Congresso Madrid - Maggio 88

Problems caused by the water table in lot 2B of line 3 of the Milan Subway

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ABSTRACT: Line 3 of Milan Metro crosses the city center in north-south direction on an underground route of 11 km with 15 stations. Lot 2B is the longest one of this line running southwards from Piazza del Duomo, in the very heart of the city, to Porta Romana. The closeness of buildings, the complexity of public utilities and the necessity to minimize traffic disruptions have required all treatments to be executed underground by means of a pilot drift driven from 4 adit shafts. The bottom of excavations is mostly 2 to 6 m below the water table. The water and the presence in the alluvial soil surrounding the excavations of some clayey-silty layers originated very difficult situations. The authors shortly describe herebelow the special treatments that had to be adopted in order to allow the excavations of the tunnel to be carried out safely.

1 INTRODUCTION

Lot 2B is one of the longest and the most important of Line 3 of the Milan Subway and the problems arising from its planimetric and altimetric features make it the most complex and difficult ever to be built in Milan.

As shown in figure 1,

- it covers a length of 2000 meters
- it runs under the city center, going from Piazza del Duomo to beyond Porta Romana
- the tunnel passes right under all the buildings on the north side of Via Mazzini and involves the foundations of all the houses of Corso di Porta Romana
- it includes three large stations: Missori, Lamarmora, Medaglie d'Oro, the first two of which are carried out by tunnelling below the water table
- all the lower tunnels are involved with the water table except for a short section further south towards Medaglie d'Oro.

We would like here to examine with particular care the problems encountered by excavation executed at a depth of 6 meters below the water table. Although the water head may seem rather small, the tunnels' peculiar situation in connection with the structures above should be taken into account. These buildings are old and fragile and cannot withstand any movement (such as lifting or settling), except for very small ones, which could affect their structural integrity. Because the alluvial soil is heterogeneous and with a varying grain size, unique and different techniques had to be adopted.

2 SOIL TREATMENT TO ENSURE SAFETY DURING EXCAVATIONS

The system used to ensure safety when excavating the tunnels is briefly described below. The Milan subsoil consists of alluvial soil where strata of more or less clean gravel are alternated to more compact mixtures of gravel and sand with some silt (15% to 25%). Homogeneous medium-fine sand layers are frequent while clayey-silty strata are rarer.

With this kind of soil, by grouting suitable mixtures, the soil can usually

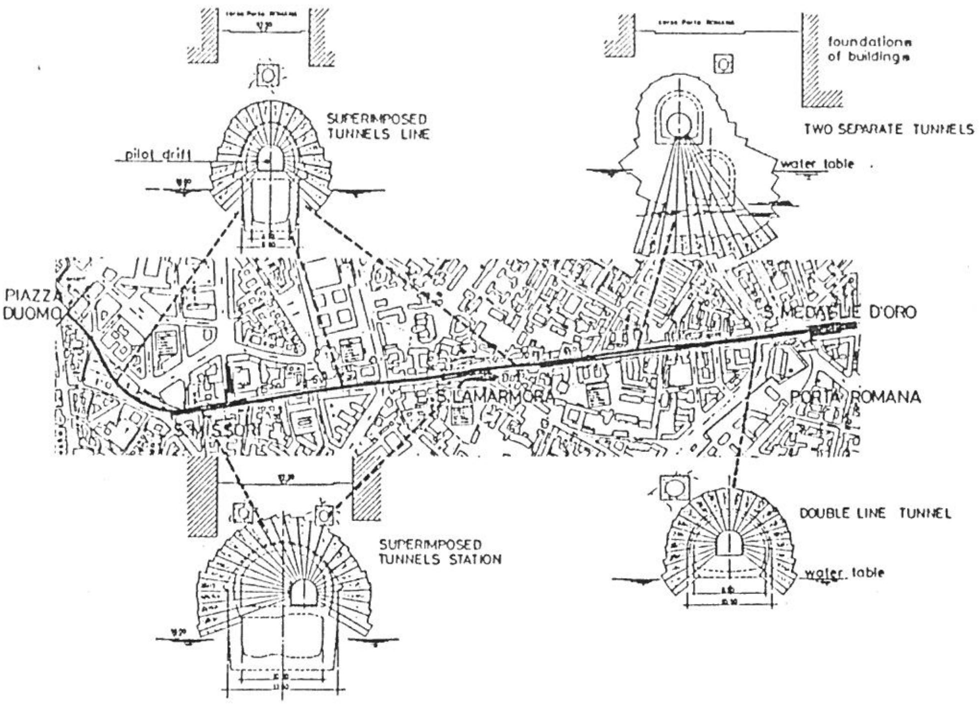


Fig. 1 Layout of lot 2B and typical cross sections of the tunnels

be consolidated to a satisfactory degree and waterproofed below the water table, in order to allow excavations in an acceptably dry environment.

In the case of lot 2B, owing to the prevalence of fine soil, an additional chemical mixture capable of penetrating the smallest voids was added to the cement mix so as to consolidate even sandy or sandy-silty soil. Since the relative volume of the "groutable" voids varies between 30% and 35%, the necessary degree of consolidation (and waterproofing) was achieved, on average, using the quantity of mix shown below, where Vt is the theoretical volume of soil to be treated, Vc is the volume of cement mix and Vg the volume of silica solution (with inorganic reagent) used

- consolidating effect only (above the water table) $\begin{cases} V_c = 0.16\ V_t \\ V_g = 0.14\ V_t \end{cases}$
- consolidating and waterproofing effects (below the water table) $\begin{cases} V_c = 0.14\ V_t \\ V_g = 0.21\ V_t \end{cases}$

Figures 2, 3 and 4 show the typical treatments used to protect the excavations of various types of tunnels (superimposed line tunnels, superimposed station tunnels, one level line tunnels).

We must, however, point out that the lot includes many entirely unique cases which required specific detailed designs. In figure 5 we are showing, as an example, a section of the situation of Lamarmora station.

In order to check the stability of the excavations, stress analyses with the finite-element method were carried out. The geotechnical parameters of the natural soil and the consolidated soil were introduced in the calculations. These parameters were checked also through in situ tests. The modulus of elasticity of the soil was verified by plate loading and dilatometer tests (both in natural and treated soil).

The strains of the treated soil arches were slightly lower than the calculated values, which on average were 5 mm at the roof and 2 mm at the sides.

The excavations under existing buildings were carried out with a high degree of safety even when the foundations of the buildings were quite close (slightly more than 3 meters away) to the top of the tunnel.

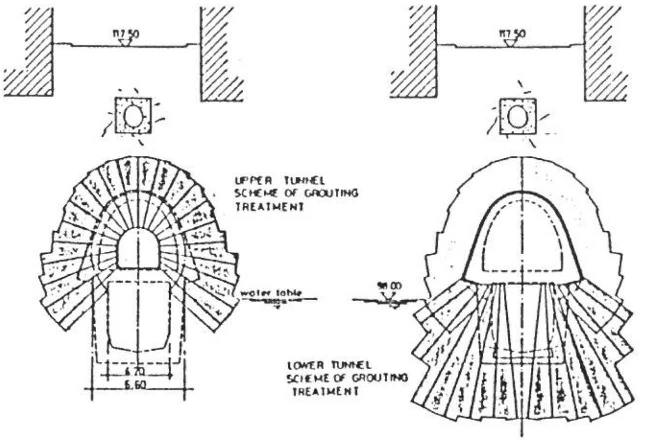


Fig. 2 Grouting treatment of superimposed tunnels

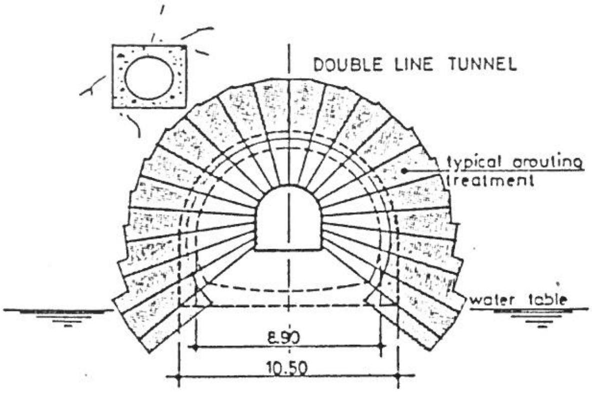


Fig. 3 Grouting treatment of one level tunnel

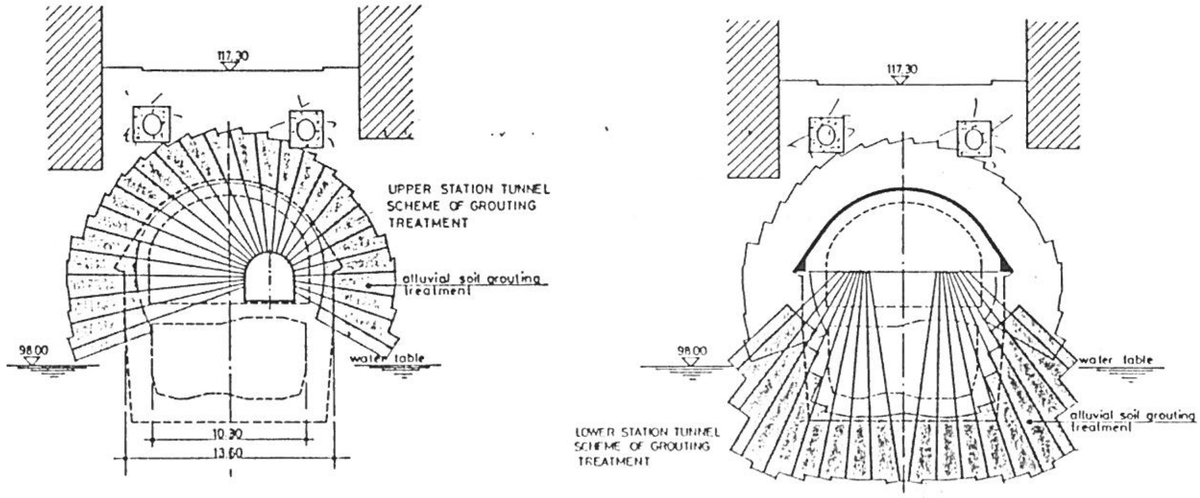


Fig. 4 Typical grouting treatment of station tunnels

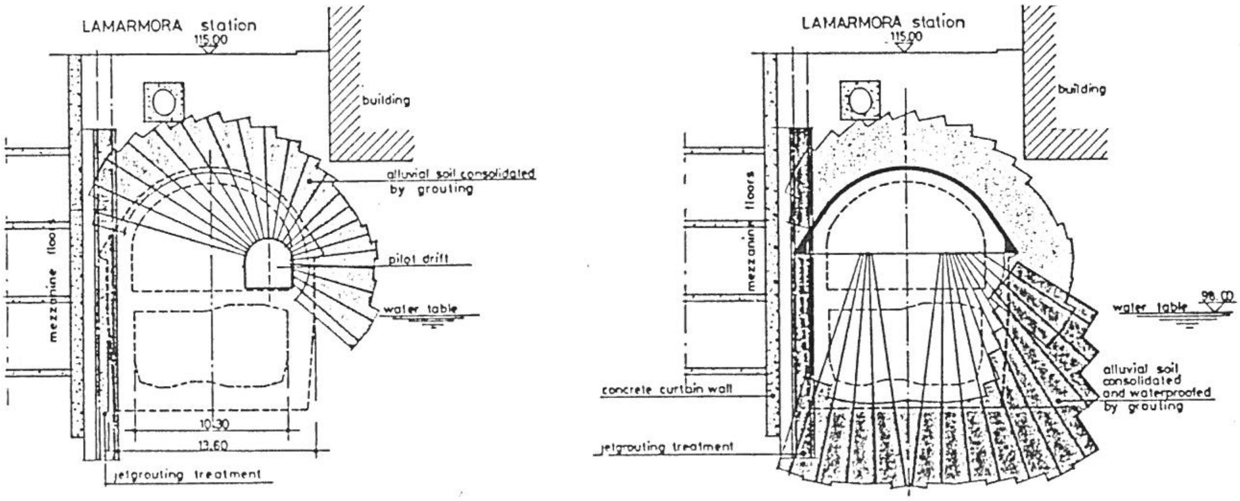


Fig. 5 Particular consolidation treatments of Lamarmora station

3 EXCAVATION IN WATERBEARING SOIL

The greatest problems faced in excavating lot 2B were not those, as previously expected, arising from deformations (lifting and settling of the buildings above), but those caused by the presence of the water table.

Here, too, a distinction must be made concerning the grain size distribution of the soil layers. Actually, with the percentages of mixtures envisaged in the design and described above, the excavations below the water table could be carried out without difficulty in areas where the effective diameter of the soil was $d_{10} \geqslant 0.02$ mm, that is to say in largely heterogeneous soils with silt concentrations below 25% (see figure 6).

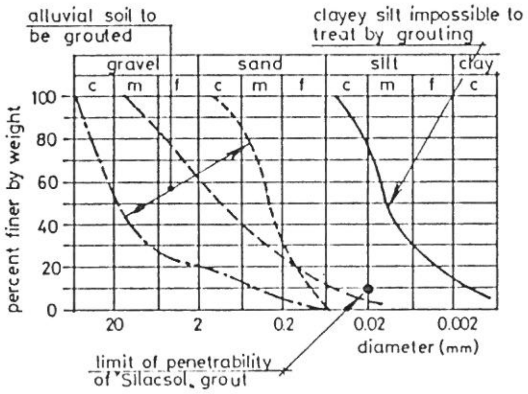


Fig. 6 Typical grain size curves of soil surrounding the excavation

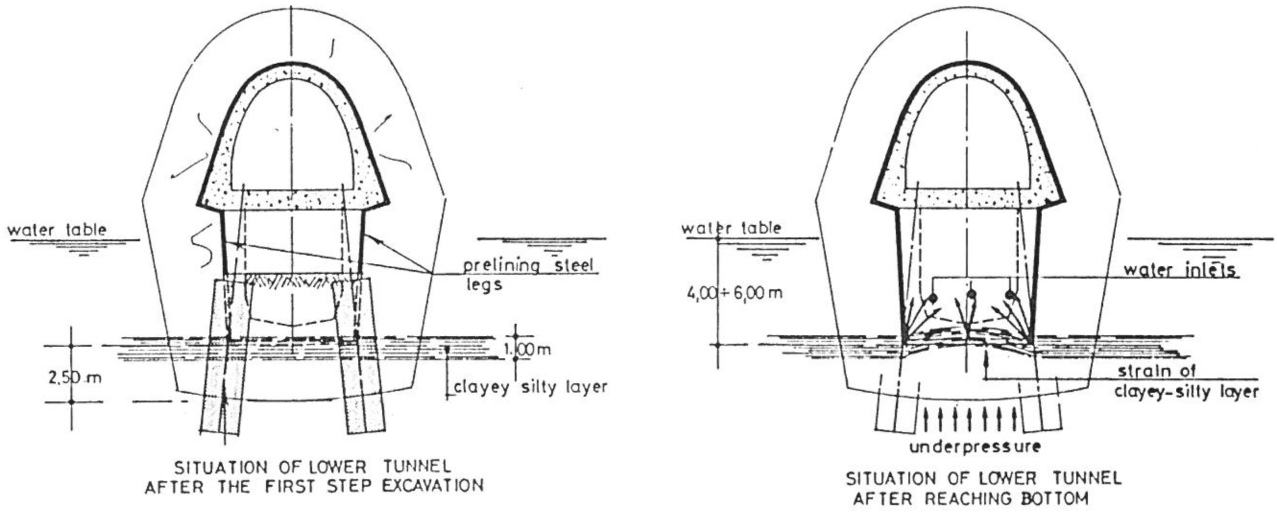
In these areas, during excavation, water inlets were extremely rare and could always be kept under control and stopped by rapid and local treatments: grouting pipes were inserted in the water seepage area and simultaneously cement and sodium silicate mixture were pumped (Joosten system).

The real surprise, which caused also the collapse of the consolidated invert and the piping effect (which were not easily stopped), was the presence of a one-meter thick layer of clayey-silt located in the delicate area of the bottom of the lower tunnel. This has been so far detected in two areas: downstream the Lamarmora shaft for about 150 meters and on both sides of the S. Nazaro shaft for about 100 meters.

Owing to the variability of the alluvial soil and to its discontinuity, this particular clayey-silty layer was not detected in the preliminary exploratory borings and therefore it had not been possible to study and design a solution for this difficult situation from the start.

A more detailed and accurate series of exploratory borings (with a tighter pattern) was recently carried out, which pointed out the exact location of the fine clayey-silty strata.

The collapse of the invert and the water inlets are shown in figure 7. As can



SITUATION OF LOWER TUNNEL AFTER THE FIRST STEP EXCAVATION

SITUATION OF LOWER TUNNEL AFTER REACHING BOTTOM

Fig. 7 Location of the clayey-silty layer and piping effect in the invert area be seen, the clayey-silty layer located in the upper part of the consolidated invert caused its collapse due to a series of parallel factors

- the thickness of the consolidated soil arch, which the calculations by finite-elements had envisaged to be at least 2.50 meters to guarantee the stability of the tunnel, was reduced by 40% since the silt could not be treated with conventional procedures
- the impermeable clayey-silty layer did not allow the water to drain, which would have reduced the underpressures
- the strain of the silty layer, once completely freed from the load of the ground above it, caused collapses which generally occured laterally at the base of the vertical supports, where the greatest stress is concentrated.

A remarkable quantity of water could therefore come into the tunnel, together with fine material (fine sand and silt). Difficult drainage and backfilling operations had to be carried out in order to stop the piping effect. This occurred four times in a small area around the Lamarmora shaft.

Attempt was made to carry out additional consolidating treatments by grouting chemical solutions based on sodium silicate, trying to continue the excavation in short stretches, but this was not successful.

Only ten meters of invert were completed with great difficulty and time expenditure.

So in order to avoid further piping and damages to the buildings above, freezing of the soil had to be adopted, as the only means of giving the clayey-silty layer the necessary high degree of consolidation.

4 GROUND FREEZING TO ALLOW EXCAVATION BELOW THE WATER TABLE NEAR LAMARMORA SHAFT

The method of the liquid nitrogen was adopted for the following reasons:

- it ensures a quick formation of the frozen soil structures (slightly more than two days)
- very low temperature can be reached giving a high degree of mechanical strength to the soil
- this method does not require a bulky and complicate equipment.

In fact the alternative method adopting brine would not have been suitable in this situation.

Liquid nitrogen was pumped directly in the freezing pipes from the storage tank placed near the Lamarmora shaft or directly from the trucks carrying liquid nitrogen from the producing factory.

Here below are some characteristic data concerning the freezing process and the nitrogen consumption:

- liquid nitrogen temperature at 2 bar pressure	-196 °C
- average discharge gas temperature	- 60 °C
- maximum frozen soil temperature 50 centimeters apart from the freezing pipe (before maintenance operations)	- 7 °C to -10 °C
- minimum temperature reached in mixed sandy soil	- 50 °C
- minimum temperature reached in the clayey-silty layers (where freezing is harder to obtain)	- 20 °C
- average nitrogen consumption for freezing	1100 l/m3 of soil
- nitrogen consumption for maintenance	40 l/m3 per day

Figure 8 shows the lay-out of the freezing process at the critical point (a 20 meters stretch), where, in order to stop piping during excavation, temporary reinforced concrete slabs were cast at the bottom of the excavation.

In order to remove the temporary concrete slabs and reinforcing steel beams and finally cast the normal concrete invert under safe conditions, it was necessary to create a sort of frozen shell underneath the area to be excavated. This would have ensured the protection and the watertightness during the excavation for several days.

Several freezing pipes had to be inserted with a steep inclination as shown in figure 8. After freezing, all the operations took place normally in quite solid and dry soil.

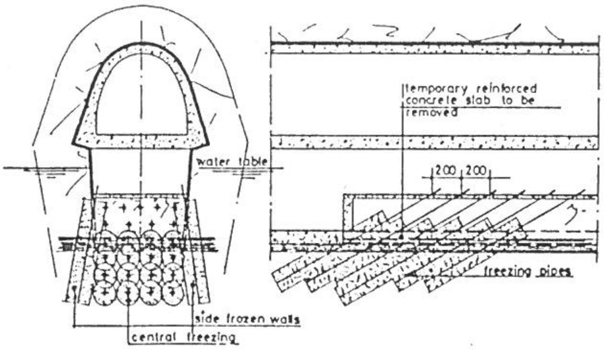


Fig. 8 Ground freezing scheme adopted in most critical areas

Figure 9 shows the operating pattern applied to tunnel sections where freezing technique was carried out previously with the only aim to strengthen the clayey-silty layer.

As can be seen these operations are much simpler. In fact, two frozen side walls are created (which can be maintained also during the excavation). In the central portion, the vertical freezing pipes are disconnected as the excavation progresses.

The length of the excavation stretches depends on the time required by the central section to defrost.

By sensibly lowering the soil's temperature (-15° to -20 °C) and under the protection provided by the two frozen side walls, a 12 meters length for each excavation stretch could be achieved.

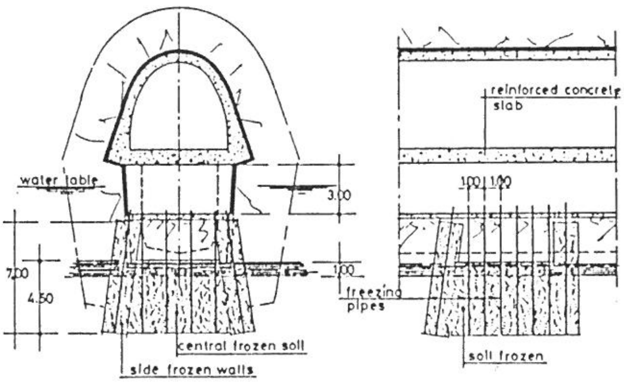


Fig. 9 Soil freezing normal scheme

5 EXCAVATION IN THE WATERBEARING SOIL WITH VARIOUS TREATMENTS AND DRAINAGE

In paragraph 4, the system used under the most difficult circumstances has been described: here the clayey-silty layer is rather thick and wide and had to be removed in order to ensure a safe use of the railway line in the future (that is to say to eliminate the settlement of the tunnel structure, due to vibrating loads).

There are, however, some intermediate situations where the silty layers are thinner and less homogeneous, but where conventional grouting alone cannot face piping effects.

Systems alternative to massive freezing have therefore been designed and are described below.

5.1 Additional grouting and frozen side walls

The system is shown in figure 10. The central area is protected by additional injections, mostly of silicate mixes owing to the very fine sand located under the silty layer.

The two frozen side walls guarantee the lateral watertightness. They prevent water from reaching the tunnel by filtering horizontally across the deformable silty layers and at the same time they consolidate even very fine soil.

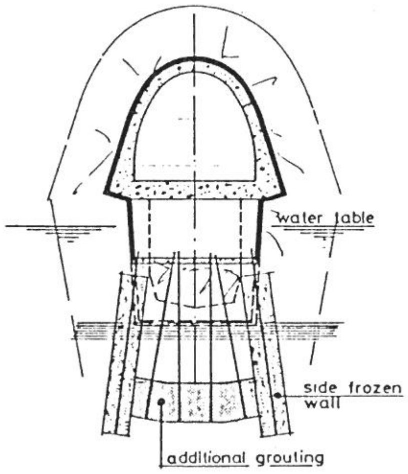


Fig. 10 Combined treatments of freezing and additional grouting

5.2 Additional grouting

In some cases, the consolidation of the soil was simply achieved by additional grouting. In this way, less difficult problems caused by the presence of some silt have been solved. In fact sometimes the clayey-silty fractions were either included in the alluvial soil with a percentage higher than 25% or concentrated in small discontinuous lenses.

Figure 11 shows different situations.

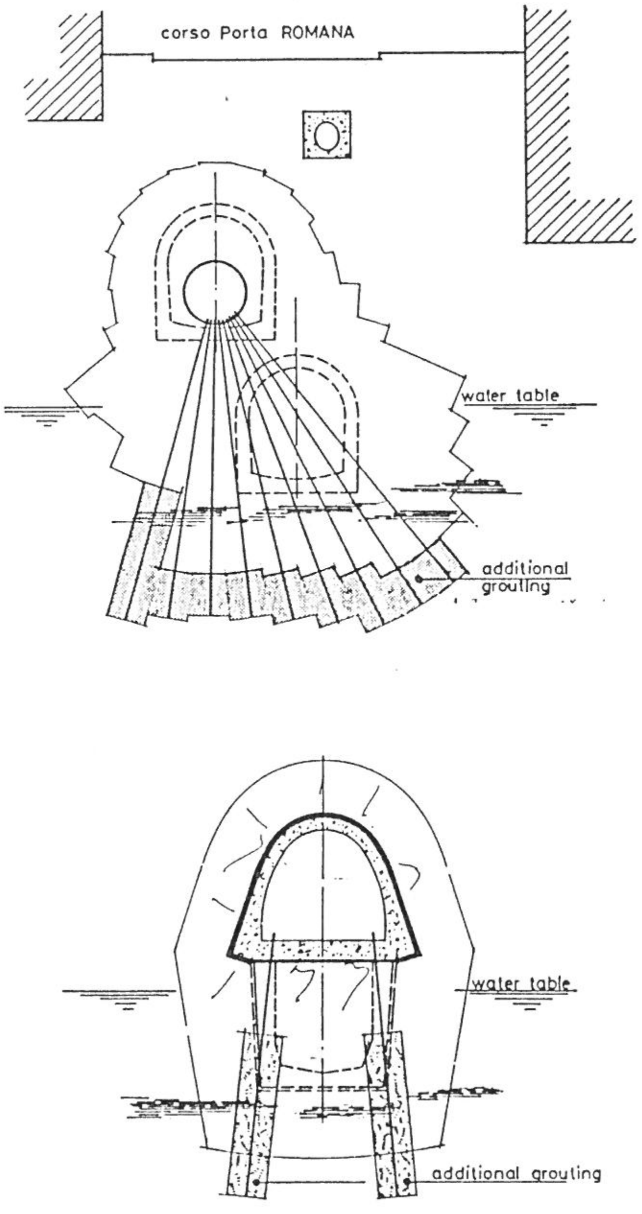


Fig. 11 Two different schemes of additional grouting to allow safe excavation in very fine soil

5.3 Additional grouting and lateral drainage

This system has not been used yet.

It is here described for complete information, since it will be tested in some cases where the water table level is rather limited (not higher than 3 meters from the bottom of the tunnel).

The aim is to create localized lowering of the water pressure, through pumping, below the silty layer, along the two lateral sides and on the face of each stretch of excavation.

The safety obtained is obviously inferior to that provided by the frozen lateral walls. We believe, however, that in the less difficult cases, a small extra support in addition to the grouting treatment can help to ensure the stability of the excavation. The length of the excavation stretch depends both on the result of the drainage effect and on the volume of water to be discharged. As shown in figure 12, we believe the optimal length will be of 8 to 10 meters.

An actual lowering of the water table would, instead, be impossible due to the permeability of the alluvial soil. The considerable amount of water involved could not be drained and could affect the stability of the overlying buildings.

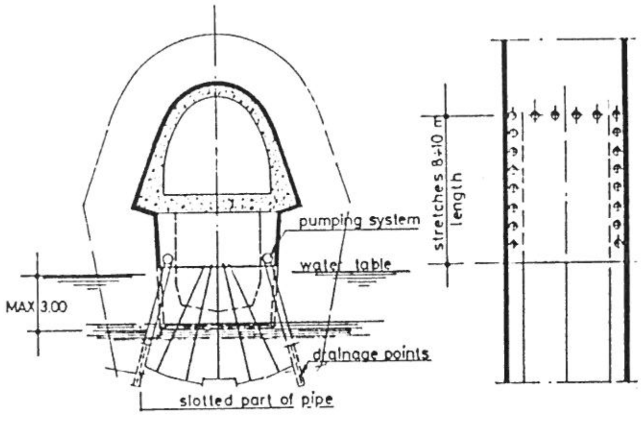


Fig. 12 Attempt to protect excavation by additional grouting and drainage

6 CONCLUSIONS

The water table played a significant role in the excavations of the lower tunnel of lot 2B of line 3 of the Milan Subway. In fact the presence of water created further problems connected with the integrity of the structures above (buildings, sewers, narrow and heavy-traffic streets).

The different kinds of consolidating and water-proofing treatments adopted had to take into account the grain size composition of the alluvial strata.

- In cohesionless mixed soils and sandy soils, conventional grouting (of cement and silicate mixes) ensured the stability of excavations in the water table, even with 6 meters water head.
- The presence of fine clayey-silty strata, about 1 meter thick, required the adoption of freezing in order to reach a satisfactory degree of safety.

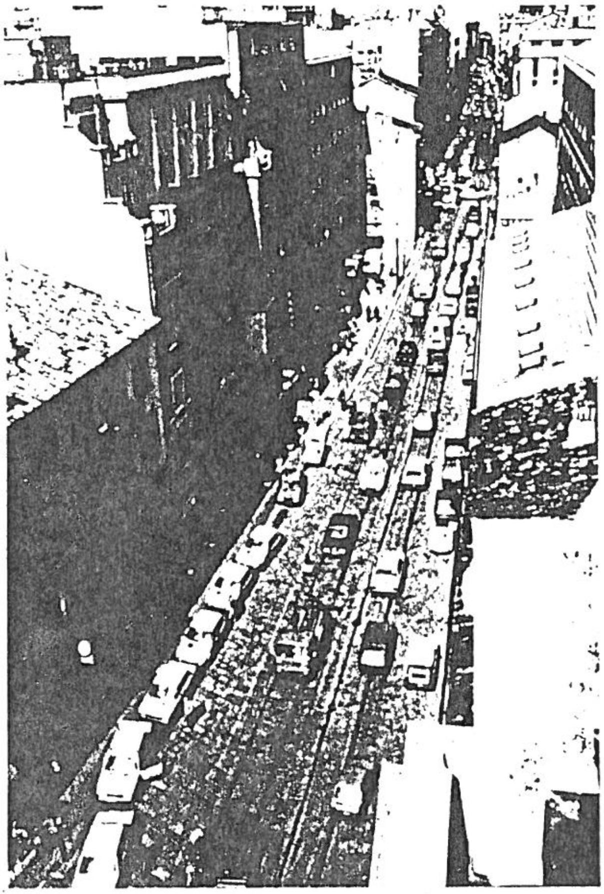


Fig. 13 General view of Corso di Porta Romana underpassed by the tunnel

Areas with discontinuous lenses of silt could be treated by using several methods (additional injections, frozen lateral walls, drainage systems).

The systems briefly described in this paper, in addition to special safety measures adopted in the excavation and pouring operations, made it possible to complete the most difficult stretches of the subway tunnel without affecting the building foundations and the activities on the surface.

Figure 13 shows a general view of Corso di Porta Romana under which line 3 of the Milan Subway runs.

ACKNOWLEDGEMENTS

- Owner: Metropolitana Milanese S.p.A.
- Main Contractor: Imprese Riunite Lodigiani - Grassetto - Romagnoli - Tettamanti, Milano
- Special geotechnical works Contractor: Rodio S.p.A., Casalmaiocco (Milano).

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