The Cellular Arch Method: Technical Solution for the Construction of the Milan Railway's Venezia Station

P. Lunardi

Abstract—The author describes the Milan Railway Link, a line of the Lombardy, Italy, regional railway transportation system. The link will create a railway corridor between the Milan North-West and South-East lines. The Milan Railway Link will be totally underground. The line's Venezia Station will form the largest underground project in the regional railway transport network. The author describes the phases of the "Cellular Arch Method" used to excavate the rail tunnel.

Aim of the Project

The Milan Railway Link is a line of "Ferrovie dello Stato" (F.S.), which, together with "Ferrovie Nord Milano" (F.N.M.), operates a railway network in the Lombardy region of Italy that is intended to contribute to the creation of a unified system of regional railway transportation. It is also connected to Milan's main subway and surface transportation lines. The railway link connects the Certosa F.S. and Bovisa F.N.M. railway stations to Porta Garibaldi and to Porta Vittoria Stations, thus creating a railway link between the Milan North-West and South-East lines. The result is an urban and metropolitan transport system that shares the Porta Garibaldi-Porta Vittoria track (see Fig. 1).

The new railway link will be developed totally underground, with both lines and stations built mainly by direct subsurface excavation. This link will largely contribute to the reduction of the surface traffic caused both by the commuter traffic and the city's technological concentration, and therefore will help preserve the good quality of life and the attractiveness of the Lombard metropolitan area.

The most important part of the link will be the Venezia Station, which also

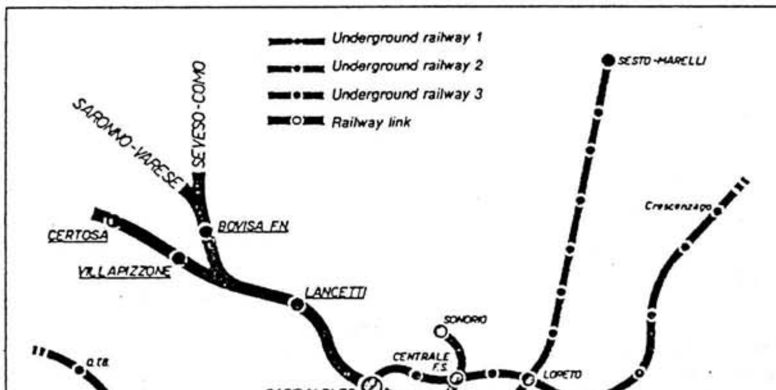

Figure 1. Plan of the Milan underground railway transport network.

Present address: Pietro Lunardi, Rocksoil S.p.A., Piazza San Marco, 1, I-20121 Milan, Italy. Dr. Lunardi is also a professor at the University of Parma, Italy.

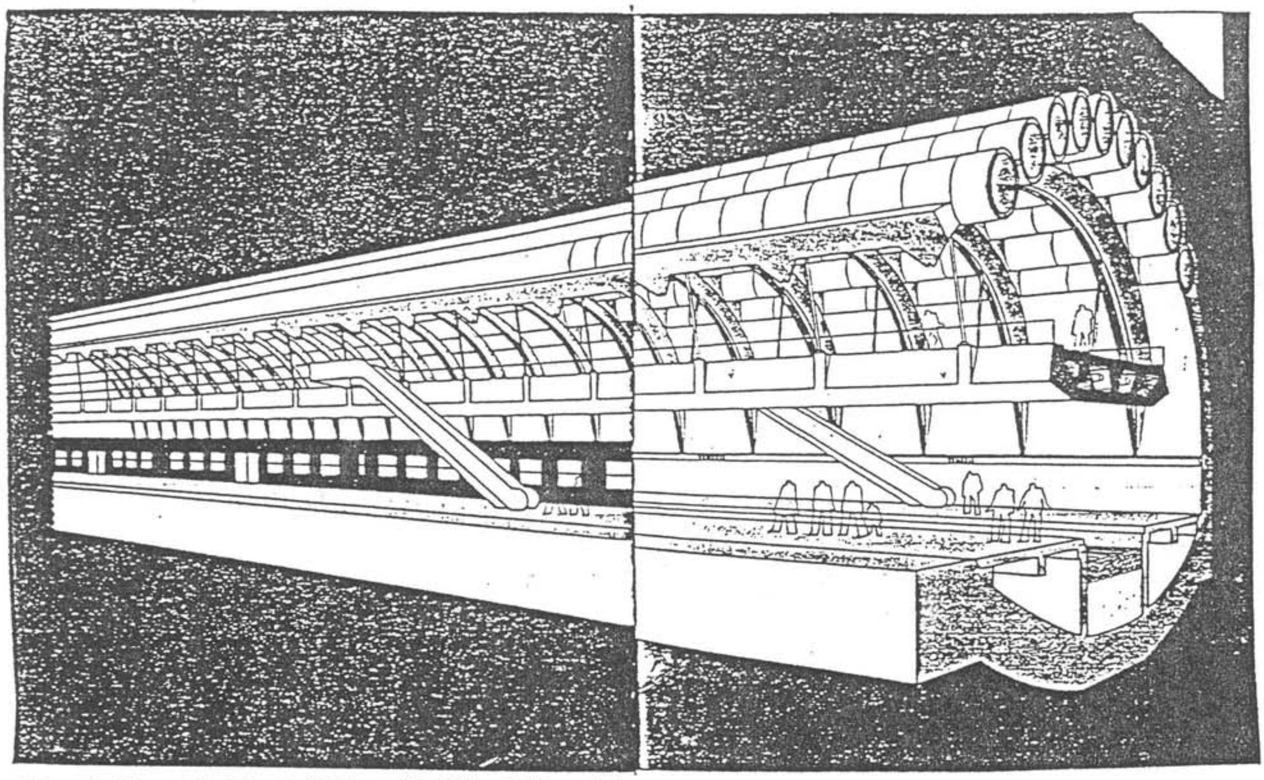

Figure 2. View of the Venezia Station of the Milan Railway link.

comprises the largest underground project in the entire regional railway transport network.

The Three Tunnel Sections

As shown in the plan and longitudinal views in Figures 2 and 3, respectively, the portion of the tunnel described in this article consists of three different tunnel sections having inside widths of 8.80 m, 16.40 m, and 22.80 m, respectively.

A combination of factors—the large dimensions of the station tunnel section (which has an external width of 28.80 m), the overburden thickness of only 4–5 meters, the alluvial nature of the soil, the existence of ground water, and the restriction of not reducing the surface traffic—resulted in a need to use new building technologies, particularly the "Cellular Arch Method."

This method, specifically conceived by the designer engineer and worked out in detail in cooperation with the project engineers in charge of the Metropolitana Milanese S.p.A., as well as engineers of the Giemme joint venture and Rocksoil S.r.l. in Milan, permits construction of a structure capable of supporting the soil before the actual excavation is begun. As a result, excavation operations are safer and, at the same time, it is possible to control the soil behavior and its deformations—both of which are essential requirements for subsurface construction an urban area.

Determining the Appropriate Building Method

In Milan, large tunnel construction usually requires heading-bench, side draft or multiple-drift methods. Generally the work includes a shotcrete pre-lining, reinforced with steel ribs and final lining with reinforce concrete.

Initially, the construction of the Venezia Station was planned to be carried out according to the multiple-drift method, trying to fit it in with the extraordinary dimensions of the project. However, the Finite Element Method simulation of the excavation showed the impossibility of obtaining, using conventional techniques, both a sufficient guarantee tunnel stability (due to soil failure during excavation of the roof), and adequate limitation of the soil settlement (the resulting settlement was estimated to be on the order of 10^{-2} m). The two main factors contributing to this conclusion were:

1. The small overburden, which did not allow homogeneous consolidation of the soil at the crown; and
2. The tunnel pre-lining structure, which was extremely flexible.

It was not easy to resist using proven and reliable construction methods. However, after having examined several possibilities and having made further investigations and calculations, all those involved in the project concluded that another construction method had to be used. For this reason the "Cellular Arch Method" was developed. The FEM analyses of the various excavation stages of the station executed by this method gave satisfactory results with regard to the surface deformations, the stresses in soil, and the stresses in the structure. Consequently, the Cellular Arch Method was selected for the tunnel construction.

Construction Stages of the "Cellular Arch Method"

The "Cellular Arch Method" applied to the excavation of the 22.80-m-wide tunnel consists of a series of "side by side microtunnels," connected to each other with reinforced concrete arches, in order to form the vault. The microtunnels, formed by reinforced concrete pipe segments 2.10 m in diameter, are driven by pipe-jacking.

Construction of the arch involves the following phases (see Fig. 4):

1. Grouting, from a central service drift, of the ground around the perimeter of the side drifts.
2. Heading-bench excavation of the side drifts and completion of grouting around the perimeter of the station tunnel, followed by the pouring of concrete to form the posts.
3. Jacking, from a thrust pit, of 10 microtunnels, consisting of reinforced concrete pipe segments 2.10 m in diameter.

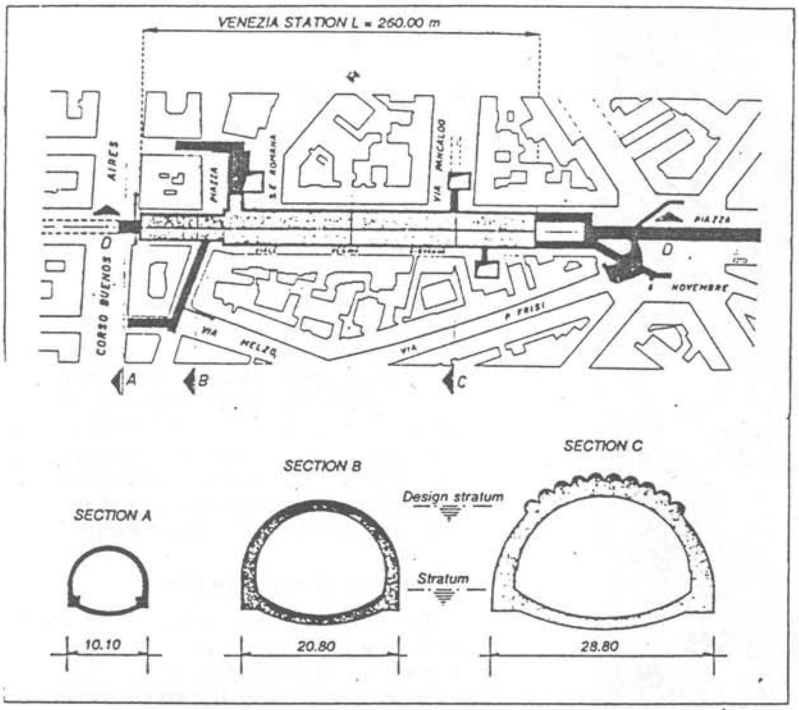

Figure 3. The tunnel sections and their locations.

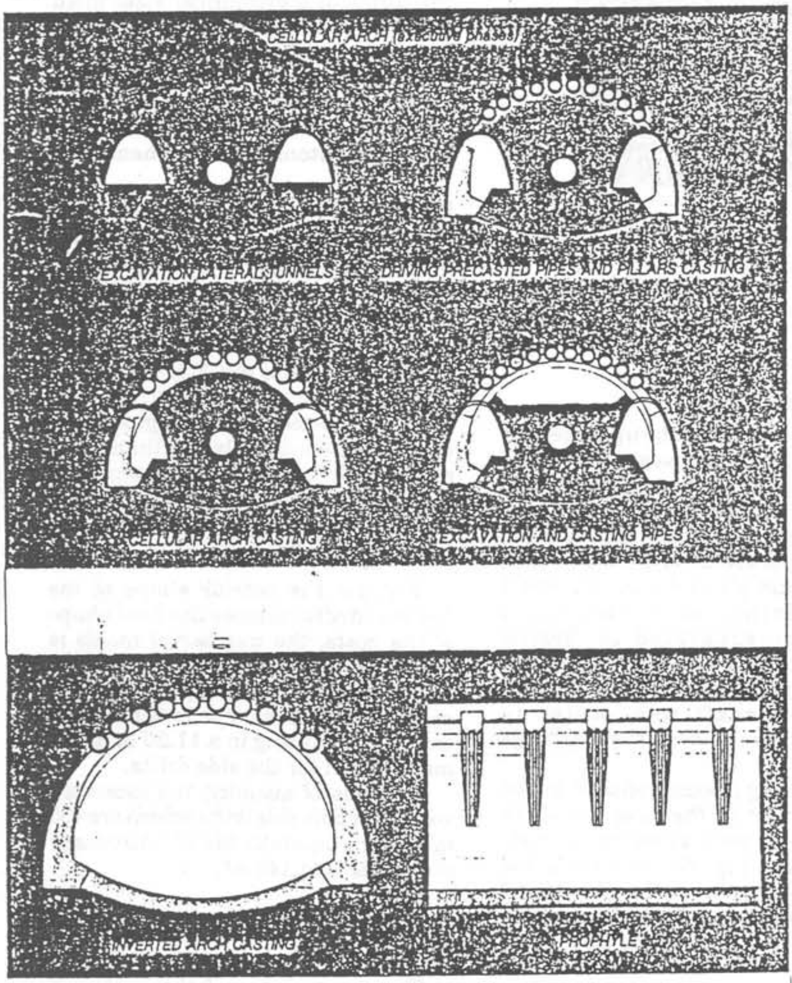

Figure 4. Construction phases of the "Cellular Arch Method".

4. Excavation of tunnels connecting the side drifts to the ten microtunnels. These tunnels will form the molds within which cellular arches will be cast.
5. The placing of steel reinforcement and the pouring of concrete to form the arches and microtunnels.
6. Excavation of the tunnel in several stages and simultaneous finishing of the upper section.
7. Excavation and casting by sections of the invert.

It must be pointed out that the ground grouting in the microtunnels zone aims to avoid decompression and instability of the ground during pipe jacking and the excavation of the connecting tunnels. It is the non-cohesive nature of the soil beneath Milan and the lack of overburden that demand grouting; however, this procedure is not always necessary and therefore does not constitute a rule for this method.

Testing of the Cellular Arch Method

Before applying the Cellular Arch Method, complex testing was carried out in order to:

1. Ascertain the need to grout the area for pipe-jacking purposes.
2. Check the possibility of jacking the microtunnels into consolidated ground, from a thrust pit.
3. Simulate pipe demolition, connecting tunnels excavation, the steel reinforcing of cellular arches, and concrete pouring operations.
4. Define the characteristics of the concrete grout mix, and the grouting intensity for the progression of microtunnels.
5. Acquire information about and improve the knowledge of the mechanical characteristics of natural and grouted soils.
6. Monitor ground deformation and surface displacement during various stages of the project.

One test involved driving three reinforced concrete pipes into the ground by jacking from a thrust pit, which was constructed by taking advantage of a discharge tunnel in Pancaldo Street. The three test microtunnels, each 31 m long, were covered over their length with 16 circular steel reinforced concrete segments. Testing was completed by simulation of pipe connection by means of two arches (see Fig. 5).

The cellular arch tests were performed in Pancaldo Street along the access to the Venezia Station. This site was chosen because of geological soil features similar to those at the new station.

Grouting

In non-cohesive soils, grouting generally precedes direct underground

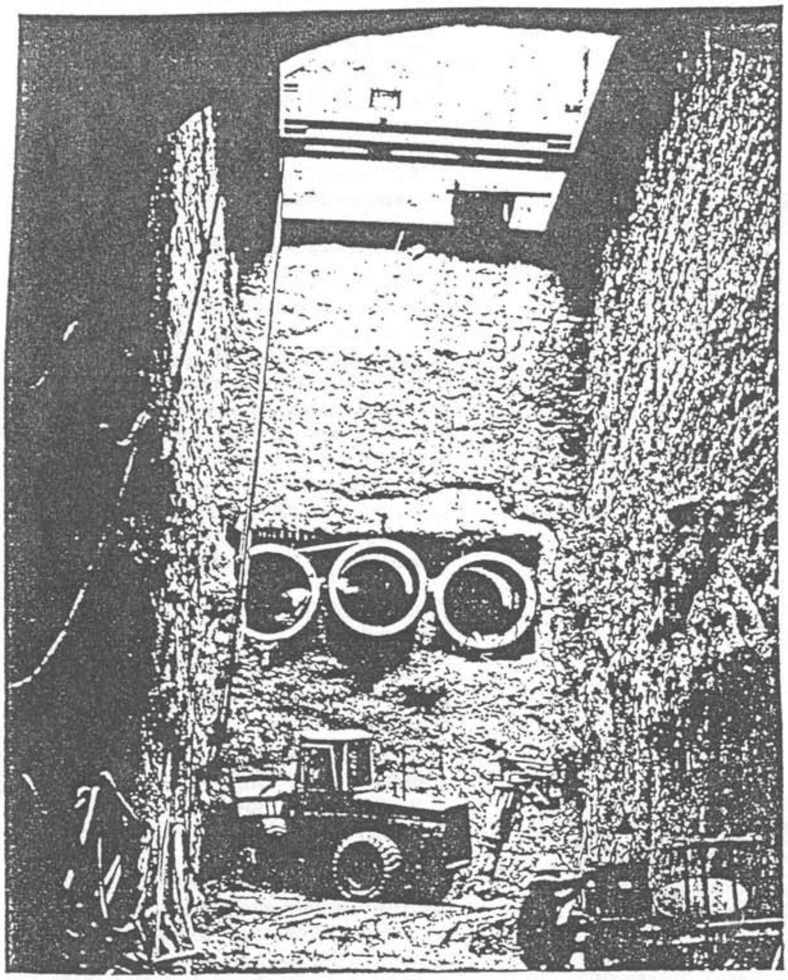

Figure 5. Test thrust pit: results of test pipe-jacking.

excavation. Because non-cohesive soil is very common in Milan, this technique has been generally used in subway tunnel construction. Grouting has been even more necessary in the railway link because of its large dimensions. Soil grouting has been carried out by the Rodio-Icos joint venture in several stages; concrete grout sometimes has been integrated with chemical admixtures. The consolidation stages, as illustrated in Figure 6, are:

Stage 1: Consolidation of the post area from the central service drift.

Stage 2: Consolidation of the microtunnels area, executed from the central service drift.

A new concrete grout called "Mistrà-S" was developed by Rodio during the testing of the Cellular Arch Method. This grout guarantees homogeneous consolidation, which facilitates pipe jacking.

Stage 3: Consolidation from the central drift and from the side tunnels of a 6.5-m-thick layer, under the ground water level corresponding to the posts. Boring and injecting operations are performed by modern, highly reliable automatic control equipment installed on site.

The Thrust Pit

The pipes forming the upper section are jacked from a thrust pit, situated so as to avoid traffic flow problems caused by moving equipment and pipes (see Fig. 7). It was therefore impossible to construct pits at each end of the station—i.e., a thrust pit and a pit for shield recovery. Instead, one thrust pit, 10 x 20 m, was excavated in Regina Giovanna Avenue. Jet grouting was used to support the excavation walls. The access shaft was located in Pancaldo Street, above the discharge tunnel.

The jacking is accomplished in two steps, the first in the direction of 8th Novembre Square, covering distance of 50 m (see Fig. 8). Inverting the jacking tools, pipes are then driven 160 m towards Buenos Aires Avenue. In order to avoid any traffic flow problems, a steel frame tramway bridge and two steel-frame roadway bridges were built and laid before the start of excavation. The thrust pit is equipped to handle shields, as well as to feed and move the pipes.

Excavation Equipment

The excavation equipment consists of an 8-m-long steel shield split into three sections. The first section is 1.30 m long and movable; it is provided with a cutting edge that allows the operator to control vertical and horizontal movements. The shield has a computer-governed front drilling head about 3 cm smaller than the outside diameter of the shield, in order to limit cavities outside the pipes. Excavated material is transported on a conveyor belt to muck cars on a rail, to be dumped through a shaft into the lower tunnel. The thrust equipment includes two hydraulic jacks, thrust distributing structures and a 60-MPa hydraulic pump.

Reinforced Concrete Pipes

The reinforced concrete pipes have a 2.10-m outer diameter, a 1.80m inner diameter, and are 2.00 m long. They are manufactured by the radial compression method, in which concrete is squeezed and mechanically rolled, by means of a rotating spindle, against the inside of a cylindrical steel mold. This method ensures both a high degree of compactness in the material and a well-finished inside surface. The pipes are reinforced with heavy longitudinal and transverse steel reinforcement, and placed by automated equipment.

Excavation of the Side Drift

Taking into consideration the large dimensions of the cavity, the surface restrictions and the construction method, it has been necessary to build side drifts, at each side of the tunnels. These side drafts are 7 m high, 5 m wide, and shaped to match the future tunnel cross-section (see Fig. 9). The side drifts, which are larger than many road or rail tunnels, are supported by steel ribs and shotcrete lining.

Casting the Posts

Because the outside shape of the two side drifts matches the final shape of the posts, the number of molds is reduced, resulting in speedy construction. Before the concrete pouring of the posts, it is necessary to lower the excavation, resulting in a 11.20 m maximum height for the side drifts.

In terms of quantity, the excavated volume for both side drifts (which are 435 m long) amounts to 25,230 m^3. The volume of concrete is 11,140 m^3.

Pipe Cutting and Arch Construction

The construction of the arches is accomplished from within the

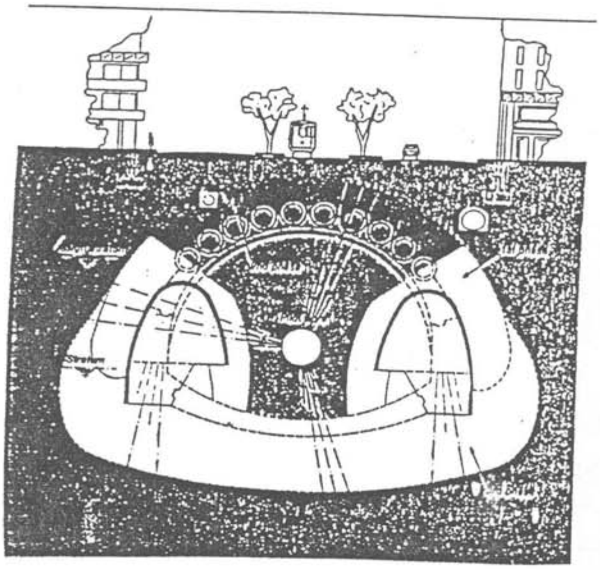

Figure 6. Grouting phases for soil improvement.

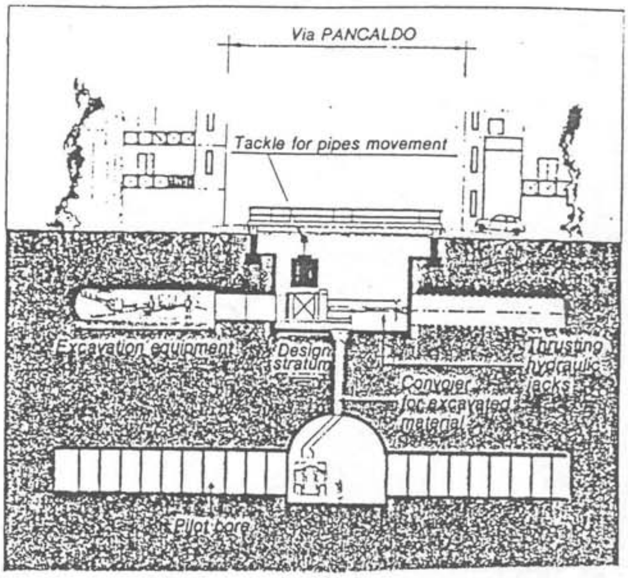

Figure 7. Longitudinal section of the thrust pit used for pipe jacking.

microtunnels. For this purpose, the first step is to cut the lower half of the pipes, using a special disk cutter. The second step is the 1x1 m excavation for the housing of the arch, outside the underside of the pipes. The excavation starts from the lower outer pipes and proceeds towards the top, dumping the excavated material into the side drifts.

Casting of the Arches

The molds and reinforcing steel are supplied by means of the pipes or the side drifts; thus the arch moulds and steel reinforcements are assembled and the pipes are connected from arch to arch.

Finally, the concrete for the arch and the ten relevant pipe segments are poured. The triangular section of the upper section of the arches has a minor visual obstruction than other equivalent sections, thus conferring a slimmer appearance to the structure.

Future Work Stages

Once grouting has been completed around the perimeter of the station, the concrete posts poured and the arches completed, it will be necessary to excavate the station by stages and to finish the exposed part of the upper section.

The invert will be excavated and poured by sections, thus completing the entire structure. The inside finishing includes the construction of a mezzanine formed by a slab suspended from the vault by means of tension members. The suspension of the mezzanine from the arches of the upper section improves the visibility and the access to trains at the platform level, which is free from supporting structures. It neither causes visible impediment nor obstructs the traffic on the mezzanine floor (see Fig. 10).

Checks and Measurements

Because of the large dimensions of the cavity and of surface boundary values and surface conditions, the construction of this station requires a solution to complicated construction problems. This makes necessary the installation of instrumentation in order to evaluate:

- Heave and settlement of the surface during works.
- Deformation at the internal wall of the cavity and in the ground adjacent to existing buildings in-

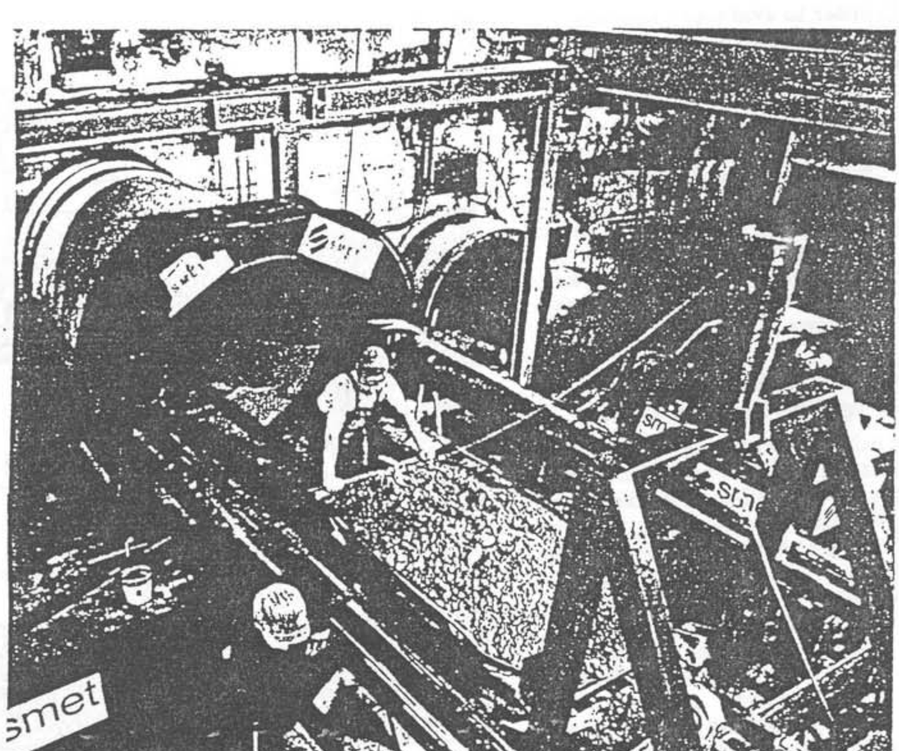

Figure 8. Pipe jacking from the thrust pit.