The technical management of the permeation grouting works in the execution of the new Metro Line 4 in Milan

A. Pettinaroli, P. Caffaro
Studio Ing. Andrea Pettinaroli s.r.l., Milan, Italy

M. Lodico, A. Carrettucci
MetroBlu s.c.r.l., Milan, Italy

ABSTRACT: The new Metro Line 4 in Milan requires the treatment of alluvial soil by permeation grouting, in order to allow stations and service shafts excavation. The Line stretch underpassing the city involves the careful scheduling of site activities for minimizing the impact on the city life. An efficient grouting work management has been planned from the beginning. For each working site, geotechnical investigations have been executed, detecting stratigraphy and granulometric composition of the soil layers to be treated, showing their variability along the Line. First grout mixtures were set up in laboratory, and work organization tested on site. During the work, actually in progress, TAM meshes and grouting parameters are optimized for each site. Regular checks on mixture, daily examination of injection parameters and of surrounding buildings structural monitoring allow to implement a real-time management of the grouting activities tailored on each site, respecting the general work development and scheduling.

1 INTRODUCTION

The new Metro Line 4 in Milan runs from east to south west. It connects Linate Airport to the city center, continuing under the so called “Cerchia dei Navigli”, an ancient water channel designed by Leonardo da Vinci, which is currently buried though it will be probably restored in the next years. The line consists of two main tunnels, excavated with EPB-TBMs, connecting 21 stations and including 26 service shafts. It can be divided into three stretches: the central segment, underpassing the city center and the “Cerchia dei Navigli”; the east segment, up to the east line terminus at Linate Airport Station; the south segment, ending at the south line terminus, San Cristoforo Station.

The tunnels of the peripheral stretches are excavated by 4 TBMs, 6,70 m diameter, pass through the stations.

The central stretch runs under an urban context of narrow and busy streets. In order to reduce the interferences of the works with the city viability, the dimensions of the station shafts have been minimized, including just the stairs and the access area.

The platforms are obtained inside the two tunnels, which are excavated with a diameter of 9,15 m, and run beside the shaft. The two TBMs are going to excavate the tunnels starting from the last shaft of the eastern stretch, Tricolore Station, to Solari Station (Figure 1).

The connection between the platforms in the tunnel and the shafts, in the city center, must be consequently excavated with the traditional method, being in presence of a hydraulic head from 8 to 15 m above the tunnel crown.

These difficult conditions require a consolidation and waterproofing treatment of the sandy-gravelly soil, typical of Milan subsoil, to be carried out mainly from the street level.

Once the decision was taken to proceed by using the technology of the permeation grouting with TAMs, due mainly to the long-time experience gained in this context in Milan, all the activities were oriented and managed to minimize the impact of the works on the city-center life, according to the following steps: a detailed geotechnical investigation on each work site; the development of the grouting design, tailored on each site; an accurate method-of-statement defining the activities and the controls procedures for each stage of the work. The following chapters will describe those activities.

Figure 1. Plan view of the Metro Line 4 City Center stretch.

2 PRELIMINARY PHASE: INVESTIGATIONS AND GROUT SET-UP

The geotechnical characterization of the soil, focused on the use of the permeation grouting technology, has required the execution of additional borehole investigation on each site of the city center stretch (6 stations and 7 service shafts), including on site and laboratory tests.

Then an accurate stage of laboratory tests was started on the grout mixtures, in order to optimize the mix design as a function of those properties, which are necessary for the efficient treatment of the soils: penetrability, stability, workability, mechanical properties.

2.1 *Geotechnical investigations*

The Milan subsoil is composed by recent alluvium with widely variable alternations of gravel and sand, including “lenses” of silt, that may have an extension up to some dozens of meters; the silty components tend to increase with the depth, becoming prevalent around 40 m under the ground level. These surficial strata include the upper aquifer, having a water table level that lies about 13-15 m under the street level during the activities, with a possible seasonal fluctuation of about 0,70÷1,00 m.

A borehole has been carried out for each site, recovering several specimens at different depth, on which granulometric analysis were performed. Therefore, it has been possible to obtain a detailed stratigraphy of the ground. The general tendency has been approximately confirmed, with local exception. The silty layers broadly start from 36-38 m of depth. “Lenses” of silty sand, 2÷3 m thick, were detected between 20 m and 25 m, predominantly in the central stretch of the line.

The granulometric curve has been compared with the standard injectability curve of two different grouts: the fine-cement grout (curve “c” in the following Figure 3) and the silica grout (curve “s”). These are indicative references of the optimal granulometric composition of a soil that can be properly treated by permeation grouting. The efficient diameter d_{10} of the soil is usually assumed as the critical parameter for the injectability, equal to 0,2 mm for the curve “c” and 0,02 mm for the curve “s”.

The soil layers were classified on the basis of the granulometric analysis, referring to their injectability. As shown in Figure 2, the normally injectable layers were marked in green (d_{10}≥0,2 mm) and yellow (d_{10}≥0,02 mm), while the not injectable in blue. In red are marked the layers in which the injection must be carried out adopting a particular care in the management of the operative parameters on site, as described in a further chapter.

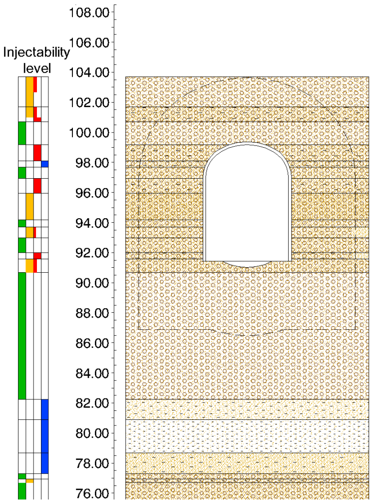


Figure 2. Soil stratigraphy and relative injectability level.

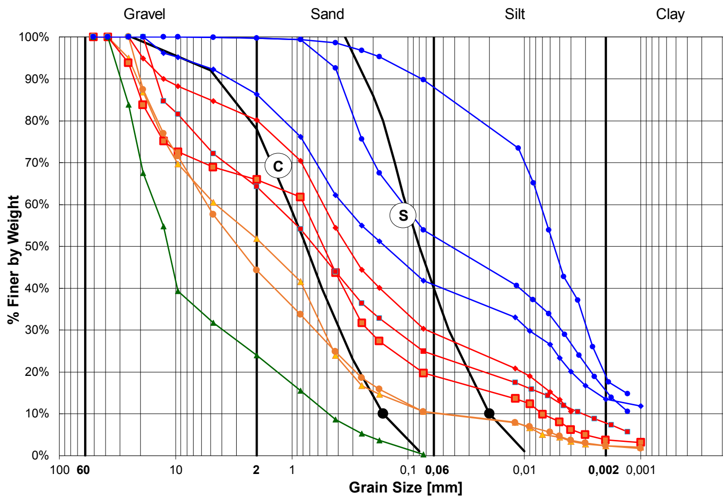


Figure 3. Granulometric curves of soil specimens and standard groutability curves: cement grout (c) – silica grout (s).

The section in Figure 2 shows the case of a site in which the arch and the sides of the drift to be excavated lie in sandy gravelly strata, including few thin layers with finer soil, where the silica grout is definitely necessary for homogenously penetrating the ground. The layer just under the invert, composed by sandy gravel, is well treatable; beneath it lies a silty-clayey layer, classified as not groutable.

In chapter 5 some case histories describe how the permeation grouting has been executed in different stratigraphic conditions.

2.2 *Grout mixtures set-up*

Once the granulometric composition of the layers to be treated is known, the suitable grouts must be set-up. The injection works generally foresee 3 subsequent stages, using the appropriate operative parameters as well as mixtures having growing penetrability properties. The 1st and the 2nd grouting stages are carried out using a stable fine cement mixture, in order to permeate the soil, filling the voids of large and medium size (gravel and medium sand). The 3rd stage is carried out using a silica mixture suitable to permeate and consolidate the finer soil fraction (medium and fine sand).

The set-up of the grout properties (rheology and mechanical properties) has been carried out before the beginning of the works, by executing some laboratory test.

As widely experienced with the injection works in Milan subsoil, a grout with cement and bentonite, with a cement/water ratio c/w=0,4 and a stabilizing, superplasticizing admixture, allows to obtain optimal results in terms penetrability and stability. This can be evaluated by executing standard test of viscosity with the Marsh funnel, bleeding test and stability test with filter-press under a pressure of 0,7 MPa. The frequent presence of sandy layers (yellow marker – Figure 2) in the ground to be treated leads to maximize the penetrability performance. Several laboratory tests were carried out, using different types of bentonite and admixtures. The chart in Figure 4 shows the filter press stability versus the Marsh viscosity for several mixtures made varying the components and the dosage of bentonite and admixture. The best results were obtained with a highly fine bentonite (circle symbol), which works properly with all the admixtures: a good viscosity, 35,5÷36 seconds with Marsh funnel, and 75-85 cm^3 of filtrate after 30 min at the filter-press test. The choice of the admixture has fallen upon the one that allowed to minimize the dosage of the bentonite and the admixture itself. The triangle-shaped data refer to a standard bentonite for grouting mixtures.

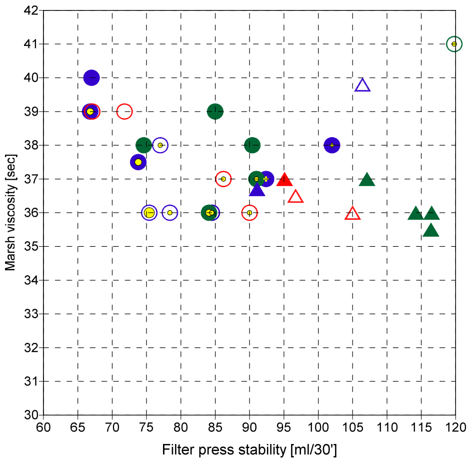


Figure 4. Tests on cement grout mixtures: Marsh viscosity vs. Filter press stability.

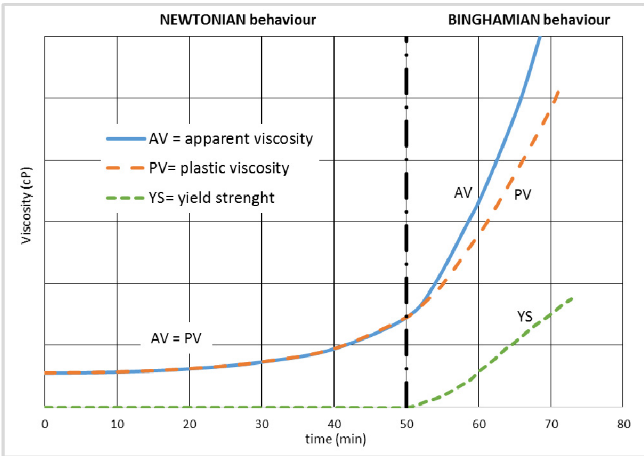


Figure 5. Tests on silica grout mixtures: viscosity vs. time - groutability time

The silica grout is a highly penetrability mixture, based on silica solution and inorganic reagents that, mixed together, react producing a crystalline, stable structure, not affected by syneresis. The reaction starts at the beginning of the mixing. In the initial phases the grout maintains a low, stable viscosity (with a Newtonian behaviour), which then increases with time, gradually showing a Binghamian behaviour up to the final setting. The occurrence of the change of rheological behaviour determines the groutability time of the grout. This period must be long enough in order to allow the complete injection of the grout into the ground (Figure 5).

Preliminary test carried out in laboratory allowed to set up the rheological properties of the mixture, which evolves during the reaction. The chosen grout had an initial viscosity of 5÷7mPa*s and a groutability time varying between 50 and 80 minutes. Laboratory grouting tests on standard monogranular sand column were carried out; UCS test on several samples of the grouted columns gave strength resistance results between 1,2 and 1,8 MPa.

3 DETAILED DESIGN OF THE TREATMENTS

The detailed design of the treatment for each site has taken into account two basic aspects:
- the very complex local context of the work sites in the historical city center of Milan;
- the specific geotechnical soil conditions.

The layout of the treatments (geometry, length and inclination of the drillings) has been defined as function of the effective work site area as well as of the interferences with buildings (underground floor of existing buildings, old masonry), urban roads and traffic, underground facilities (aqueduct, sewerage, gas pipes, electric, lighting and data ducts) as shown in Figure 6.

The interpretation of the previously described results of the geotechnical investigations gave information such as the soil stratigraphy, the granulometric composition of the various and significant soil layers and their relative injectability levels. These information allow to define the grouting operative parameters.

The effective permeation radius of the grouting has been evaluated on the basis of the percentage of the fine grain size (silt and clay) of the soil, varying from 0,95 m for the gravelly sandy soil (green marker) down to 0,80 m in the layers classified with red marker (with finer fraction around 25%). The drilling meshes were consequently drawn.

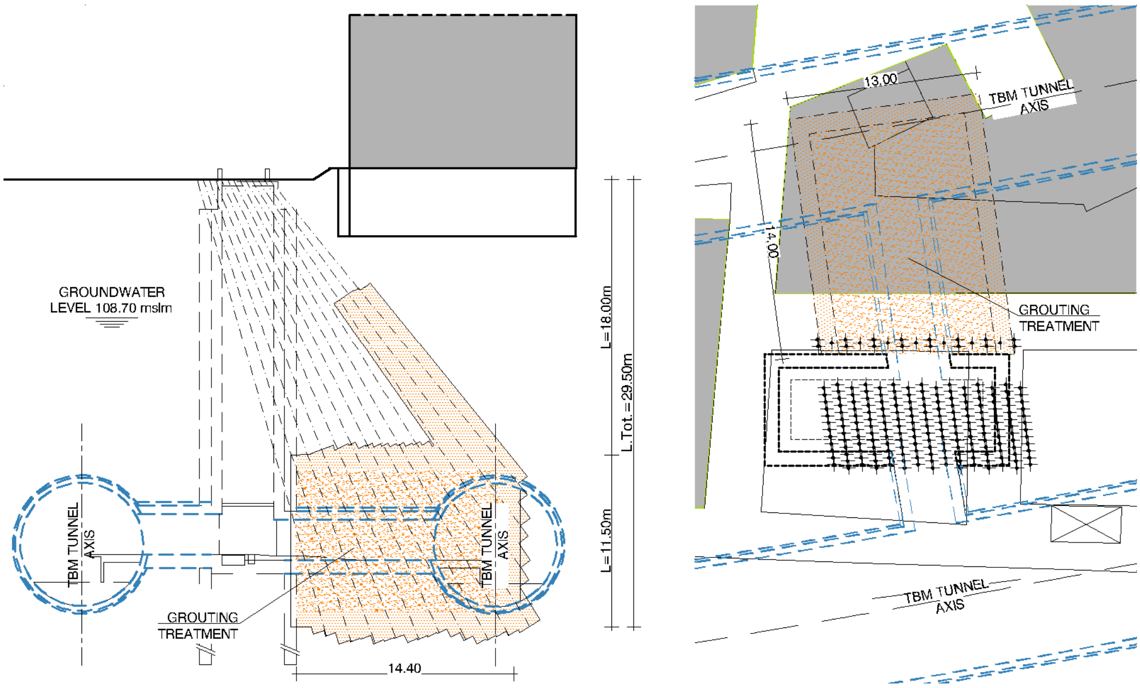


Figure 6. Grouting treatment of the ground for the junction tunnels excavation: section type and plan view.

The planning of the quantity of cement and silica grouts to be injected has been strictly correlated to the different geotechnical soil conditions.

In case of gravelly sandy soil, the volume of injected stable cement grout is preponderant compared to the silica one (ratio V_s/V_c~0,6÷0,8). Otherwise, in case of sandy soil, or soil with fraction of silt and clay up to 25%, a higher volume of silica grout is necessary (V_s/V_c ~ 1÷1,2) in order to penetrate the finer fraction of the soil.

The maximum injection pressure has been fixed for each granulometric condition and for each grouting stage, in order to avoid the hydro-fracturing phenomena (claquage), which may lead to possible uplift of the ground during the injection, as well as to a lack of treatment homogeneity, with high risk of piping during the excavation.

It must be pointed out that all the executive parameters foreseen in the detailed design phase (volume, pressure, etc.) are verified and optimized in real time during the works.

4 THE MANAGEMENT OF WORKS ON THE SITES

The activities on site start with the drilling and the installation of the sleeved pipes (or TAMs: tube a manchettes), regularly checking the sheath grout used for the embedment and the sealing of the pipes in the boreholes (Figure 7). The behaviour of the buildings beside or above the working zone is monitored by regular topographic survey.

The rigs for the injection (the mixing units for the bentonite slurry and the grouts, the grouting pump skids, the data logger for the control and record of the grouting operative parameters) are installed in the yard. Due to the coincidence in time of the works for different shafts, it is very common that the teams, the rigs and the supplier of the grout components may vary from site to site. Therefore, it is planned to proceed in any case with a preliminary phase for setting up the mixtures (cement- and silica-based), using the yard's own equipment; a particular care is given to the calibration of the automatic control and record unit of the grouting operative parameters (pressure, quantity, flow rate).

Figure 7. Drilling and grouting works (respectively on the left and on the right).

The cement grout requires, in this phase, a careful final test, in order to verify the good activation of the bentonite and the correct quantity of admixture necessary to respect the design parameters of stability and viscosity. A correct initial set-up usually allows to forge ahead with the work during the injection phase. Quality controls are then carried out on the cement grouts during the injection stages, by daily measuring the density, the Marsh viscosity and the bleeding; furthermore, a weekly check of the grout stability is carried out by using the filter press. Silica-based grout is very sensitive both to temperature of the air and of the liquid components. The mix-design is consequently calibrated preliminary on each site, on the basis of the average temperature of the current season and as a function of the expected productivity on site, optimizing the groutability time of the mixture. The setting time is evaluated during the works for each mixing using the quick method of the Cup test (a cup half-filled with grout can be tilted 90° without flushing the set mixture). Regular controls are then carried out on the density, and by measuring the groutability with the rheometer. Sometimes it is necessary to adjust the mix design, usually because of the variation in temperature of the air, more frequently in mid-seasons.

The injection operative parameters are controlled and recorded by data loggers (Figure 8.a). The model of the latter may vary from site to site, so that a preliminary calibration is necessary before the start of each work. For each grouting stage the grout quantity to be injected in a single sleeve, the limit pressure and the maximum instant flow-rate must be set (Figure 8.c). A specific setting, to be calibrated from time to time, allows to manage the reduction of the instant flow rate whereas the grouting pressure rises. The injection is automatically stopped when the limit pressure value is reached.

Each injection line, connected to a single tube, is always equipped with a manometer at the head of the borehole (Figure 8.b), so that it is possible to control directly on site the injection development, and to verify the properly functioning of the data acquisition system. If abnormal values (particularly about the pressure) are pointed out after a first check of the operative parameters, additional investigations could be necessary (for instance, check of possible presence in the subsoil of facilities, obtacles, old wells or other structures not previously indicated). It may be also possible that during the works an alert is given by the structural monitoring system. Then it would be necessary to modify the injection procedures, by varying the grouting sequence of the holes or by reducing the limit pressure or the grout quantity per sleeve.

The data processing are daily updated, by plotting charts (Figure 9) showing the pressure values recorded at the end of each stage of injection for each sleeve of the TAM. The cromatic scale adopted for the plot allows to easily check the injection pressure reached in the soil, pointing out also the sleeves where the limit pressure has been reached and the grouting stopped.

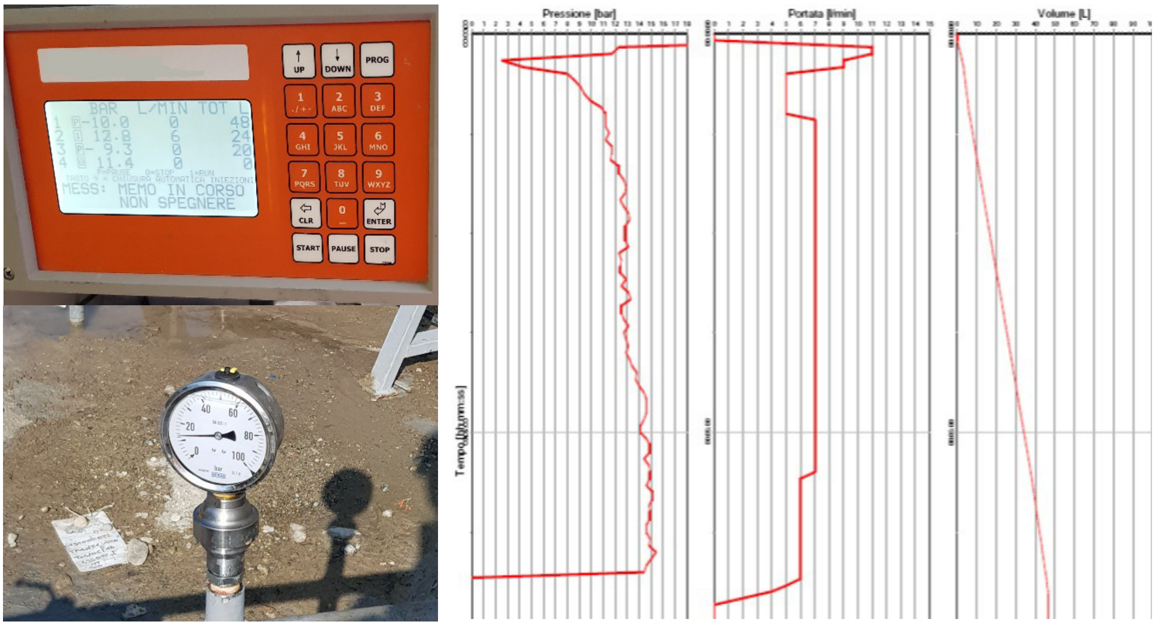


Figure 8. a-Data logger for the grouting parameters recording (in the upper left). b-Manometer at the head of the injecting borehole (in the lower left). c-Charts of the recorded grouting parameters (on the right)

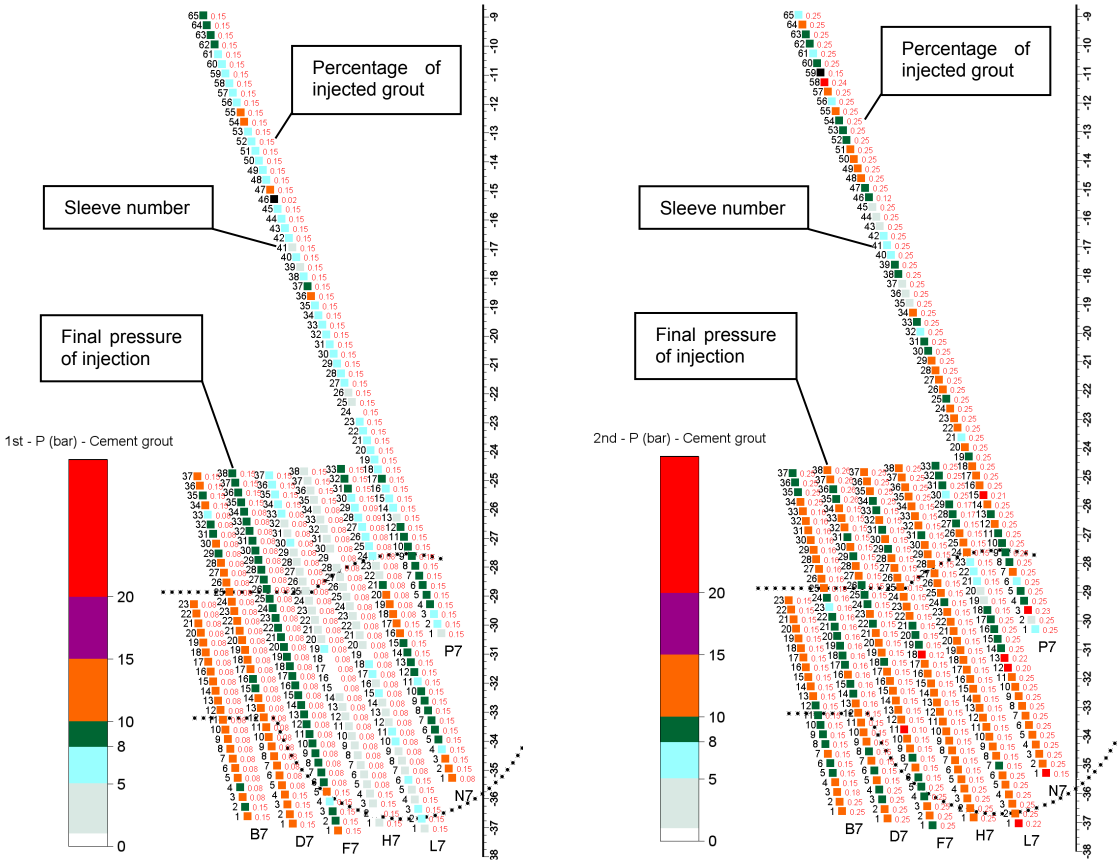


Figure 9. Grouting pressure-volume diagrams: 1st grouting stage on the left and 2nd on the right

In detail, Figure 9 illustrates the pressure of injection at the end of the 1st and 2nd grouting stages of a certain section. The charts show that the pressure is increased during the 2nd stage; in fact, the medium values of pressure rise from 4÷10 bar in the 1st stage (predominance of cyan, grey and green colours) to 8÷14bar in the 2nd stage (predominance of orange and green colours). After the completion of a grouting stage, the analysis of those diagrams allows to evaluate where the soil has been already satisfactorily treated and where to proceed with an intagrative injection of grout, in order to reach a good homogeneity of the treatment. If the grouting pressure doesn't reach an adequate value (approximately 8÷12 bar, depending on the grouting stage) in some sleeves, additional grout is then injected. This evaluation is carried out taking into care the structural monitoring data.

As a result, the total quantitaties of cement and silica grouts injected in the soil may then differ, more or less, from the volumes predicted by the design. It has been observed that at the moment, for the Metro Line 4 in Milan, this difference can be up to ± 5÷7 %, because of the good accuracy of the project method.

The following chapterwil describe the grouting works carried out in a couple of sites of the Line 4, putting in evidence the aspect here above expressed.

5 GROUTING CASE HISTORIES

5.1 *Site A: grouting in gravelly sandy soil*

This first case history illustrates how the grouting works have been managed and carried out in a site which is mainly characterized by gravelly sandy soil.

As shown in Figure 10, the soil to be treated around the tunnel at the invert and the sides consists of sandy gravel with a fine fraction (silt and clay) below 10%.

Moving to the upper part of the treatment, the percentage of sand increases slightly, whereas the one of the gravel declines; however, the fine fraction in those layers is lower than 20% and the efficient diameter d_{10}>0.02mm.

Therefore, the soil interested by the grouting treatment in this site can be globally classified as "well injectable" (green marker). The Figure 10 shows that not injectable layers (blue marker) are present right above the treatment volume (silty sand) and below it (sandy silt).

These assessments led to prescribe the injection in the ground of a slightly greater quantity of cement mixture compared to the silica one: a ratio V_s/V_c~0.85 has been predicted, taking into account the sandy layers at the top of the treatment.

The analysis of the pressure and volume diagrams after each grouting stage has led during the works to prescribe additional cement and silica grouting, respectively at the end of the 2nd and 3rd stages.

As a result, a total quantity of cement and silica grout of about 30% of the theoretical volume of soil to be treated has been injected, with an effective ratio V_s/V_c =0.90, close to the design hypothesis.

5.2 *Site B: grouting in sandy soil with presence of finer fraction*

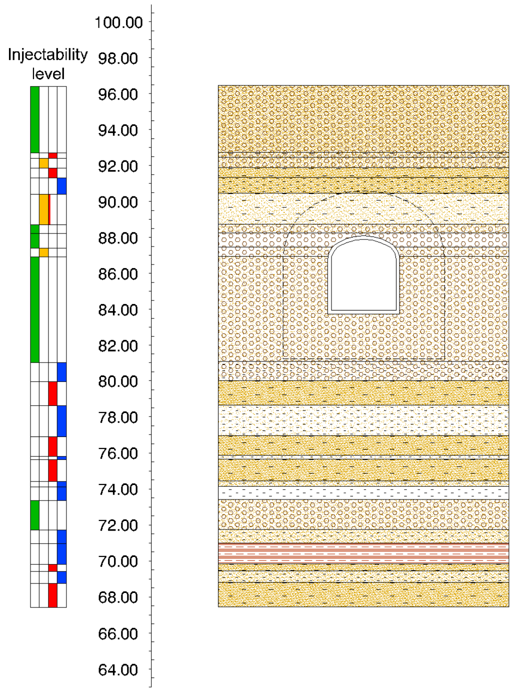
The second case history illustrates the management of the grouting works in a site which is characterized by a slightly more complex geotechnical condition (referring to the injectability level) compared to the previous one. In fact, the investigations have detected the presence of a sandy soil layer with 25% of silt and clay.

In detail, as shown in Figure 11, the treatment at the level of the tunnel sides has interested a sandy layer (percentage of sand greater than 75%) with a quantity of fine fraction between 10% and 25%.

The soil layers above the crown tunnel and at the bottom of the treatment are characterized by sandy gravelly soil with a percentage of silt and clay of about 20%. Gravelly layer has been detected only at the tunnel invert.

In general, as regard to the injectability level, the soil interested by the treatment (Figure 11) can be classified as "injectable" (yellow marker), often needing a particular care in the grouting management where the fine fraction is higher (layer marked also with a thin red line).

Therefore, a higher quantity of silica grout has been predicted in order to permeate the sand and the finer fraction and to obtain a homogeneous soil consolidation. In detail, a ratio $V_s/V_c = 1$ has been prescribed.



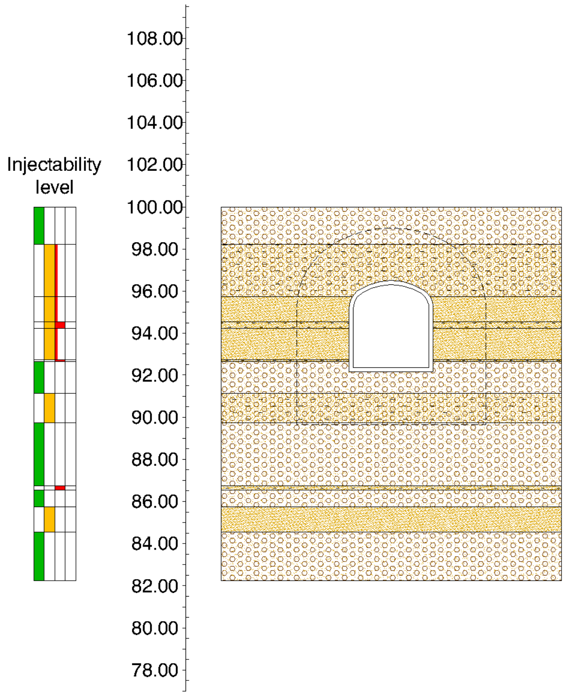


Figure 10. Site A: soil stratigraphy and relative injectability level

Figure 11. Site B: soil stratigraphy and relative injectability level

During the 2nd stage, the injection through several sleeves reached the limit pressure; a lower volume of cement grout has been absorbed by the layers with a rather remarkable fine fraction (fine sand and silt). The silica grout instead permeated regularly the soil, and at the end of the 3rd stage additional quantities were still injected.

The volume of grouts injected on this site has been 28% of the volume of soil treated. The ratio between silica and cement grout volume has been $V_s/V_c = 1.2$. This value, as described in the previous paragraphs, fully accords to the granulometric composition detected by the investigation.

6 CONCLUSIONS

The permeation grouting treatments necessary for the construction of the new Metro Line 4 in the city center of Milan require to operate from several sites, in correspondence of the stations and the service shafts. The soil injectability conditions, which are function of the granulometric composition of the same, are rather variable from yard to yard.

The preliminary phases of investigations were followed by the design of the treatment, the set-up of the grouts as well as the working procedures that all together have defined in details the activities to be carried out. The works are now ongoing. The injections are managed on each site by mean of the daily analysis of the grouting data (pressures and quantities) and the simultaneously control of the monitoring system of the existing buildings. The processed diagrams allow to verify the evolution of the grouting in progress and to give an overall vision of the soil treatment outcome. Good correlations are generally obtained between the recorded grouting parameters and the granulometric soil characteristics.

Therefore, all the grouting activities are carried out in safety conditions, in compliance with the general timetable of the works.

7 BIBLIOGRAPHY

American Petroleum Institute 2003. Recommended practice for field test water-based drilling fluids. ANSI/API 13B-1/ISO 10414-1.

Balossi Restelli A., D' Alò G., Pettinaroli A. 2002 Due differenti metodologie di avanzamento nell'ambito di un lotto della linea 3 della Metropolitana Milanese. *Atti del XXI Convegno di Geotecnica,* L'Aquila, 437-446

De Paoli, B.; Bosco, B; Granata, R.; Bruce, D.A. 1992. Fundamental Observation on Cement Based Grouts: Traditional Materials. *Grouting, Soil Improvement and Geosynthetics Proceedings, GT Div/ASCE, 25-28 February 1992*. New Orleans, 474-485

Fraccaroli, D.; Grosina, S.; Balossi Restelli, A.; De Sanctis, F.; Galvanin, P. 2013. Linea Metropolitana M5, Milano. Esperienze di scavo e di monitoraggio strutturale in prossimità di edifici a torre. *Congresso Società Italiana Gallerie: Gallerie e spazio sotterraneo nello sviluppo dell'Europa, 17-19 ottobre 2013*. Bologna, 424-435.

Mongilardi, E.; Tornaghi R. 1986. Construction of large underground openings and use of grouts *International Conference on Deep Foundations, 1-5 September 1986*. Beijing.

Tornaghi, R.; Bosco, B; De Paoli, B. 1988. Application of recently developed grouting procedures for tunnelling in the Milan urban area. *Fifth International Symposium Tunnelling 88, 18-21 April 1988*. London.

Tornaghi, R.1978. Iniezioni. *Atti del seminario su consolidamento di terreni e rocce in posto nell'ingegneria civile, 26-27 May 1978*. Stresa.