THE LOWER STRETCH OF LINE 1 OF NAPLES UNDERGROUND

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SUMMARY: The lower stretch of Line 1 of the Naples subway is at present under construction. It is characterized by the relatively great depth of the tunnels, which are located within the base formation of Yellow Neapolitan Tuff, up to 30 m below the water table. The geological framework is briefly presented. The design criteria and construction methods adopted for the shafts and the tunnels are then reviewed, stressing the most relevant aspects of the project.

1. INTRODUCTION

1.1. General features

The Line 1 of Naples subway was initiated with a first draft design of 1976, providing the connection of the upper zone of the town with the city center. A 5 km long extension on viaduct towards the peripheral zones to the north of the town was added at a later time.
Upon approval of the municipal transport plan in 1997, Line 1 was extended to form a closed ring, integrated in a railway network characterized by a set of switch nodes connecting all the lines of interest for the town and the region.
At present, the stretch between the stations Piscinola and Vanvitelli is operating; by the end of the year it will be extended to the Dante station, totaling almost 14 km and 14 stations. The construction of the stations in the stretch from Dante to Centro Direzionale (the so called Lower Stretch) has been recently started, while the stretch from Centro Direzionale to Piscinola - that closes the ring – is at present in the preliminary design stage.
This paper is devoted to the lower stretch which crosses the old town, the Greek-Roman Neapolis, which dates back to the 5th century BC and whose ancient fabric is now coming to light by the preliminary archaeological excavations. The Line follows an underground path under via Toledo, located on the layout of the ancient Aragonese walls. After a wide bend it reaches Piazza del Municipio, where the archaeological excavation uncovered the

ancient walls enclosing the Maschio Angioino castle. Following the axis via Depretis-corso Umberto I, it reaches finally piazza Garibaldi and the Centro Direzionale (Fig. 1).

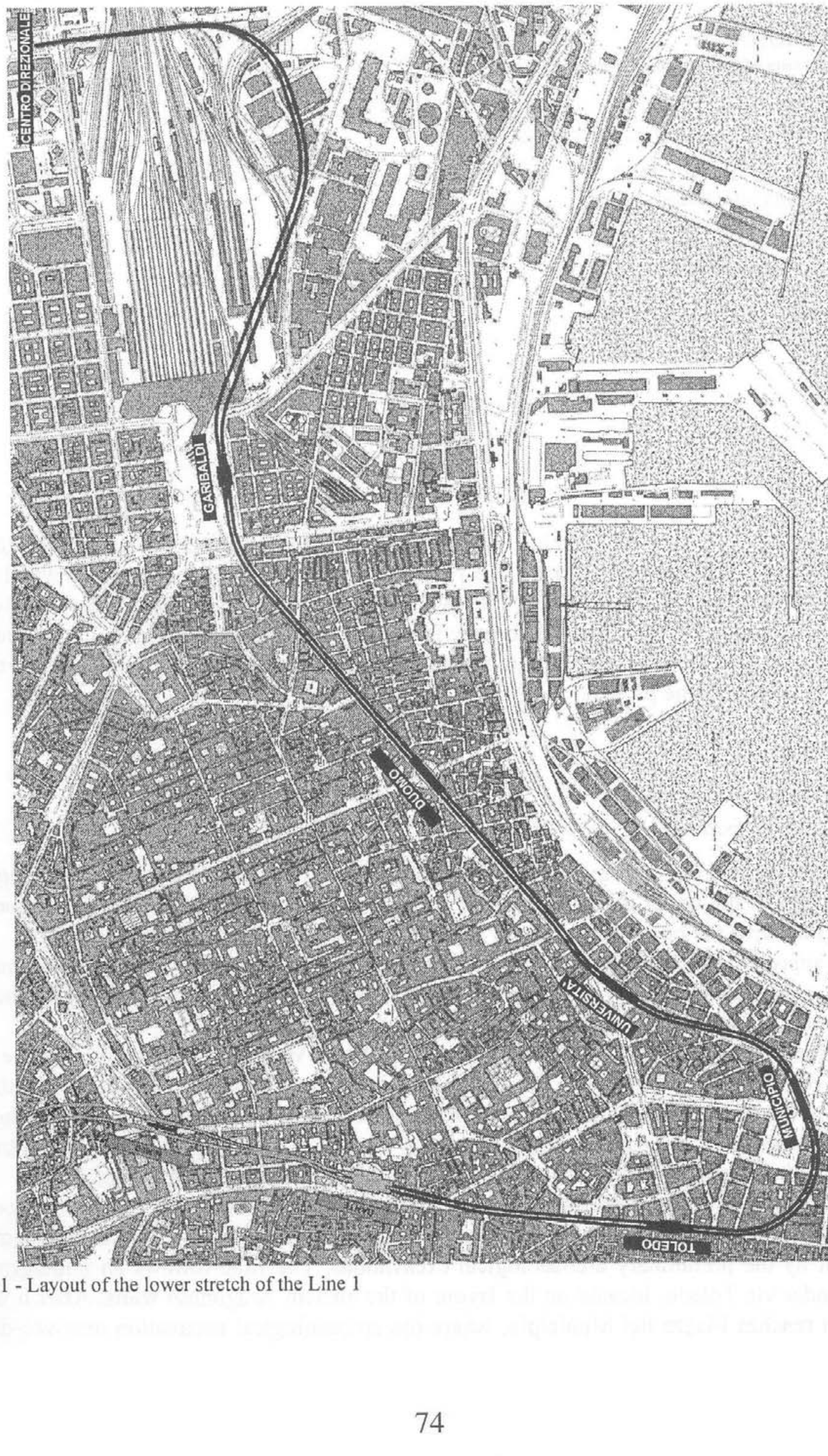

Fig. 1 - Layout of the lower stretch of the Line 1

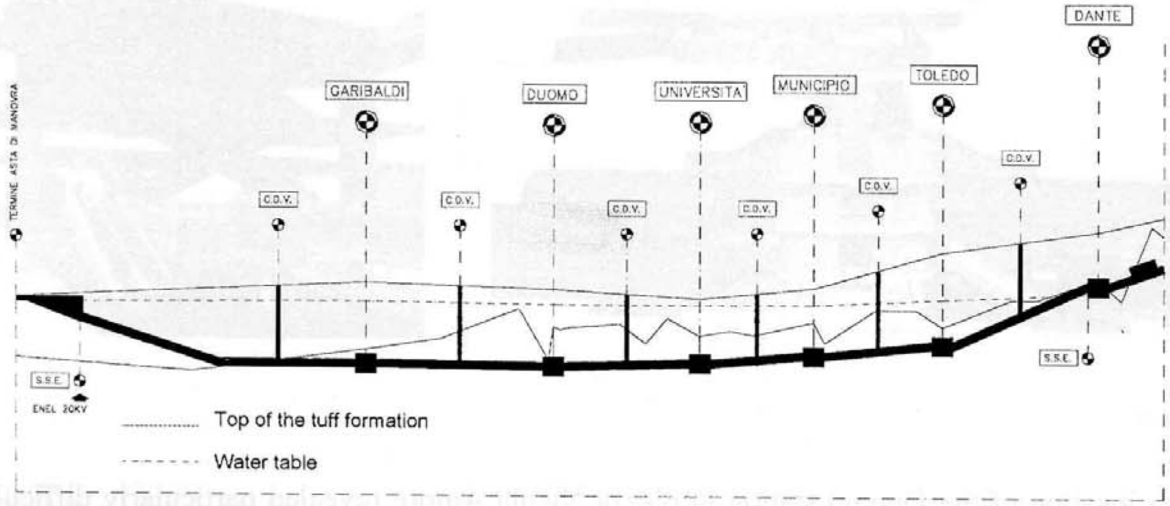

Fig. 2 - Profile of the lower stretch of the Line 1

1.2. Constraints and functional choices

The original design of the lower stretch, approved by the Naples Town Council in 1982, was based on a shallow line constructed by the cut and cover method. Later the Council stressed new requirements: (i) the inclusion of a new station in piazza Municipio, an important switch node with other subway lines, and (ii) the reduction of open cast works to a minimum, in order to minimize the interference with the surface traffic and the archaeological remains.

To comply with the aforesaid requirements, deep tunnels running within the tuff formation were finally adopted. To this aim, it has been necessary to exploit as much as possible the layout standards, i.e. the highest admissible slope of 5.5% and the minimum radius of 170 m.

A new functional and structural solution was developed for the stations, with rectangular shafts located on the station axis, orthogonal to the platform tunnels. Inside the shafts escalators and lifts connect an intermediate level to the mezzanine, located just under the roadway. The connection between the platforms and the intermediate level is serviced by two couples of inclined tunnels, located outside the platforms and parallel thereto (Fig. 3).

Instead of adversely affecting the station layout, the decision of creating a deeper line resulted in better internal paths, realizing the separation of the travelers' flows according to the destination since the entrance turnstiles.

The stations keep the locations they had in the previous solution, except the position of the mezzanines which has been re-defined not to hinder traffic during the works and to get a more rational arrangement of the subservices.

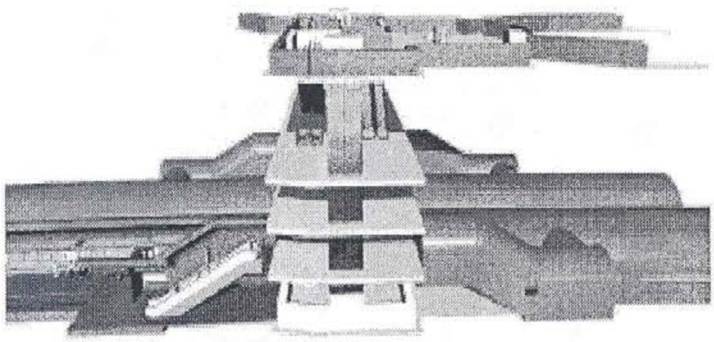 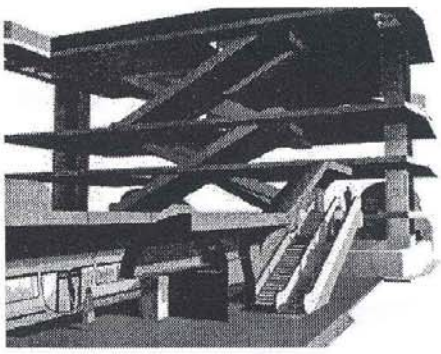

Fig. 3

The location of the Duomo station in piazza Nicola Amore revealed particularly difficult, since the surface works occupy up to 80% of the overall surface of the place. The area of the yard will be changed during the works, in order to be at any time compatible with the vehicle traffic of one of the most busy arteries of the old town.

2. GEOLOGICAL BACKGROUND

The territory of the city of Naples is rather uneven, as a result of its geological history and in particular of the occurrence, in the immediate vicinity of the town, of the two large volcanic centers of Vesuvius to the east and Phlegrean Fields to the west.
The lower town extends in the plains along the coast of the bay. The densely built town rises along the surrounding slopes and spreads on the plateau of the "Vomero" till the hill of "Camaldoli", 458 m above sea level.
The subsoil of the town is composed essentially of pyroclastic products (ashes, lapilli, scoriae, pumices, pozzolana and tuff) rather well ordered in some places, chaotically mixed elsewhere. On the hillside and the tableau they were directly deposited by the eruptions of the Phlegrean volcanoes; in the coastal area these materials have been washed out from the surrounding hills and deposited as alluvial or beach sediments.
The backbone of all the range is composed essentially of the Neapolitan yellow tuff, originated by a Phlegrean eruption 12.000 years before present. The tuff results from the cementation of pozzolana after its deposition. It is a soft rock whose porosity ranges from 50% to 60%; its uniaxial compressive strength is in the range from 2 MPa to 10 MPa. It is characterized by two main families of discontinuities. The so called "suoli" follow sedimentation planes, and are thus sub-horizontal; they are relatively rare. The discontinuities of the second family, called "scarpine", are believed to be an effect of the cooling of the mass after its deposition. They are rather frequent and sub-vertical; generally thin and tightly shut. Sometimes the "scarpine" are found in bundles, relatively close to each other; sometimes they are widely spaced and randomly oriented. Their location by boreholes or other site investigation techniques is difficult and rather uncertain.
All over the territory the water table is found at an elevation of a few meters above the sea level. It is thus rather shallow in the lower town, while it is very deep and out of the range of engineering interest in the rises.
The Line 1 of the Naples subway meets all the existing subsoil situations. For the purpose of the present paper, a schematic profile of the lower stretch of the line is reported in fig 2 . The two tunnels run up to 30 m below the water table; such a high depth has been chosen

in order to dig the tunnels through the yellow tuff, thus minimizing the surface settlement and the damages to the buildings and the infrastructures network. Because of the risk of collapse by cleft pressure in undetected "scarpine" close to the excavation, the running tunnels are being excavated by an EPB machine, while the larger platform tunnels will be excavated by traditional techniques after having consolidated the surrounding soils by grouting and freezing. The shafts of the stations, containing the lifts and escalators, will be excavated within peripheral diaphragms by reinforced concrete panels excavated in bentonitic mud.

3. STATION SHAFTS AND MEZZANINES

The choice of a deep layout, while producing crucial advantages, involves severe static and constructional requirements, for the following reasons:

- shaft depth, ranging from 36 m below ground surface at Piazza del Municipio to about 45 m at the Garibaldi station. The soil profile at the sites of the stations is characterized by the formation of Neapolitan yellow tuff, whose top is found at a depth between 20 and 30 m, overlain by cohesionless sediments (pozzolana, more or less silty sands and made ground). The water table is found at a depth below ground level of 2 m at the University station and 10 m at the Garibaldi station (Figs. 4 and 5);

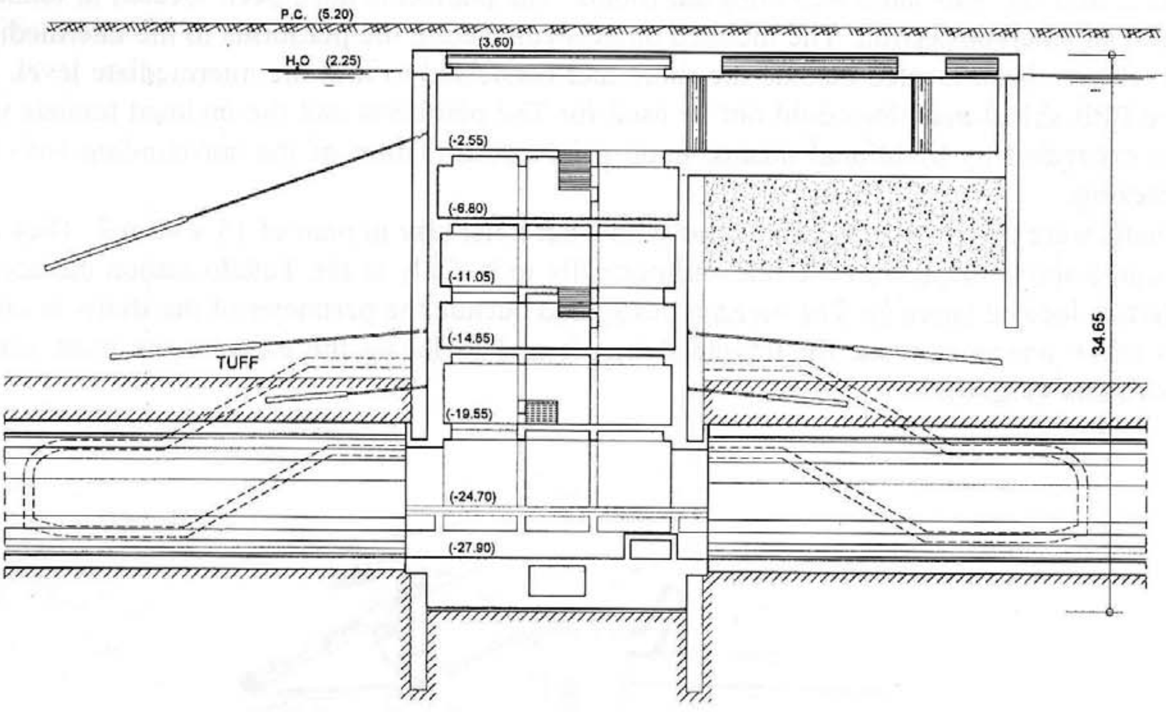

Fig. 4 - University Station; longitudinal section

- occurrence of heavy masonry buildings with shallow foundations in the immediate vicinity of the perimeter of the stations;
- heavy restraints to the area available at the surface because of traffic requirements.

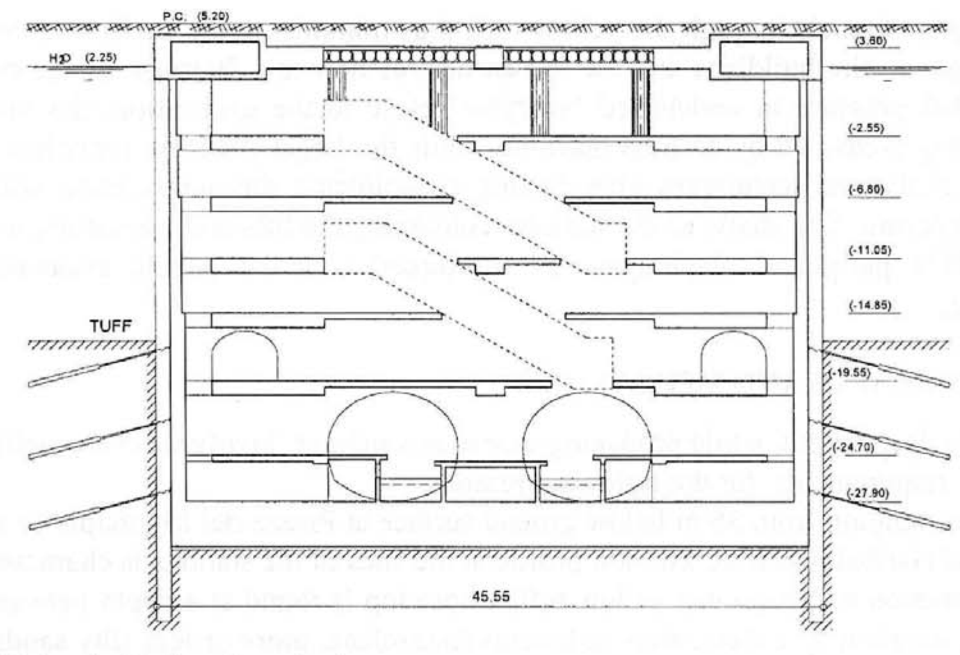

Fig. 5 University Station– Cross Section

These circumstances heavily affected the design choices. First of all, the size of the access shafts was kept as small as possible and strictly sufficient to contain the escalators and stairs and the associated technological rooms. The platforms have been located in tunnels, with an enlarged section. The inclined tunnels connecting the platforms to the intermediate level have been located outside the shaft, and connected to it at the intermediate level. As the EPB shield-machine could not be used for The platforms and the inclined tunnels will be excavated by traditional means, upon prior consolidation of the surrounding soils by freezing.

Shafts were given a rectangular shape with a net inner size in plan of 15 x 45 m2. They are located above the axis of the line and normally to it. Only at the Toledo station the access shaft is located laterally. The mezzanines spread outside the perimeter of the shafts in order to allow adequate room for travelers' transit and to locate the exits in the most suited positions (Fig. 6).

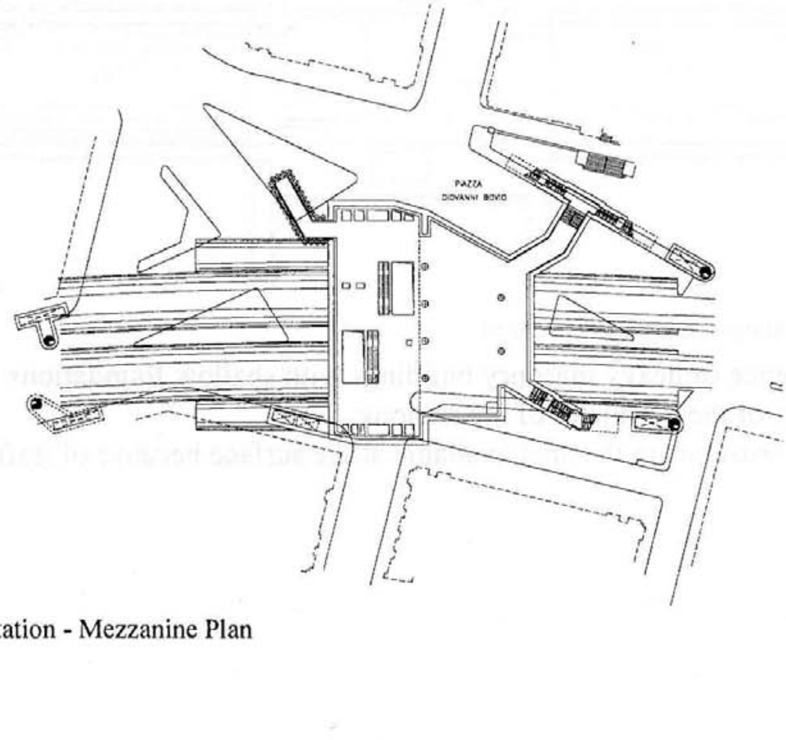

Fig. 6 - University Station - Mezzanine Plan

3.1. Constructive aspects

The main problem of the shafts has been the choice of the retaining structures and the associated construction methods. At the perimeter of the shaft reinforced concrete diaphragm walls have been adopted, excavated in panels using bentonite slurry. The panels have been selected because of the more efficient section and the smaller number of joints, compared to tangent or secant piles. The final impermeabilisation system uses a reinforced concrete counter wall, lined with a double PVC membrane suitably compartmented in order to localize possible leaks and speed up the ensuing repair works.
Since the usual clamshell buckets are not suitable to dig through the tuff, Hydrofraise or Trenchcutter rigs will be employed, capable of cutting through both the soft rock and the overlying soils, wit reverse circulation of the slurry for cuttings removal.
Different solutions have been adopted for the temporary support of the panels during the excavation steps, according to the specific features of the different stations. Where the tuff formation is relatively shallow and the distance of the buildings from the well perimeter is greater (as at the Municipio station), prestressed ground anchors have been adopted, with lengths and inclinations such as to allow, as much as possible, the anchorage to tuff (Fig. 7). Only at the upper levels, where the earth pressure is relatively small, anchorage within the cohesionless soils has been allowed.

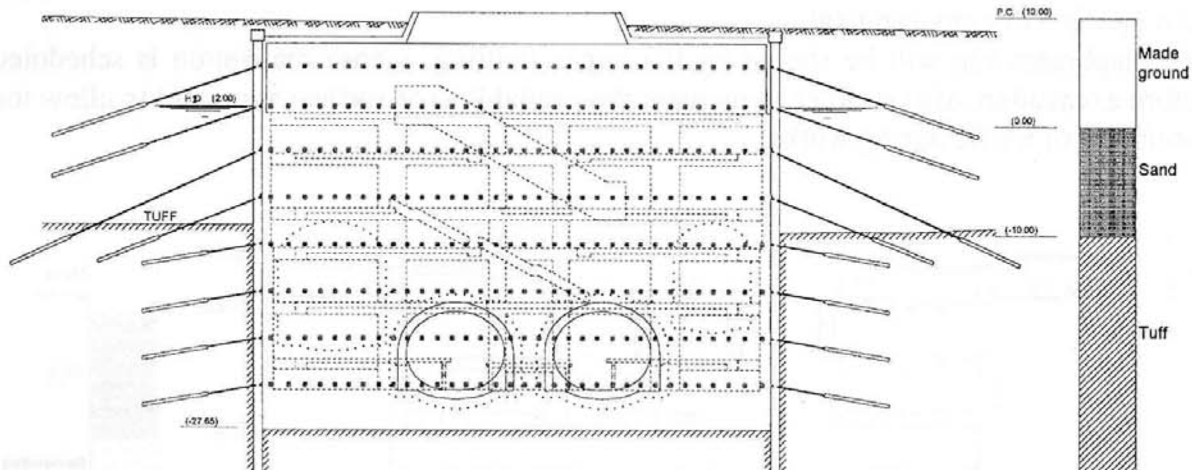

Fig. 7 - Municipio Station; shaft bottom excavation stage

In the other stations, the depth of tuff, the poor characteristics of the upper layers and the proximity of buildings have suggested the adoption of a mixed system. At the upper levels the contrast to the diaphragm is provided by floorings, possibly integrated by provisional metal struts. They will be cast on site according to the classic "top-down" method and directly anchored to the diaphragms by means of suitably prepared pockets. At the lower levels the supporting action is provided by prestressed ground anchors, anchored to the tuff (Fig. 8).
In both cases, once the excavation bottom has been reached, the bottom raft will be cast and the activities of construction of the platform tunnel started. The freezing holes for the prior consolidation of the soil around the platform tunnels will be drilled from inside the

shaft . Because of the complex activities that will be carried out at the bottom, the lower part of the shaft has been kept free from any provisional work during the construction. Once the tunnels have been completed, the structures of the station (counterwalls, central baffles, staircases, floors not executed during the excavations, etc.) will be executed from the bottom up. A structural organism will thus be realized, resisting not only vertical loads, but also the horizontal thrusts by the soil and the water. In the long term, the ground anchors are not relied upon.
The geometry of floorings has been controlled by functional requirements. The system of escalators and stairs, as well as lifts, ventilation ducts, installations, etc. involved the necessity of wide openings, the biggest ones being near the outer shaft walls. Furthermore, when floors are realized with the top-down technique, the openings shall be even larger to ensure the vertical handling of the materials and, especially, the huge equipments necessary for the construction of platform tunnels. In such cases, once the platform tunnels have been completed, the floors will be brought back to their final form by means on completion castings (Fig. 9).
For these reasons and also to control the stresses in the diaphragms, intermediate provisional frameworks have been added to the project.
Diaphragm walls will be used also for the mezzanine extension zones, as the water table level is generally very shallow. In this case, however, the diaphragms will be realized by clamshell buckets. The soil below the floor of the mezzanine will be consolidated and made watertight by means of compenetrated jet-grouting columns, in order to permit work activities in a dry environment.
The diaphragm top will be shored by the upper flooring, whose realization is scheduled before excavation, also in order to increase the availability of surface areas and to allow the continuity of traffic during works.

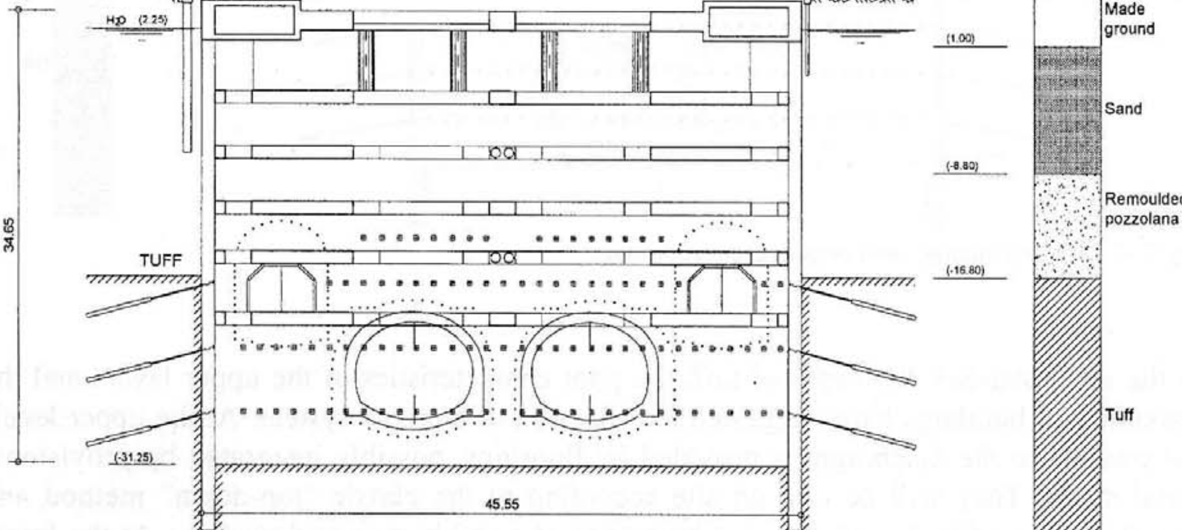

Fig. 8 - University Station; shaft bottom excavation stage

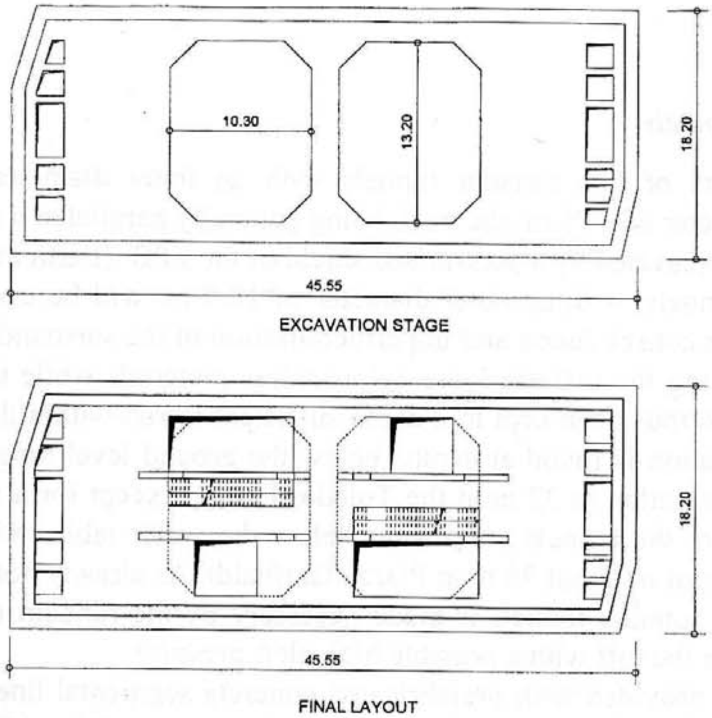

Fig. 9 - University Station; flooring

3.2. Design aspects

For the analysis and design of the different structural elements, the finite element method has been generally used.
The calculation of the diaphragms has been carried out by taking into account all the steps, of excavation and construction of the internal structures. Special attention has been paid to the effects of the deactivation of ground anchors for the construction of platform tunnels. All the soils have been characterized by an elastic-perfectly plastic Mohr-Coulomb behavior. Interface elements have been introduced between the soil and the diaphragm.
The regime of axial stresses in the diaphragm over the openings for the construction of the platform tunnels was analysed in detail, again by finite elements. The wall was modeled as a series of vertical panels connected only at the top by a reinforced concrete beam. The lateral interfaces between the panels have been given an elastic-plastic behavior .
A three dimensional structural analysis of the internal structures has been carried out, both during the construction stages and in the final configuration. Special attention was paid to the stresses near the large lateral openings; sometimes the stress state was so severe to impose the adoption of subsidiary prestressed ground anchors.
In order to optimize the anchors design and the construction techniques, a number of test anchors have been installed and load tested up to pull out. The test site was in the vicinity of the University station, and included anchors in the tuff and in the cohesionless overlying soils. The test program lead to very satisfactory results, validating the design assumptions.
The resistance to uplift of the station structures has been checked, ensuring safety factors ranging from 1.2 to 1.3. These values have been calculated without taking into account any contribution of the soil-wall friction, and are therefore largely conservative.

4. TUNNELS

4.1. Running tunnels

The line consists of two circular tunnels with an inner diameter of 5.85 m and an excavation diameter of 6.75 m, the track being generally parallel at a distance of 11 m. The tunnels will be excavated by a pressurised shield of the EPB (Earth Pressure Balance) type. The platform tunnels, with an outer diameter of 10.9 m, will be excavated by traditional means after prior consolidation and impermebilisation of the surrounding soil by freezing.

The soils overlying the tuff are loose cohesionless materials while the tuff itself is a soft rock; the line has thus been kept to a depth sufficient to run within the tuff formation. The top of this formation is found at depths below the ground level ranging from 15 m at the site of the Dante station to 32 m at the Toledo station. Except for a short stretch just after the Dante station, the tunnels are always below the water table, with a maximum water head above the roof of about 30 m at Piazza Garibaldi. As already noted, the use of an EPB machine for the running tunnels is made necessary by the random occurrence of vertical discontinuities in the tuff with a possible high cleft pressure.

The tunnels are provided with prefabricated concrete segmental liner, installed inside the shield and sealed against the soil by extruded concrete (Fig. 10). The liner is made watertight by gaskets, housed along the whole perimeter of the liner segments, tightened with special bolts. In the stretches above the water table, as the one near the Dante station, in order to increase the production the shield can be easily adapted to an open front advancement.

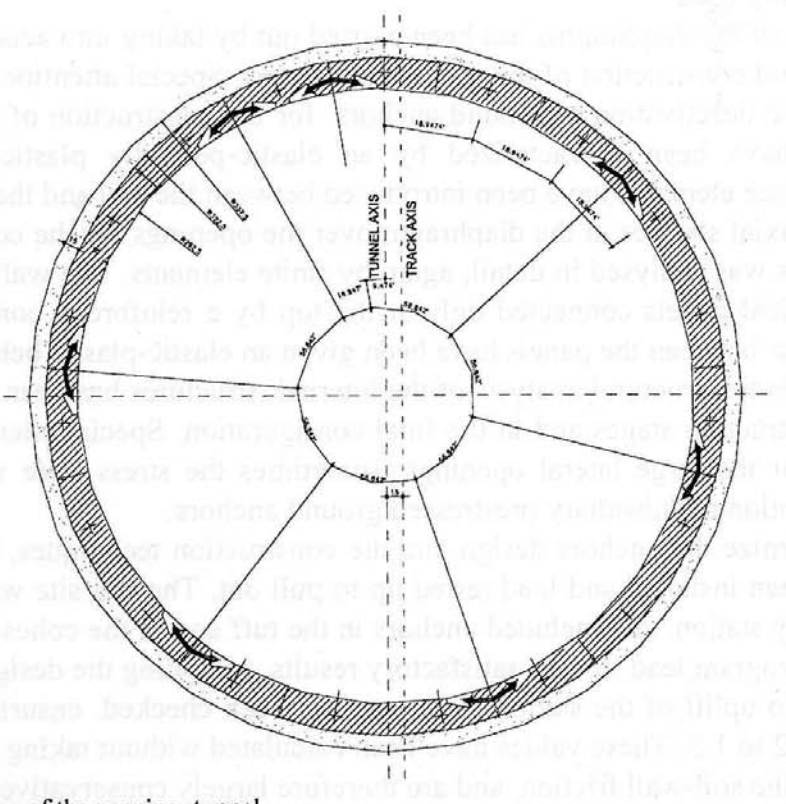

Fig. 10 - Cross section of the running tunnel

4.2. Platform tunnels

The roof of the platform and inclined tunnels is generally located within the materials at the transition between the tuff and the overlying soils, or in the cohesionless soils. Given the poor geotechnical characteristics of these materials and the high water heads, consolidation and impermeabilisation by freezing will be carried out prior to the excavation. Freezing will be carried out through the insertion of steel tubes provided with freezing probes into holes drilled from the station shafts (so called "indirect" method) (Fig. 12).

Brine will be used as a refrigerating fluid. In fact, it allows the formation of the frozen soil structure in a time (about 4 weeks) longer than that obtainable with the utilisation of liquid nitrogen; but once the steady temperature has been reached in the soil, the maintenance stage is relatively less expensive.

The maintenance is controlled by means of special thermometric probes located inside the soil to be treated in a peripheral position. A frozen thickness of about 2 m with a temperature of about – 20°C is capable of ensuring the stability of the excavation and preventing the water inflow.

The freezing technique cannot be applied to the bottom plug of the tunnels, because of the interference of the tubes with the excavation. For this reason high pressure cement and chemicals grouting will be employed for the plugs (Fig. 11).

The excavation will be carried out on the full section by means of a point cutter; the installation of the sprayed concrete pre-liner will follow immediately. The impermeabilisation and the casting of the final reinforced concrete liner will be carried out as soon as possible, before shutting the freezing plant.

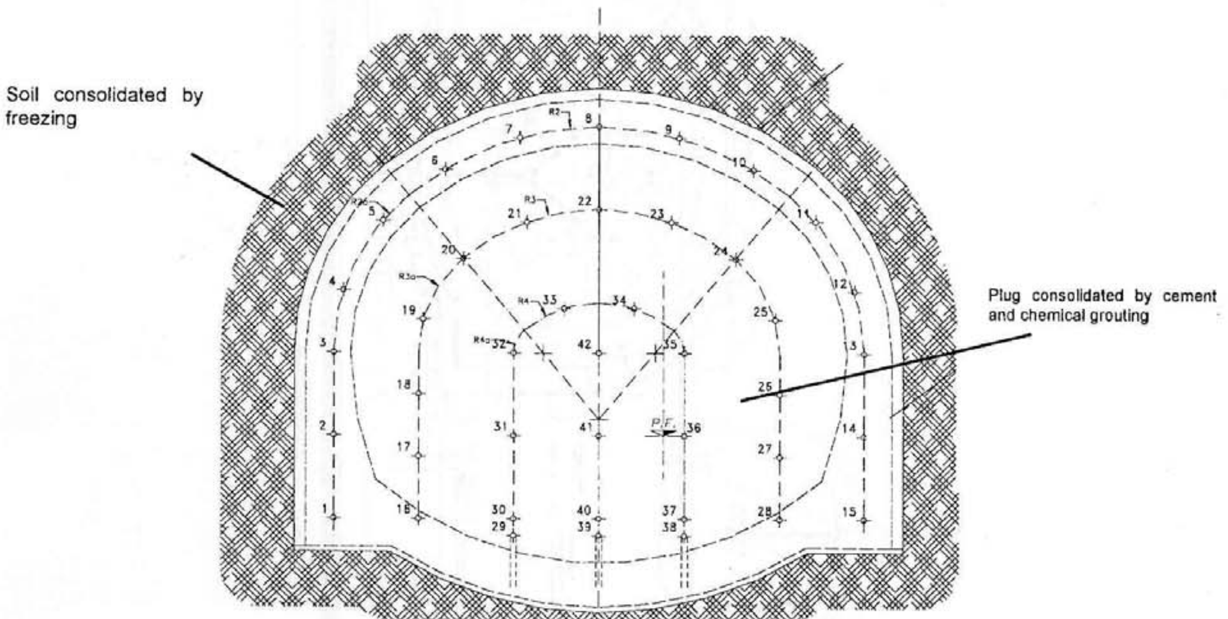

Fig. 11 - University Station; consolidation and plugging of the platform tunnels

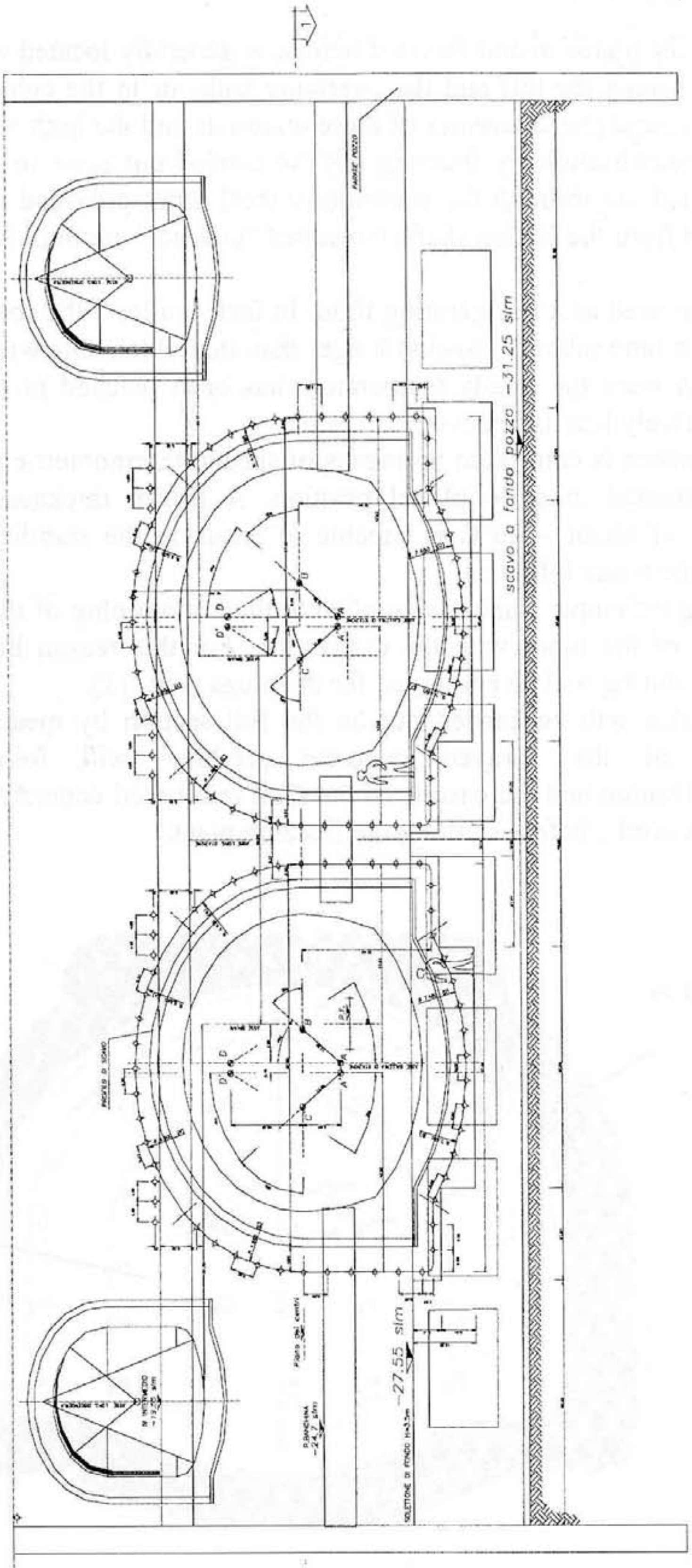

Fig. 12 - University Station; prospect of the excavation front of the platform and inclined tunnels

4.3. Design problem

The stress analysis of the tunnels and surrounding soil has been carried out by the code FLAC, using finite differences in conditions of plane strain. The progressive transition from the fully three-dimensional stress state at the excavation front to the plane strain state far from the front has been simulated with a gradual reduction of the "excavation forces" (radial outward forces applied to the nodes of the excavation profile), according to the suggestions by Panet.

The analysis has been carried out in subsequent calculation stages, to model the different construction steps of the tunnel, coupling them to the progressive reduction of the excavation forces and the different load conditions. In particular, the interactions between the two parallel lines have been taken into account both for the running tunnels and the platform tunnels.