Rome Metro Line C under Historical Centre

Francesco Maria Rotundi, Eng., General Director Metro C s.c.p.a., Rome/I

Roberto Sorge, Eng., Engineering Manager Metro C s.c.p.a., Rome/I

1 Introduction

One of the most significant infrastructure works presently being executed, not only in Italy, the Rome Metro Line C (Fig. 1) is indisputably important due to the logistical and historical context within which the works are being executed and the significance of the infrastructure as such within the urban area. For this reason, the most sophisticated technology presently available in tunnelling or, more precisely, in the sector of mechanised tunnelling in urban areas, is being exploited. The construction of Line C will almost double the area covered by the current underground network. Its design and construction are a real engineering challenge because the new line

- has unique characteristics due to the need to preserve the historical monumental and archaeological heritage of the covered areas, heritage that required careful preliminary investigations prior to the construction of stations and tunnels, as Colosseo/Fori Imperiali Station
- crosses the city from the northwest to the southeast, facing different situations and problems that require spe cific solutions and are difficult to standardise, as Mirti Station

2 Historical Centre and Metro Line C 2.1

2.1 Preservation of monuments

Allowing historical heritage and modernisation to coexist: this is the great challenge involved in Line C, which encounters historic buildings and monuments of great value. The Historical Centre of Rome is a UNESCO World Heritage site. To ensure construction of the new metro line does not damage this site, a Scientific Technical Committee (STC) was constituted, comprising world famous professors. The task of STC was to ensure high quality research methods and to analyse potential interactions between the new line and the historical and monumental heritage. STC, which oversees both the design stage and its execution, coordinates and supervises the activities of working groups of specialists. These perform a range of activities aimed at defining the status of 40 valuable historical buildings (including “Palazzo della Cancelleria”, “Palazzo Venezia”, “Palazzo Sforza Cesarini”, the Church of “Sant Andrea della Valle”) and 13 monuments (including the Colosseum, the Basilica of Maxentius, Trajan’s Column and the Vittoriano), in relation to the construction of the new underground (Fig.2).

2.2 Archaeology

One of the difficulties encountered in Rome in defining an efficient underground network is due to the value of the pre-existing archaeological substratum, emerging each time an excavation is carried out, not only in the Historical Centre, but in the whole city.

To protect this immense archaeological heritage site, all planning stages were preceded by accurate field surveys in areas where stations and ventilation shafts will be situated (tunnels do not encounter this problem because they are built at a depth between 25 and 30 m, i.e. below the archaeological layer). More than 400 boreholes were drilled along the whole Fundamental Layout, with the recovery of the stratigraphic column, accompanied by the archaeological reading of the soils crossed.

2.3 Construction techniques

Line C mainly extends underground, with the exception of the first 10 km, which are open-air, on the old route of the Rome/Pantano railway line. It will run in 2 single track tunnels side by side, which will be linked to the surface at stations and ventilation shafts only.

The construction works involve 3 basic steps:

- building stations and ventilation shafts
- digging deep tunnels
- constructing of entrances to the stations

2.4 Tunnel excavation

The project consists of boring 2 twin tunnels with a length of 17.6 km each and a boring diameter of 6.70 m. Four EPB TBMs are being employed to build the tunnels, with 8 to 10 m daily average speed, with peaks greater than 30 m, and a tunnel depth of 25 to 30 m from ground level below the archaeological stratum (generally located at about 6 to 10 m and at a maximum of 20 m).

3 Colosseo/Fori Imperiali Station

One of the most characteristic works of the central stretch of Line C is Colosseo/Fori Imperiali Station (Fig. 3), located along Via dei Fori Imperiali and directly connected to the platform of the existing Colosseo Station of Metro Line B via 2 pedestrian tunnels.

In its vertical development, the work affects the entire stratigraphic succession, from carryovers, since the land fluviallacustrine sinvolcanic (Tb1a, Tb1b and TB2) to the sands with gravel (SG) up to large marine clays (Apl) varies along the longitudinal and lateral

development of the work. The groundwater level is at 14 to 16 m above sea level, in the area of Colosseo/Fori Imperiali Station.

The constraints of the layout of stations and galleries and those of the particular territorial context led to the need to make the 2 ends of the platform of odd underground rail with tunnel widening. This is executed after the passage of the TBM, in length equal to 27.00 and 49.00 m from one side to the other. To design the platform galleries with an excavation diameter equal to 11 and 12 m, respectively, field trials were performed in 2011 to verify the results of the following technologies:

- treatment using the technique of freezing
- treatment using injections

3.1 Treatment using ground freezing technique

The lithotype affected by the interventions are made up of Tb1a and SG formations. In the field trial (Figs. 4 + 5), aimed at determining the mechanical properties of frozen soils, a major intervention was made, designed to simulate the freezing of land around the portion of the theoretical gallery in order to obtain comparable results. Furthermore, in order to evaluate the effectiveness of different distances between the freezer probes, the 2 “piers” were geometricized with different meshes.

The following tests were performed:

- crosshole seismic surveys, carried out before and after freezing
- topographic measurements of the cornerstones on the surface and extensorinclinometer measurements
- consumption of liquid nitrogen
- laboratory tests on natural soil, frozen and thawed

The results were compared with those gained from CPT and SPT data on natural ground.

The frozen ground was tested at different temperatures (10° C/20° C) to verify the different mechanical behaviour and deformation, with the following results:

- freezing time of 16 days
- average consumption of about 1700 l of nitrogen per m3 of frozen ground (about 4.4 l/(mc h)) during freezing phase
- holding time of 4 days with an average consumption of approximately 115 l of nitrogen per m3 frozen ground (about 4.8 l/(mc h)) for the maintenance phase

During the freezing phase were measured:

- lifting maximum of about 2 mm away from the area, and of 5 mm in proximity, which were cancelled after the deactivation of the interventions
- cumulative increases of 4 to 7 mm, which is restricted on the depth of the treatment (approximately 30 to 32 m)
- maximum horizontal displacements with respect to the alignment of the probes:
  – in the transverse direction in the order of 7 to 8 mm
  – millimetre values in the longitudinal direction (approximately 2 to 4 mm)

The crosshole seismic tests on natural soil and frozen ground (Fig. 6) showed an improvement of mechanical properties of treated soils. In particular, the speed of shear waves in layers Tb1a show increases in the order of 300 to 400 m/s, from values of 300 to 700 m/s to 600 to 1100 m/s.

3.2 Treatment using injections

The field trial with cement and chemical injections is intended to verify the effectiveness of possible treatments for the consolidation and sealing of the soil. These are necessary to ensure safe conditions for carrying out excavations and to minimise the impact on existing structures, comparing the results of pumping tests in the field with those performed after the treatment. Two pumping wells with a diameter of 400 mm were prepared: a “superficial” PZ3, for pumping in the fluviallacustrine sinvolcanic deposits (Tb1a), and a “deep” PZ4, for pumping in the fluviallacustrine prevolcanic deposits (SG).

For the numerical processing of test results, the bed of lithotype Tb1a was considered as the basis of the “superficial” aquifer, while the “deep” aquifer was limited to the thickness of the SG lithotype. Stepping and longterm soil drainage tests were performed.

The test results of PZ3 (Fig. 7), registered in the surface layers, showed reduced boundary resentments. The maximum lowering measured is approximately 5.5 m, with stabilisation after recovery of the water level at altitudes close to those present in the groundwater of Tb1a. In “superficial” piezometers, decreases of 0.2 to 0.25 m were measured. In “deep” piezo meters, the piezometric height varied by a few inches. The results of recovery tests yield K values varying from 33.07 x 105 to 2.68 x 105.

For well PZ4, the time development of the decreases recorded during the stepping test is characterised by low subsidence (0.47 m, 1.60 m and 3.09 m), indicating the significant water supply of the aquifer. The deep piezometers at high distances from the well (30 to 45 m) suffered significant drops, varying from 0.32 to 2.21 m. However, the superficial piezometer did not suffer from the bailing, confirming the limited areal feature of pumping effects of the “deep” aquifer (SG) on the “superficial” aquifer. The values of transmissivity and hydraulic conductivity determined by the stepping test on PZ4 would then assume the

existence of an aquitard at the transition between lithotype Tb1a and SG, thick enough to “support” the water surface and make “mostly confined” to the “deep” one. For the analysis, the existence of an aquifer limited to the thickness of lithotype SG (7.95 m) is assumed, bounded below by Apl clays and above by lithotype Tb1a. The bailing in the deep aquitard yielded end pumping sags in the order of 2.80 m, noting how the resentment of the pumping was almost immediate, reflecting the confinement of the aquifer located “deep” in SG gravels.

3.3 Field testing of the permeability reduction treatments

Two separate sets of injections were carried out in the area affected by bailing tests, involving the land of the fluviallacustrine sinvolcanic deposits (Tb1a) and fluviallacustrine prevolcanic deposits (SG). These test meshes (Fig. 8) are diamond shaped, with 16 perforations equilateral triangular mesh of side 1.40 m. The boreholes reach 35.50 m with a 25 m stretch injected.

The grout was injected to mesh A in 2 successive rubs with a maximum volume of 75 l/VLV to a maximum of 10 bar to rejection; for mesh B, 3 rubs with 60 l/VLV were carried out 2 at 10 bar and the third at 12 bar. After the injection, the process was carried out with the crosshole tests and with those of pumping inside the meshes.

3.4 Summary of post-treatment

The data analysis of crosshole tests showed a material stiffness. The shear waves seem to suffer most from the treatments, increasing speeds compared to the field measurements.

With mesh A the maximum Vs registered at the heights corresponding to unit SG increase from 900 to 1000 m/s to 1200 to 1300 m/s. With mesh B, the speeds of Vs in SG increased from 800 to 900 m/s to 1200 to 1300 m/s. The chart in Fig. 9 compares the speed of seismic waves recorded before and after treatment in mesh A.

Two pumping wells were made for the respective tests (PZ7 for mesh A and PZ8 for B) and 2 tests of pumping discharge tests were performed. These yielded a reduction in the coefficient of permeability, also confirming significantly reduced pumping flows after the treatments.

The positive effects of the injection of grout and silicates determined a sensitive reduction of bailing flow (0.20 m at distances included between 27 and 57 m) measured in the “deep” piezometers attested in gravels SG, with resentment contained next to the superficial piezometers.

In summary, the field test was aimed at determining the mechanical properties of treated soils and at evaluating the effectiveness of waterproofing treatments, comparing the results of pumping tests in the field with those of pumping tests performed after the treatment, that is after grouting and chemical injections.

The soil treatment can be considered satisfactory for both mesh test, having achieved good reductions in permeability. The best results were obtained with the combined use of chemical and cement mixtures.

3.5 Design solution for tunnel's shore

The north running tunnel of Colosseo/Fori Imperiali Station is extremely complex underground work. Their development during planning resulted, amongst others things, in the execution of the abovementioned test fields. Another important decision led to the tunnel enlargement after the passage of the TBM.

Fixed these inputs, and taking into account the impossibility of performing ground consolidation from the surface, grouting works are planned underground. These works are carried out at different times and in different ways, as shown below:

1) In the first phase, the treatment of the ground around and inside the future shape of the excavation is scheduled. This occurs with radial grouting boreholes executed from the TBM tunnel (Fig. 10). On the one hand, the ground outside the widened cross section (Zone A in Fig. 10) is consolidated, applying a grout consisting of a mixture of cement, chemical materials and colloidal silicate. These consolidation works improve a strip of soil with a thickness of 3 to 4 m. On the other hand, for the ground inside the area of soil bounded by the future shape of the excavation (Zone B in Fig. 10), treatments with cement and chemical grout are applied. The proposed treatments are intended to improve the mechanical characteristics of the soil and to create a screen with reduced permeability to minimise the impact on groundwater during excavation.
2) In the second phase, the TBM tunnel is enlarged. During excavation, consolidations are planned for each stage. In this case, the consolidations are structural cemented elements put in place in the tunnel face – a measure that allows for a further tightening of the excavation core, preventing extrusion. At the same time, an additional treatment with grouting is carried out on the profile outline, with valved elements VTR. This is to achieve adequate thickness of the ground "treated" to facilitate the migration of the lithostatic stress on the sides of the opening to download them below the excavation floor ("arch effect").

The pumping tests performed at Colosseum/Fori Imperiali Station yielded the following permeability coefficients:

- soil Tb1a: 2 x 105 m/s
- soil SG: 8 x 105 m/s

The results of the field trial, performed on the mesh with chemical and cement injections, showed that from a mechanical point of view, these injections enable a significant improvement of the tested soils to be achieved (Tb1a, Tbi1 and SG) up to a 1.5 to 3.0 times increase in the elastic module “in place” variable, depending on the lithology. On the other hand, the pumping tests performed yielded values of the “global” permeability of the treated soil of 1.4 x 107 m/s: with these values, it can be estimated that the water flow in the tunnel will be between 3 and 6 l/s (on a field of excavation of a length of 6.0 m and in the presence of boundary consolidation and precoating). The particular boundary conditions, i.e. the presence of unique monuments, require utmost caution. The plan is therefore to use nanosilicate colloidal grout at the outline of the shape of the excavation. The excavation works for enlargement will be carried out in 6 m long fields. Casting of the invert arch is foreseen at a distance of 6 m from the excavation face, whilst the rest of the final lining will be built 12 m behind the face. The final face of the station will be lined with a wall of reinforced concrete, in contact with the segments placed with the shielded TBM.

4 Galleries of Mirti Station in progress

Mirti Station on Line C is located in the homonymous square in the district of Centocelle. The station is a central box type artefact with dimensions (65.50 m x 37.50 m) that respect the need to keep road traffic along the perimeter of the square (Fig. 11). The 4 ends of the platforms are not included in this artefact: they stick out 8 m onto Gardenie Station and 38 m onto Alessandrino Station.

The enlargement design of platform tunnel, realized from TBM Tunnel, was developed in function of local constraints and based on characteristics of the soils impacted from these interventions. The excavation of platform tunnel has affected only the lower pozzolanic deposits (PR units) at a depth of about 23 m from ground level. This mediumfine sandy loam is in a state of strong thickening and weak cementation, although it is not plastic. Numerous tests of direct shear were performed on samples taken from this unit; they show friction angles varying from 35° to 45° and cohesive force in direct shear tests ranging from 0 to 41.8 kN/m2. The geotechnical design parameters used for the PR unit are shown in Table 1. The weak cementation of this soil is confirmed by the results of a simple compression test performed on the sample of survey M02, which equals 0.48 MPa.

The maximum piezometric level is at 26.0 m above sea level, i.e. 6 m above the crown of the tunnels. This hydraulic situation proved to be the key issue of the excavation works. Considering the different behaviour of the soil layers encountered, the pozzolans were

treated with jet grouting (120 mm diameter) executed from the surface. Jet grouting yielded good results in this type of soil along the whole line. Furthermore, 8 rows of cement and chemical grouting were performed from the TBM tunnel.

For the enlargement tunnel (Fig. 12), the ground is reinforced with 37 pipes (12.0 m length, 88.9 mm diameter, 150 mm borehole diameter). Excavation proceeds in steps of 1.0 m and within 10 m long fields. As the segmental lining is removed, 2 steel sets IPE 180/1.0 m are placed and reinforced with sprayed concrete (0.2 m thickness). Repeating this procedure allows excavation of the dispari and pari tunnels to be completed (39.67 m length).

5 Progress of work

The progress of work for the first section (from Monte CompatriPantano to San Giovanni Station) is at about 85 %, 5 years after starting construction. 37 sites are in operation along the Monte Compatri/Pantano–San Giovanni stretch, including 22 station sites, 12 ventilation shaft sites and 3 other sites: Granite Deposit Workshop, Underpass “via Torrenova – via Laerte”, variation of the elevation of Torrenova Torraccio. 40 sites for archaeological investigations have already been completed to date.

The construction of the Granite Deposit Workshop, indispensable for the first phase of activation of the line, has been completed. Installation of systems and equipment for the distance driving of trains has started.

The excavation of 2 tunnels of Line C on the route from Giardinetti to San Giovanni station, the underground part of the railhead of Monte Compatri/Pantano a San Giovanni, has been completed. TBMs have in fact reached the station of San Giovanni, making an overall progress of 19 km in the 2 tunnels.

6 Metro C scpa: General contractor

Metro C scpa, a society set up specifically for the construction of Line C, is responsible for all project phases: from the design to archaeological excavations, from the construction of tunnels and stations to the delivering of trains as well as the startup of the line. The management ability of Metro C is the result of significant experience in the execution of complex works in the fields of civil engineering and transportation technology for infrastructures in Italy and abroad.

Line C is a turnkey project realised by Metro C scpa., a joint venture created specifically for this purpose and comprising Astaldi, Vianini Lavori, Ansaldo STS, Cooperativa Muratori e Braccianti di Carpi and Consorzio Cooperative Costruzioni. The 5 partners involved in Metro C s. c. p. a. have succeeded in creating a general contractor boasting the technologies and managerial skills needed to complete these major works.

Figures and Tables

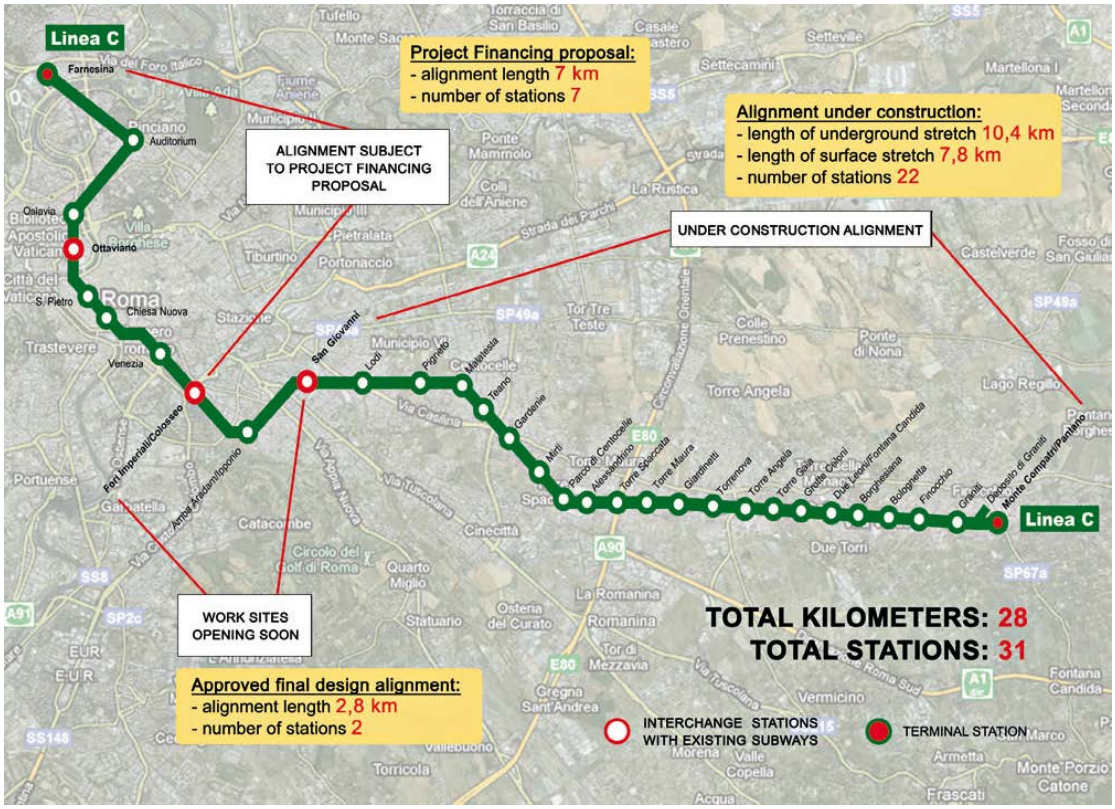

Figure 1 Main characteristics of Line C

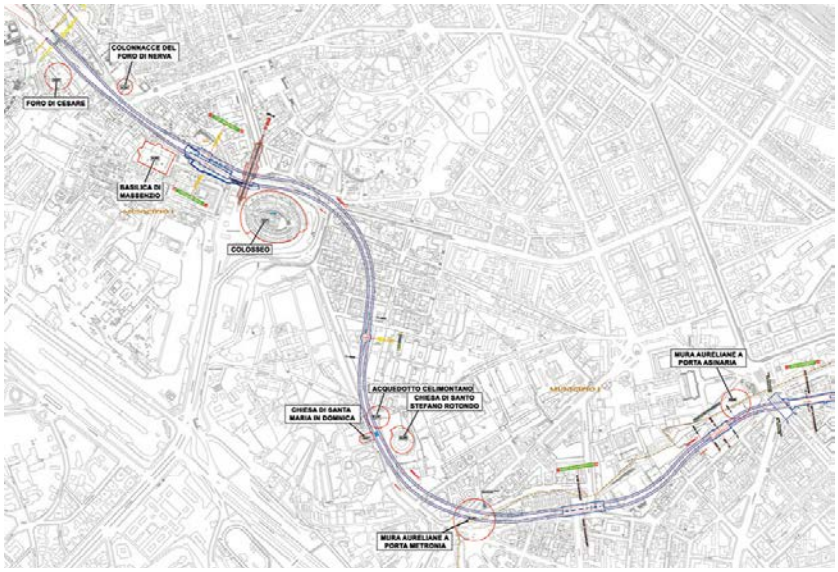

Figure 2 Line C stretch T3: historical buildings

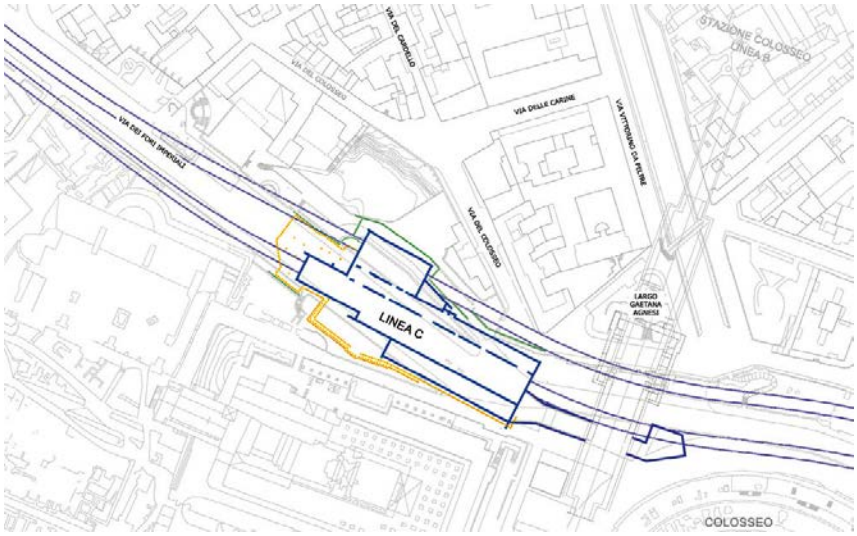

Figure 3 Colosseo/Fori Imperiali Station

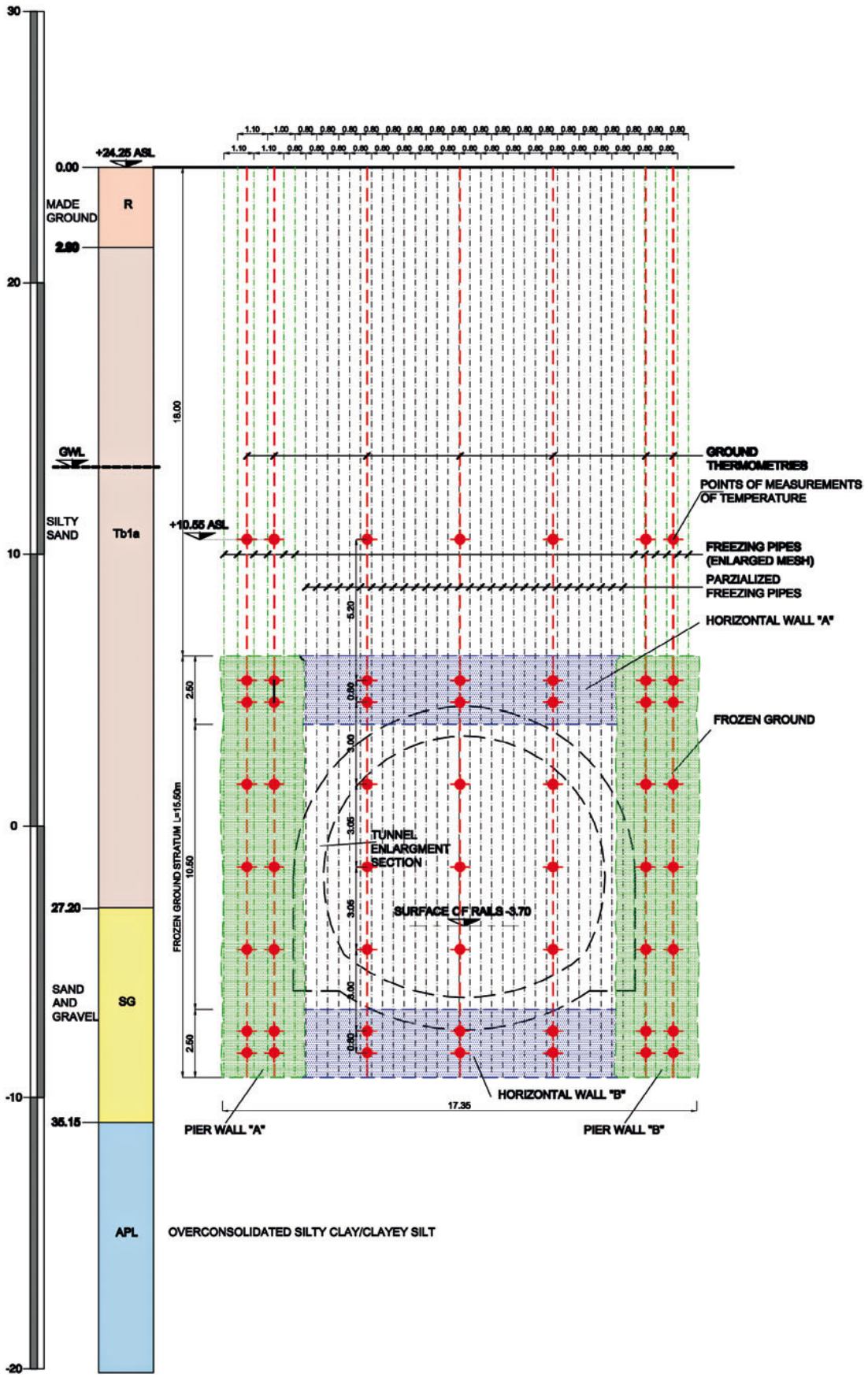

Figure 4 Ground freezing trial

Figure 5 Ground freezing trial photo – “Via dei Fori Imperiali”

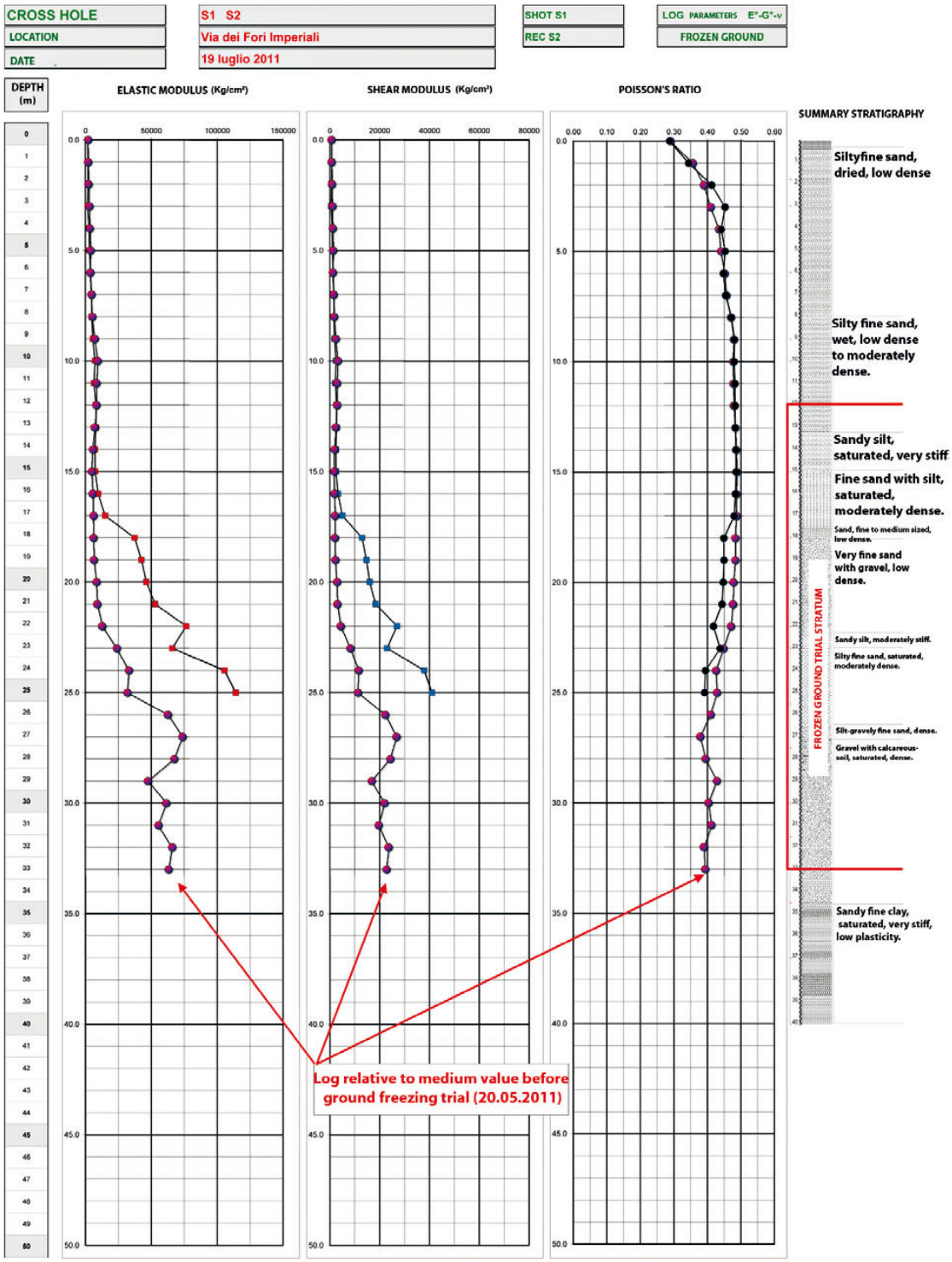

Figure 6 Result of cross-hole tests after ground freezing

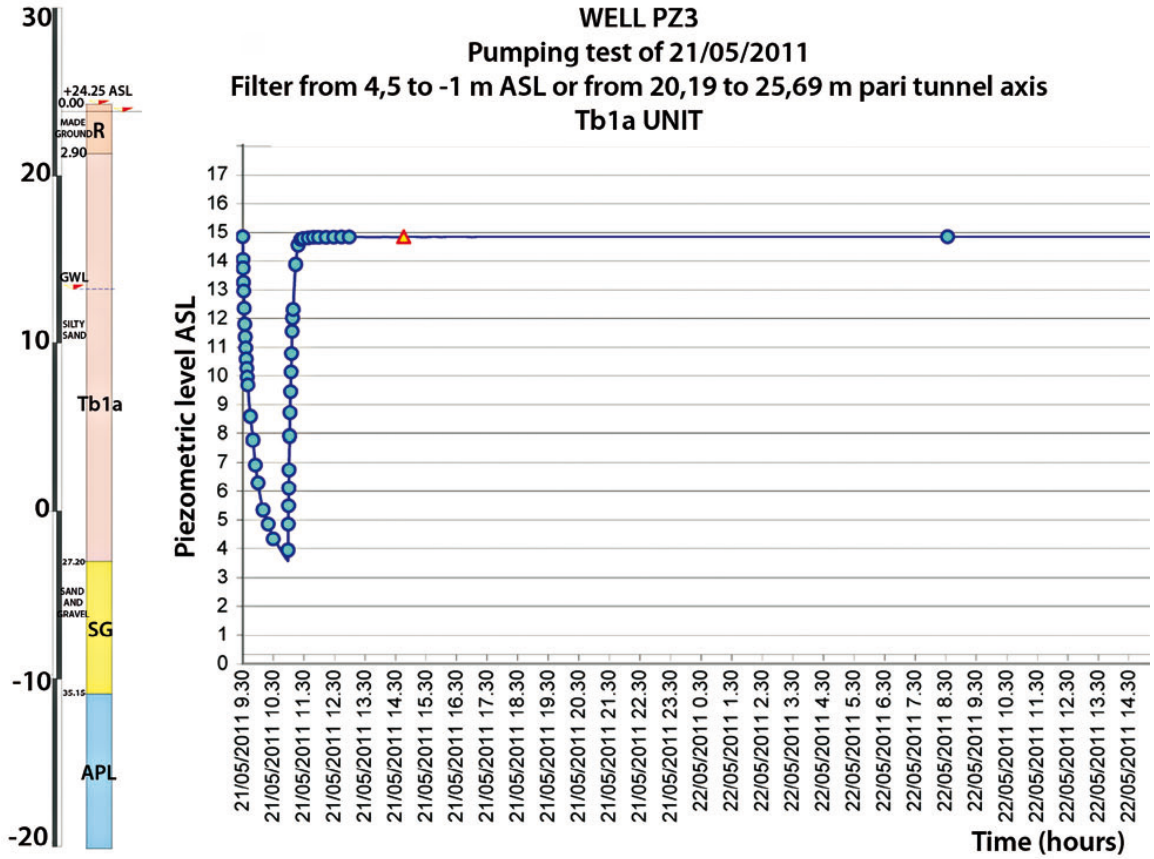

Figure 7 Soil drainage tests after grouting field trials

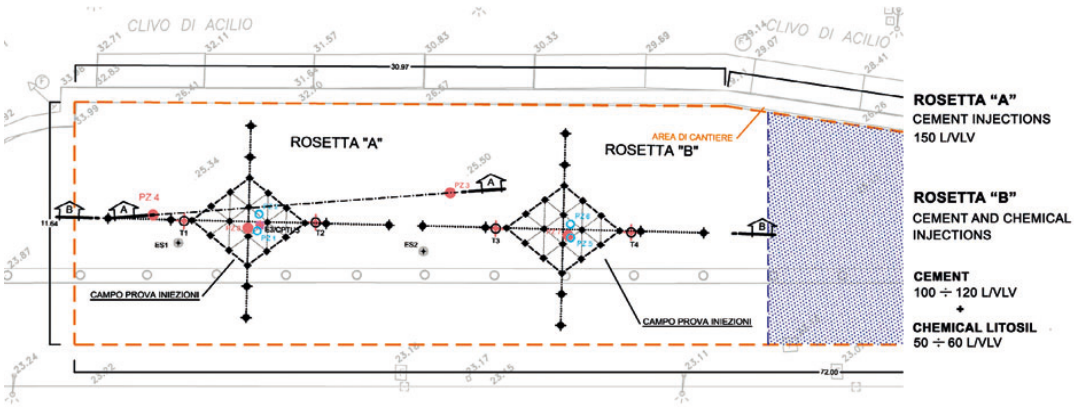

Figure 8 Layouts – grouting field trial

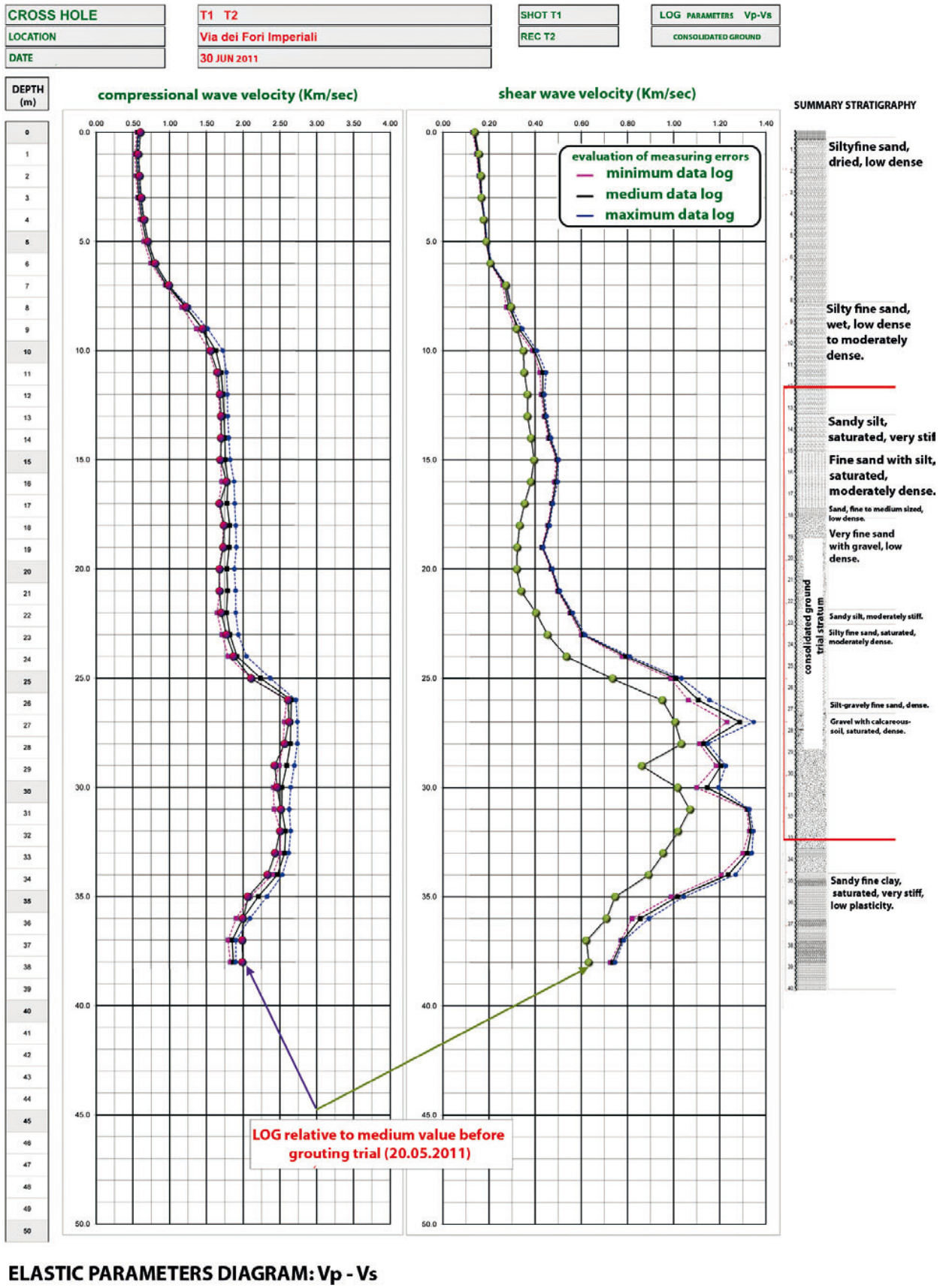

Figure 9 Result of cross-hole tests after grouting field trial

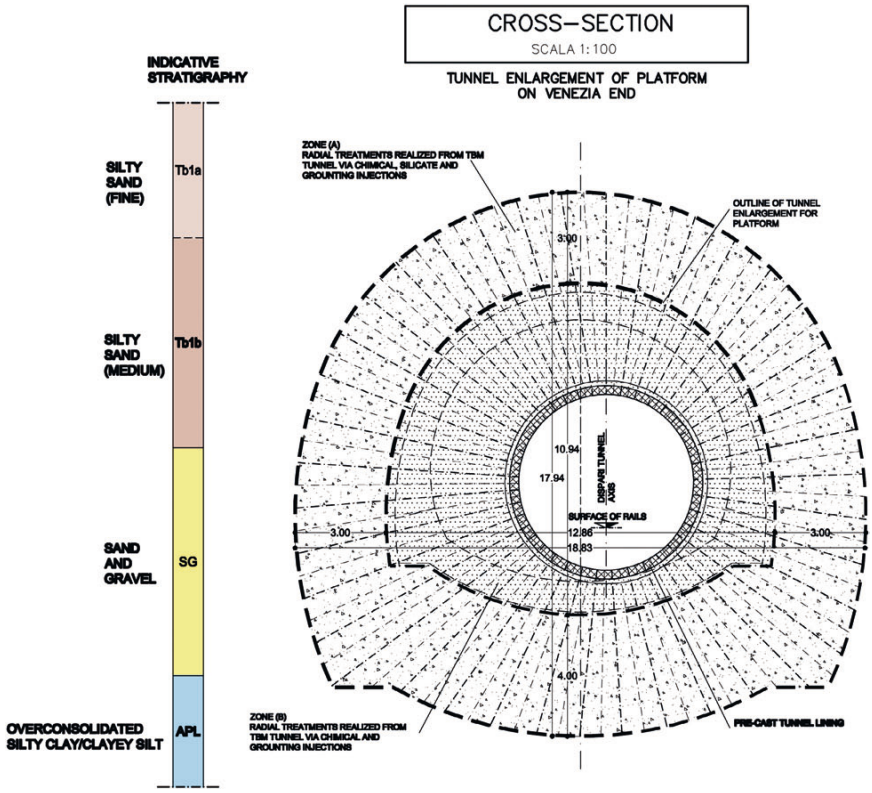

Figure 10 Radial treatments from TBM for tunnel enlargement

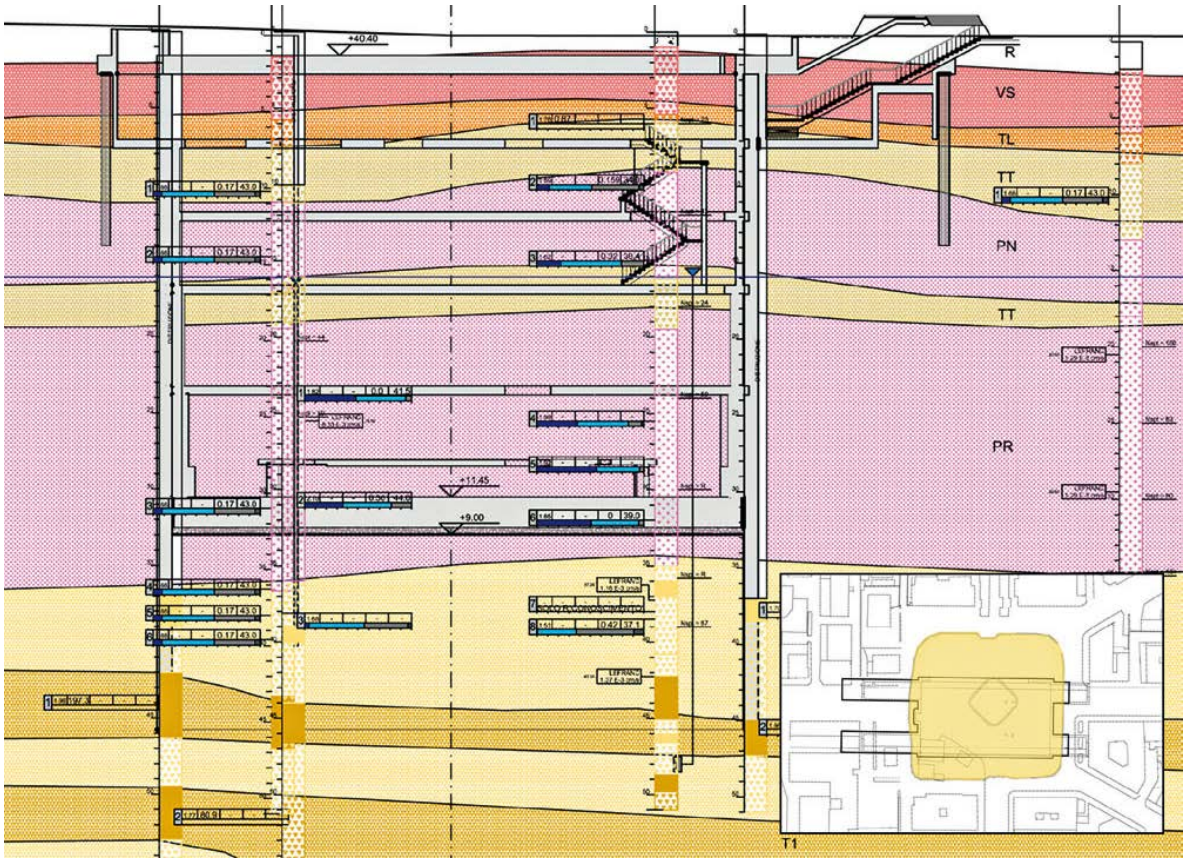

Figure 11 Mirti Station: round cross-section and station plan

Figure 12 Enlargement tunnel

Table 1 Geotechnical design parameters for the PR unit

Unit	W [%]	P.Vol. [kN/m^3]	Ø^I [°]	C^I [kN/m^2]	E_o [Mpa]	K_h [m/sec]
PR	27	17.5	35	10	210	5 E-5