafter gives a hard copy summary of each point injected (including volume, maximum and average pressures and flow rates and time). Such data then provide the basis for technical review of the grouting conducted (e.g., grout take analyses) and qualities of work executed, for payment purposes. Clearly the investment in such sophistication is economically justifiable only in projects of appreciable scale and/or complexity.

Most recently, however, a major breakthrough has been made in Italy in the exploitation of instrumentation for soil investigation and grout parameter design. The sensors of the PAPERO system continuously record the penetration rate, rotational speed, thrust, torque and flush pressure encountered in drilling a certain exploratory hole. These are combined to give a single unified factor--specific energy. Thereafter, the computer relates this factor to ground type, and prints out a geological log, with boundaries at 10cm intervals (Figure 8). This geological log, conducted in advance of grouting and tunnelling, permits optimization of the subsequent drilling and grouting parameters as well as giving invaluable information to the tunnelling contractor in that potentially dangerous conditions (i.e., sand runs) can be closely predicted. The accuracy of the geological log has proved exceptional in the conditions of the Milano Metro--mixed gravels, sands and silts to over 25m depth--and groups of three investigatory holes have been routinely drilled at about 6m intervals along much of its length.

The key to the accuracy is obviously the ability of the computer to relate specific energy with ground type. This has been developed by conducting statistical analyses of specific energies recorded at discrete depth intervals, in correlation with visual observations (from core samples) of the ground type. In this way, the influence of depth on insitu ground properties, and other factors such as the hydrological regimes and borehole inclinations are accommodated--which is not the case in other, less successful systems of drilling parameter analyses.

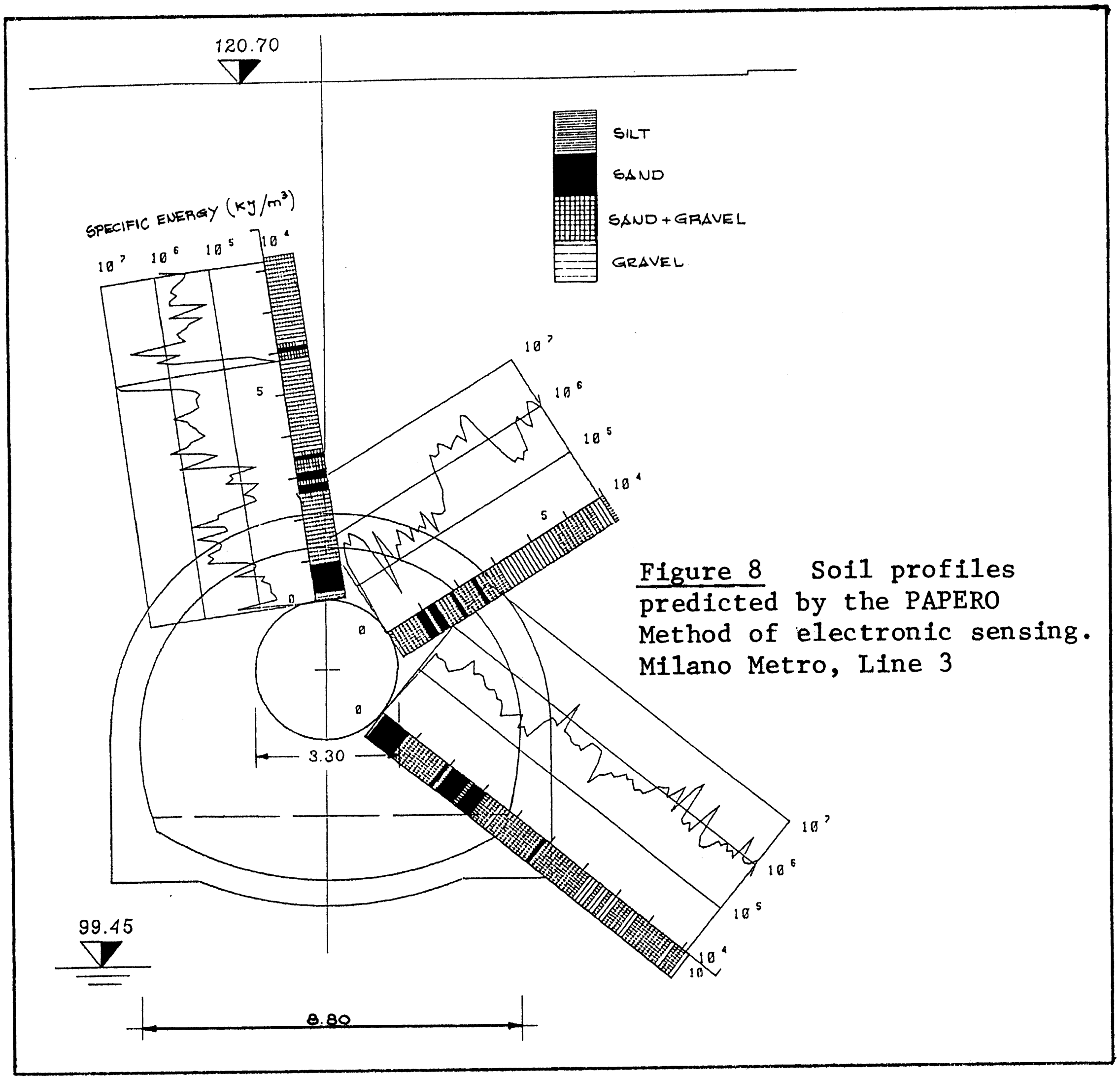

Figure 8 Soil profiles predicted by the PAPERO Method of electronic sensing. Milano Metro, Line 3

2.2.3 Innovations in Jet Grouting - Judging by the fact that the technique was not described by Clough (1981) in his comprehensive review of innovations in tunnelling, which included the field of ground treatment, it may be assumed that the whole concept of jet grouting is relatively novel to American practitioners. And yet, in contrast to the sensitivity and sophistication of some concepts of permeation grouting, the principle of jet grouting stands as a straightforward positive solution using only cement based grouts across the whole range of soils. It also bypasses the controversies about environmental pollution associated with some chemical grouts. In short, jet grouting is now an excellent choice where more traditional forms of treatment are judged unsuitable, inadequate, unsafe or too expensive.

However, it must be noted that any system which involves the simultaneous use of up to three fluid components and extremely high pressures--in this case up to 60 M_{pa}(8500 psi)--must be handled with extreme care, in order to avoid excessive ground heaves or inefficient mix and inject procedures.

The RODIO group of companies has executed successfully almost 500km of jet grouted columns in the last six years alone, in various countries in all parts of Europe and the Far East. Almost all of the applications have been for tunnel or shaft constructions (Figures 9 and 10) with much of the work being executed almost horizontally, as "umbrellas" for subsequent phased excavation (Figure 11). In conjuntion with shaft base grouting (to counteract boiling, piping or heave), Coomber (1985) noted that resistance to uplift is not dependent on the weight of grouted soil alone: the majority of the resistance is developed by contact stresses around the periphery of the plug.

With the Rodinjet 3 System illustrated in Figure 7, treated columns of up to 2.50m in diameter are achieved, depending on ground conditions and operational parameters. Alternatively, no rotation can be applied during jetting and withdrawal, and so panels are formed in the ground. When intersected by panels from adjacent holes they thus form a continuous membrane and this technique has already been applied successfully to seal leakage in the fissured sandstone bedrock of an existing earthfill dam in West Germany.

The influence of monitor nozzle type, size and number, and grouting parameters (mix design, pressure, volume, rate of extraction and rotation speed) have been widely investigated for various soils and hydrological conditions, and a firm experimental basis for design therefore exists. This does not preclude the necessity to conduct basic trials at the commencement of work on every site.

Grout mix constituents and composition can be varied to meet the specific requirements. Mix viscosity should be fairly low to promote uniform treatment to the greatest extent, and water:cement ratios (by weight) are rarely less than 1.0. In permeable granular materials, much of the injection water may be expected to be drained out both from soil and grout, whereas in a cohesive soil of low permeability, poor or no drainage is likely. This is the main reason why the strength of the grouted column, depending primarily on the final w/c ratio, is much lower for clay (0.5-3.0M_{pa},70-420 psi) than for sand and gravel (5.0-20.0M_{pa},700-2800 psi) all other factors being equal.

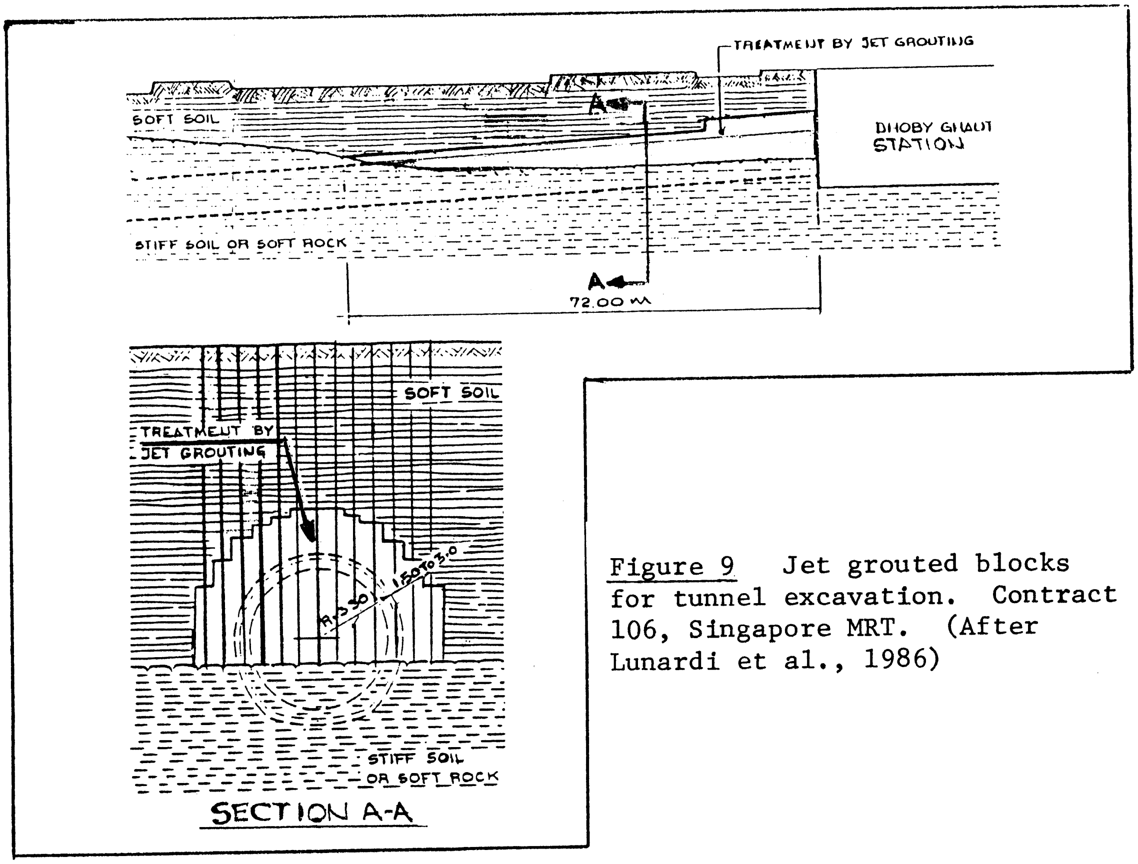

Figure 9 Jet grouted blocks for tunnel excavation. Contract 106, Singapore MRT. (After Lunardi et al., 1986)

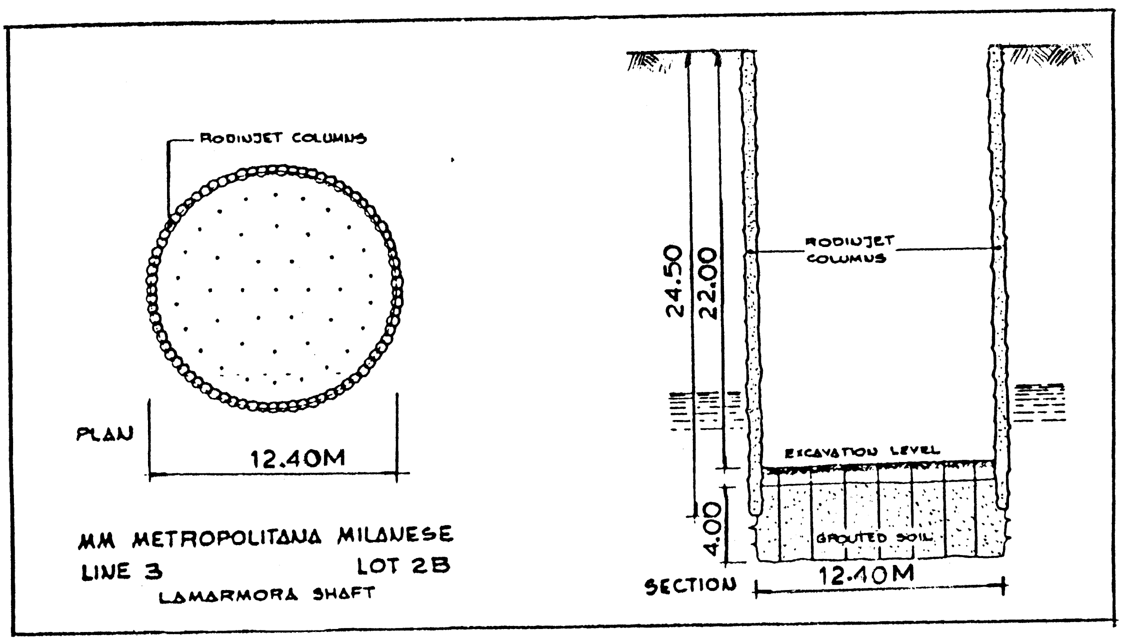

Figure 10 Jet grouting for shaft construction, Milano Metro Line 3. (Mongilardi and Tornaghi, 1984)

Extensive field research has been conducted as an integral part of several major ground treatment projects in a wide range of soils from sandy gravels to soft marine clays. In addition, a recent field test program in Milano involved the installation and excavation of 37 jet grouted columns to further investigate operational parameters.

It is with this quality of practical field experience in mind that tunnelling engineers in many countries overseas have justifiable confidence in the capabilities of jet grouting as a powerful and reliable tool.

3. ILLUSTRATIVE CASE HISTORIES

Space dictates that only four case histories can be briefly reviewed. The first two apply to cut and cover type construction, whereas the latter two describe underground tunnelling projects.

3.1 Soil Nailing for Deep Excavation: Pittsburgh PA

The PPG Industries Headquarters Building is located in the center of Pittsburgh, PA. About two-thirds of the site required excavations 12-13m deep for parking facilities; the balance of the site had basements 3.6 to 5m deep. The conventional method of driven H-beams with timber lagging, supported by ground anchorages, was used around most of the site (6000m^2). However, in three separate areas, the proximity of existing buildings caused particular concern where the excavation level had to reach 3.3-10m below their foundations:

(i) The building of the Catholic Diocese of Pittsburgh main office; built in the 1950's, of masonry and brick construction, on spread footings bearing on the alluvial sand, silt and gravel typifying the site.

(ii) Third Avenue Parking Garage; five stories high on spread footings.

(iii) Landmark Buildings; built around 1900, brick bearing wall, 3 stories high, with strip masonry and rubble footings.

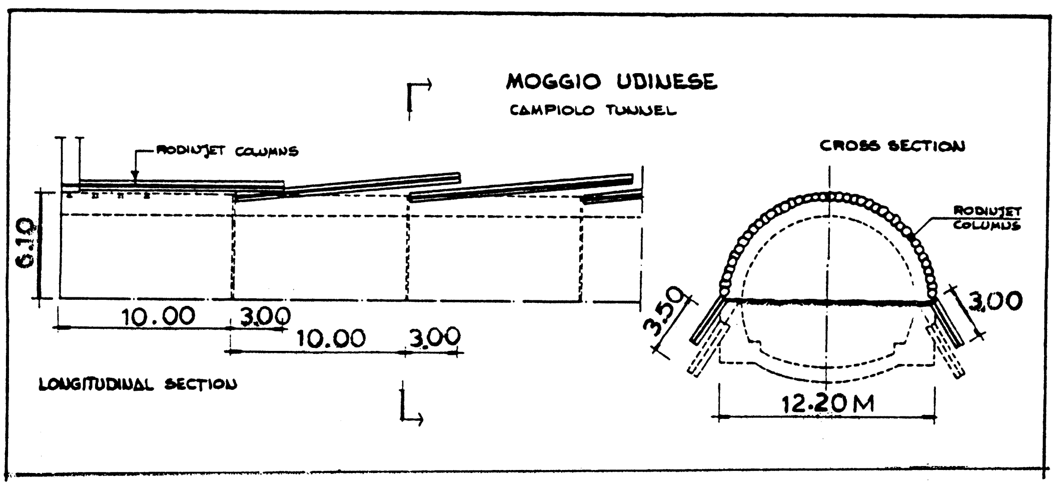

Figure 11 Jet grouting columns to protect tunnel excavation. Moggio Udinese (Tornaghi and Cippo, 1985)

The proximity of the new construction to the existing buildings precluded placing diaphragms of steel or concrete, or conventional H-beams and timber lagging for support, as the beams would have interfered with the new columns and walls. Conventional hand dug underpinning was also considered but rejected on grounds of program and costs. A solution based on soil nailing was selected modelled on the University of California, Davis studies.

The soil nailing technique was amended and adapted to local conditions and requirements as the work proceeded. In some areas, vibrations from the Main Contractor's excavation equipment induced local failures in the cohesionless granular soils. Local stability for the face of the soil nailing excavations was, therefore, improved by drilling fully cased holes of 127mm diameter at 250-300mm centers along the line of the foundations. These holes were inclined at about 8° from the vertical to avoid interference with the new structure, were taken to 1.5m below final excavation level, and pressure grouted after the insertion of a 19mm steel reinforcing bar. Excavation in 1m cuts showed the grout penetration to be sufficient to prevent further ravelling or sloughing of the face. The installation of the nails then proceeded in the standard fashion (Figure 12).

The particularly sensitive nature of the Diocese Building foundations required another level of protection against movement. Groups of vertical 450kN mini piles were installed to support about half of the total vertical load of the foundation directly, before the excavation proceeded (Figure 13).

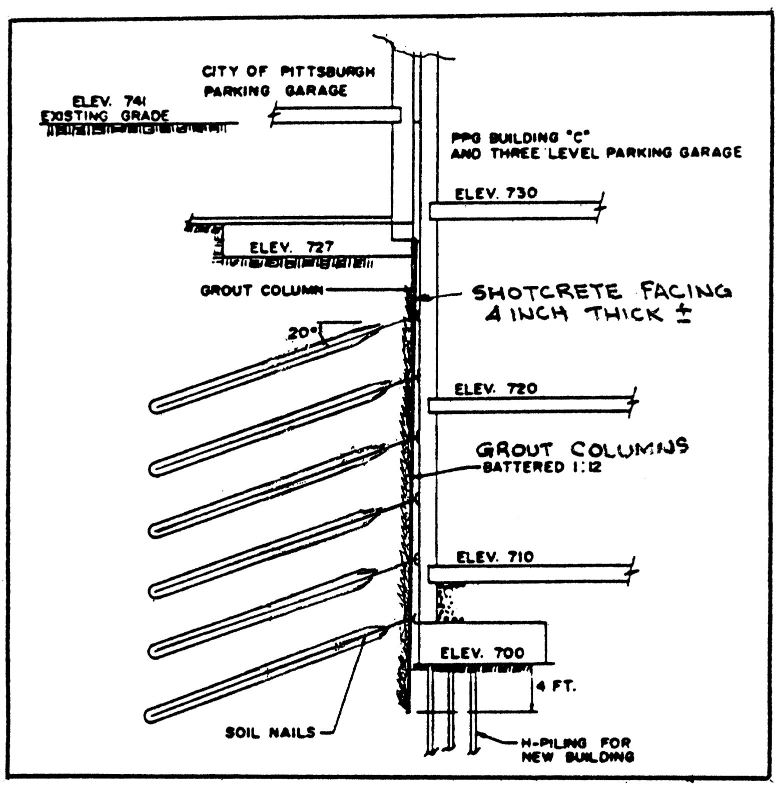

Figure 12 Cross section at PPG Building, Pittsburgh, PA, Parking Garage excavation, showing the nailed face pre-treated by grout columns. (Nicholson and Wycliffe-Jones, 1984)

Hydraulic rotary drilling with water flush was used throughout the contract with control of drill hole alignment being a critical aspect. Pressure grouting to $0.2M_{pa}$(30psi) was conducted with cement grouts. The 6-8m long nails had a plastic sheath over the upper 3m to debond the bar and facilitate nominal stressing. The average nail spacing was a 1.2m square grid, with each horizontal row connected to the grout columns by a steel channel, bevelled washer and nut. The maximum depth supported was over 9m, involving six rows of nails.

After full excavation, the foundation piling for the new building commenced with 350mm H-piles driven by a diesel hammer of 8300kg within 0.5m of the grouted column. Neither the excavation itself, nor the piling activities caused detectable damage or movement to adjacent structures. It was estimated that conventional pit type underpinning would have resulted in settlements of 10-15mm. Further details are provided in Nicholson and Wycliffe-Jones 1984, and Nicholson and Boley 1985.

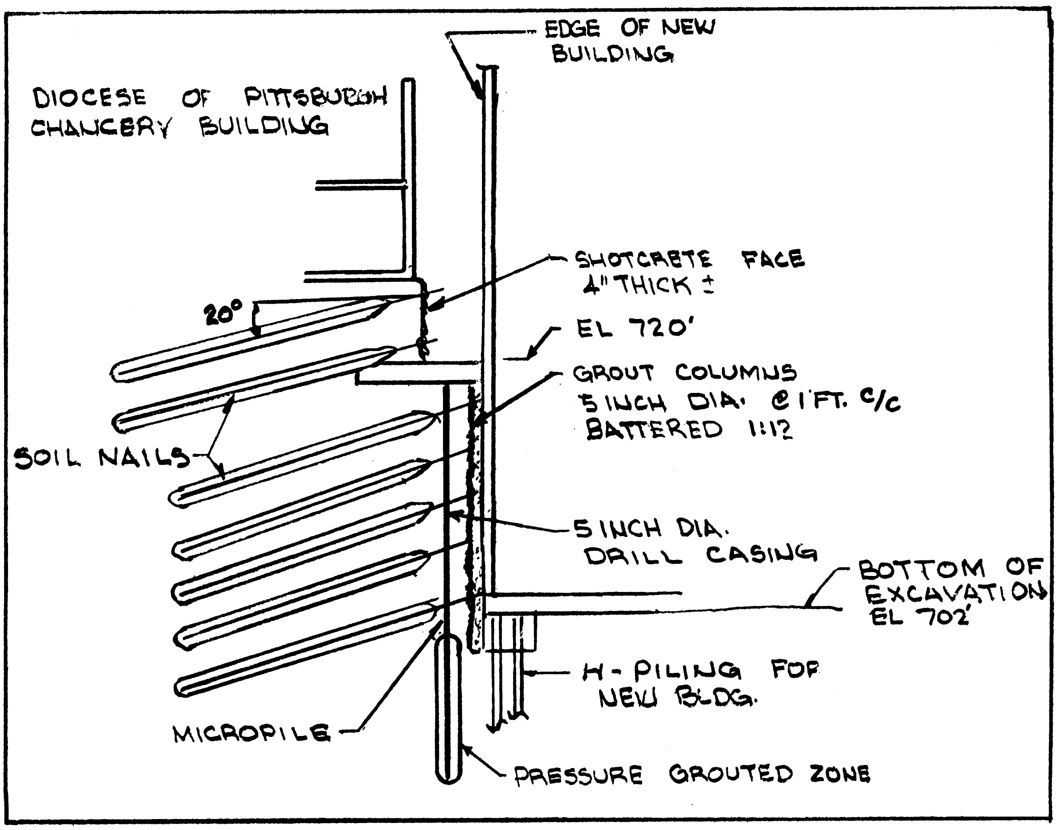

Figure 13 Excavation adjacent to Diocese Building, PPG Building, showing direct underpinning by minipiles through the nailed face. (Nicholson and Wycliffe-Jones, 1984)

3.2 Jet Grouting for Excavation Support, Torre Annunziata, Napoli, Italy

A new major sewage line is being laid through an intensely urbanized area of the town of Torre Annunziata, to the south of Naples, Italy. The scheme involves a 900m long section where a reinforced concrete collector approximately 4.5m square must be cast. The surface cover varies from 1.5 to 10.0m

The subsoil conditions are mainly soft silty deposits of volcanic origin, with 1-2m of variable fill and rubble above (containing a mass of domestic service pipes). Groundwater level is at about 5m. The route of the sewer follows an extremely busy street, with domestic and commercial buildings of several stories on each side. Clearly, minimal settlements could therefore be tolerated outside the construction boundaries, while the scale and time of environmental upheaval also had to be minimized. In addition, the very restrictive access conditions precluded the consideration of certain techniques otherwise offering potential solutions (e.g., diaphragm walls).

A solution was developed which addressed each of these environmental and technical problems while still being financially attractive:

- where the cover to the crown was to be less than 4m, the excavation would be created in cut and cover. The lateral restraint would be provided by reinforced bored piles, the lateral continuity between each being guaranteed by jet grouting. Resistance to base heave or leakage would be provided by a "floor" of jet grouting (Figure 14).

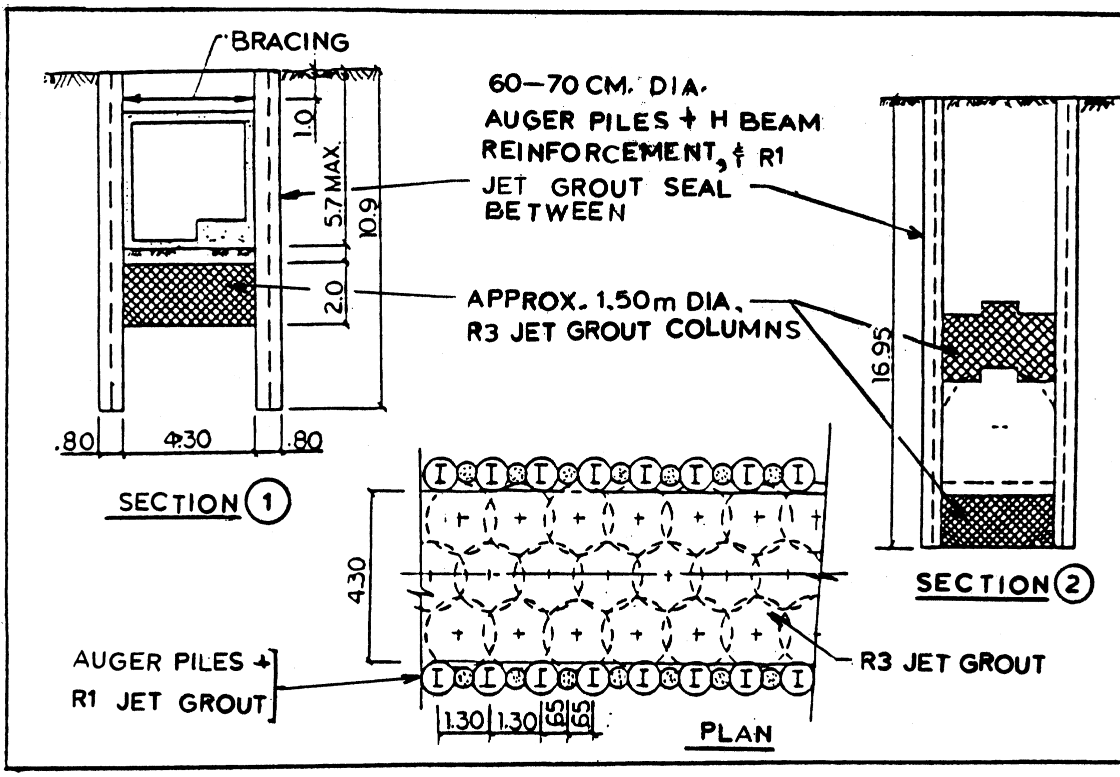

Figure 14 Jet grouting applications to enable cut and cover (Section 1) and tunnelled excavation (Section 2) for new sewer construction, Torre Annunziata, Napoli, Italy

- where the cover was greater, hand tunnelling was feasible assuming the same pile and grouting scheme as before, but supplemented by a jet grouted roof to ensure the support of the overlying roadway.

The 2118Nr 800mm diameter piles, totalling over 24,000m, were augered to depth and were reinforced with steel H-sections. They were spaced at a maximum of 1.2m centers in one row each side of the excavation. The ground between the piles was treated by the Rodinjet 1 system, giving "mix in place" columns of 600mm notional diameter . Grout of w/c = 1 was used with a jetting pressure of $40M_{pa}$ (5600 psi). The withdrawal of the monitor during grouting was accomplished by an electro-hydraulic control on the drill rig which automatically lifts the monitor a preset distance at preset time intervals. In this way the injection parameters were precisely controlled to ensure uniform, effective treatment and no surface displacement.

The grouted base (and where necessary roof) of the excavation was achieved by the Rodinjet 3 method. Over 5500m of columns, 1.5m in diameter were involved using jetting pressures up to $50M_{pa}$(7000psi) for water and $0.8M_{pa}$(110psi) for air. The subsequent cement grouting pressures were around $10M_{pa}$(1400psi).

Section by section excavation and casting sequences have been followed by the main contractor to allow both interim verification of the grouting effectiveness, and as a further aid towards minimizing the environmental upheaval.

3.3 Pretreatment of Soft Marine Deposits by Jet Grouting - Singapore MRT Tunnels

The geology of the Island of Singapore is complex with several types of soils, such as beach, estuarine and fluvial deposits, marine clay and sedimentary soft rocks, occurring. In general, beach sand and fill, 3-5m deep, overlie very soft peaty clay, marine clay and fluvial soils to combined depths in excess of 15m. The base of this sequence is often marked by a layer of silty, fine sand overlying stiff to hard cohesive soils or weak rocks. The fine nature of these materials precludes the use of permeation grouting, and jet grouting is the preferred method of ground treatment wherever required.

Lot 106 of the Island's Mass Rapid Transit System runs between Dhoby Ghaut and City Hall stations. As the tunnels leave the former station (Figure 9) they pass in part through soft highly plastic formations in which the water level is 1-2m below surface. Without any soil improvement, even shield excavation was judged difficult, unsafe and unsuitable in the conditions. Treatment from the surface was feasible and economic.

In line with the design specifications, the grouting had to be extended to the full excavation area above soft rock or very stiff clay, and had to create an arch of strengthened soil 1.5-3.0m thick around the excavation. The thicker treatment was provided close to the station where the shield could not operate. To check the proposed solution and to set up the working program a large-scale trial was carried out on site.

Two different layouts of jet grouted columns were tested--0.6 and 0.8m between centers of staggered elements. For each layout two different quantities of grout were injected (600 and 800 l/m^3 of soil). The four combinations that resulted (including a total of 62 columns) were arranged to form the sides of a square area, excavated subsequently for visual inspection. The following general procedure was applied to each scheme: drilling to 10.5m depth, treatment from the bottom to 0.5m depth by the Rodinjet 1 technique, injecting a grout with w/c=1.6, and a grouting pressure of $40M_{pa}$(5600psi).

Instrumentation included inclinometers to check horizontal soil displacements, piezometers to record pore pressure variations and datum points to check vertical soil displacements.

The total volume of injected grout was $190m^3$, which corresponded to 70% of the theoretically involved volume of soil ($270m^3$). It is estimated that about $70m^3$ of soil-grout mixture was rejected during grouting and that the overall surface upheaval corresponded to about $60m^3$ of upward displaced soil. Since no filling of natural voids can be expected in such a fine grained soil, it was inferred that the remaining $60m^3$ (almost one-third) of the injected grout caused mostly radial displacement and compression effects.

Coring afterwards confirmed that even midway between column centers, the treated ground was over 50% above the specified minimum strength of $0.3M_{pa}$(42psi). A test pit excavated inside the test area 15 days after treatment confirmed overlapping between adjacent columns, except for that group of tests with the higher spacing (0.8m) and lower grout volume (600 l/m^3). For the production work a 0.7m spacing was selected.

High surface movements were recorded--maximum horizontal displacement of 23cm, and vertical of 30cm--which necessitated variations to subsequent production parameters (always thereafter within safe limits--2-3cm).

Excess pore pressures in piezometers 6.5m deep and 3 and 6m from the perimeter of treatment were fairly low throughout (0.02-$0.04M_{pa}$: 3-6psi).

The subsequent production works involved the successful treatment of about $9400m^3$ of soil in four tunnel sections totalling 367m of running length. The interested reader is referred to the more detailed description by Cippo and Tornaghi (1985).

3.4 Permeation and Jet Grouting for Milano Metro, Italy

The existing Milano Metro network of 54km of tunnels with 63 stations is being supplemented by the current construction of a further 28km (32 stations) of line. The work is being conducted in the center of the city so that the former emphasis on cut and cover cannot be resumed. Instead ground treatment is being widely used (Mongilardi and Tornaghi, 1986), both from the surface and from underground, and solutions involving both permeation and jet grouting are being employed routinely. For example, for advancement by underground grouting, the following sequence is adopted:

(i) excavate adit shafts at 500 m intervals, formed by diaphragm walls or jet grouting, as in Figure 10.

(ii) excavate a drift (a pilot tunnel) of cross section 9 m^2 under cover of horizontal jet grouted columns (Figures 15 and 16).

(iii) treat the zone around this pilot by tube`a manchette permeation grouting.

(iv) excavate to full diameter, with the soil arch consolidated in step (iii) acting as protection.

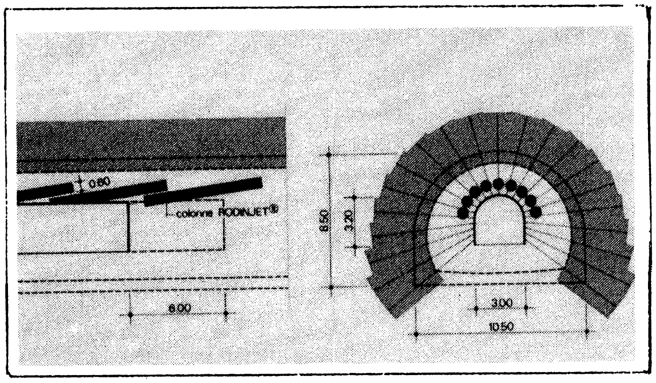

Figure 15 Principle of tunnel excavation by forming pilot (protected by horizontal jet grouting), to allow treatment (by permeation grouting) for full bore excavation. Milano Metro Line 3

Figure 16 View of pilot and full bore, showing end of jet grout columns, and radial tubes à manchette. Milano Metro Line 3.

Another novel factor, in relation to the previous Milano Metro work, was that strict restrictions were placed on the use of organic type reagents needed for higher strength silicate grouts necessary to provide ground treatment of adequate strength and durability. This led to the development of the Silacsol grout, as detailed above.

Equally, the scale of the project, the complexity of the design situations, the wide variability of the soil (gravel to silt) and the strict design specifications governing the use of chemical grouts, all combined to demand a new approach to site investigation and evaluation. Thus the PAPERO was developed.

As detailed by Mongilardi and Tornaghi (1986) the project involves a wide range of styles and combinations for ground treatment incorporating jet grouting (horizontal for adits, vertical from the surface for shafts, underpinning and earth retention) and tube`a manchette grouting. For the latter, cement based grouts are used throughout for routine consolidation, whereas chemicals are also injected for:

- underpinning of certain very sensitive buildings
- impermeabilization where tunnel sections are below the water table
- enhancing strength around the larger excavations

The purpose of the grouting is one factor which dictates the geometry and sequencing of its execution. Other factors include:

- nature of surface access and presence and density of subsurface services
- geometry and location of structure being excavated
- programming and financial considerations

Figures 17-21 illustrate various combinations which are being employed in response to these factors. It is significant to note that in Lot 2B a shield was initially used for the first 600m of pilot tunnel. However, it caused unacceptable settlements due to overbreak, at which time the construction reverted to protection by horizontal Rodinjet columns. The 9 columns in each pass averaged 9m long and 70cm in diameter, permitting excavation in 6m "runs." This sytem was thereafter used on the remaining 1300m of pilot on this section, and thereafter in the other lots.

Two other points are especially notable:

(a) chemical grouting: since the two components of the Silacsol system react so fast, they are introduced into the ground separately through twin tube`a manchettes; i.e., 2 small tubes are placed in each borehole for chemical grouting and the reaction occurs in the saturated pores of the soil.

(b) strength testing of the jet grouted gravels confirms the mechanical properties of a fairly good concrete. Treated sands give a similar mean strength but with a significantly lower deformation modulus.

The overall value of the ground treatment works under contract to RODIO in this phase of the Project is well over $100m spread over 5 years.

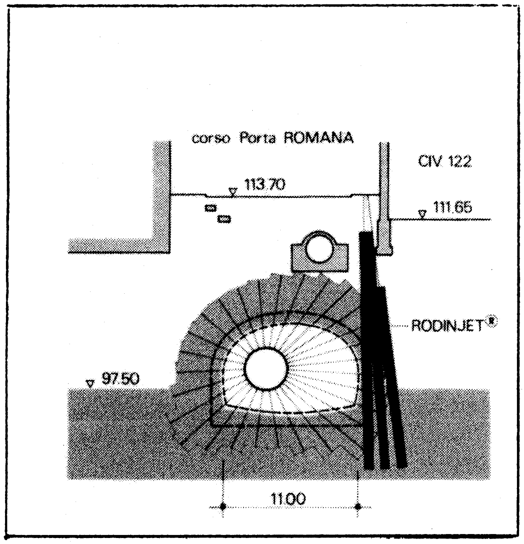

Figure 17 Radial permeation grouting from pilot, and jet grouting from surface to protect ancient building. Milano Metro

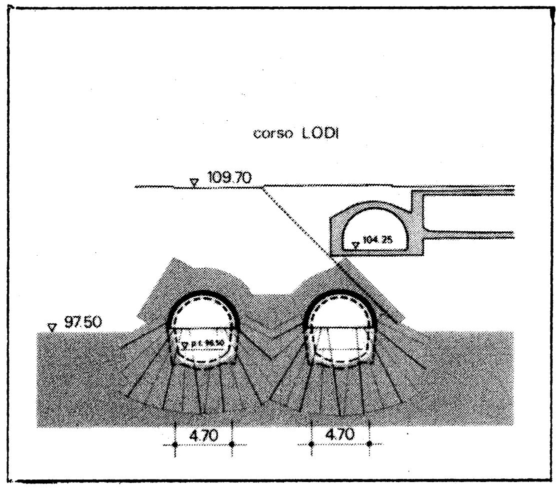

Figure 18 Permeation grouting fromsurface (to g.w.l.) plus steel micropiles for underpinning, followed by grouting from pilot under gwl. Milano Metro

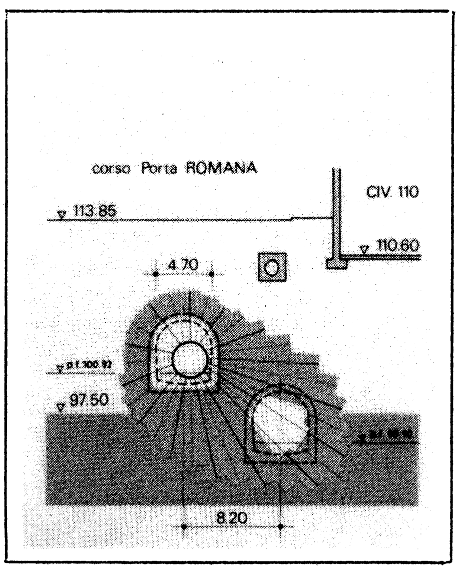

Figure 19 Permeation grouting from upper pilot, to permit excavation of two parallel tunnels at different levels. Milano Metro

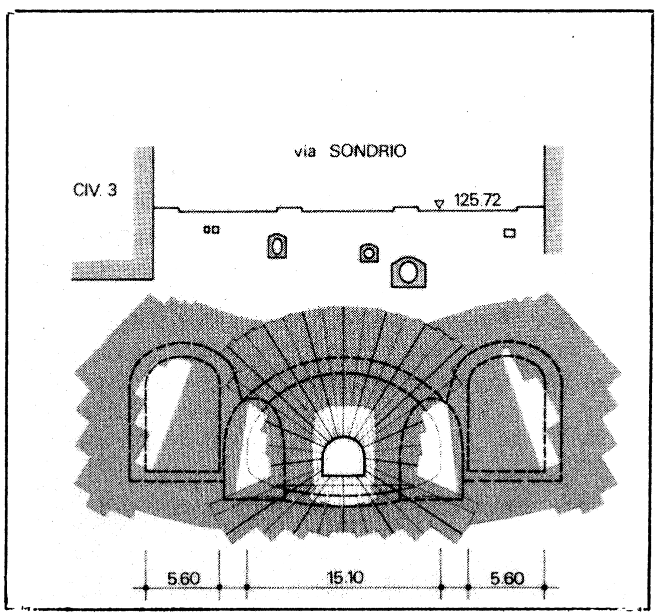

Figure 20 Treatment from surface, to protect two lateral adits, followed by treatment from central pilot to allow excavation of main central tunnel. Milano Metro

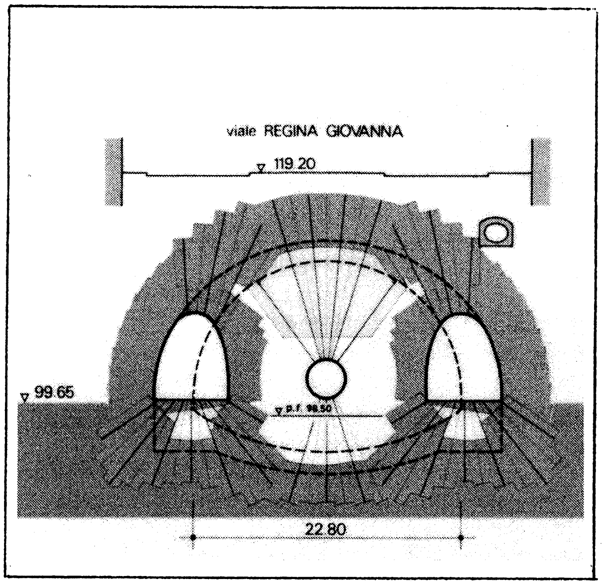

Figure 21 Treatment from surface followed by treatment from central pilot and two lateral drifts to allow excavation of large station. Milano Metro

4. FINAL REMARKS

It is a time of rapid and significant advances in the fields of ground reinforcement and treatment throughout the world. Many of these newer techniques have already had considerable impact upon contractors engaged in surface or underground excavation in this country. However, the potential of other methods has scarcely been tapped, and in this regard, soil nailing and certain types of ground treatment are prime examples. Given the increasing demands that the excavation of major structures in urban areas in soft ground are placing on tunnelling engineers, it is logical to presume that the next few years will see these new techniques being embraced, out of both technical and economic necessity, throughout the United States.

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