Design and construction of a station on the Rome Metro

Professor Dr Eng. Pietro Lunardi, Consulting Engineer, Milan, and Dr Eng. Alessandro Focaracci, Rocksoil, Milan, discuss the successful use of fibreglass structures combined with mechanical precutting on Baldo degli Ubaldi Station.

Baldo degli Ubaldi Station on the Rome Metro is one of five new stations currently under construction as part of the lengthening of the Ottaviano to Battistini Line A. This will complete the connection of suburbs in the west of the city with the city centre and the Vatican City (see location map, Fig 1, below). It is located in the centre of the city at a depth of approximately 25m next to the major road, the Via Baldo degli Ubaldi, to Fiumicino Airport.

Unusual design and construction methods, which constitute the main theme of this report, were adopted because of the large dimensions of the station (a span of 21.5m and a height of 16m), the presence of multi-storey buildings on the surface with foundations as close as 2m from the extrados of the tunnel crown, the type of ground to be excavated (Pliocene clays under the water table) and the contractual obligation to avoid interruption to traffic flows along Via Baldo degli Ubaldi.

Geological and geotechnical conditions

The ground where the station is being built can be divided into two main types:

- ground belonging to the base formation, consisting of blue Pliocene clays with sandy layers measurable in centimetres and decimetres
- recent ground belonging to the upper band consisting of slightly compacted silty sands and Paleoalveo soft sandy silts in the vicinity of the shaft on the Valle Aurelia side

A comprehensive geological survey was carried out as part of the Survey Phase in 1987 to 1994, dwelling in particular on the Paleoalveo bed near the Valle Aurelia Shaft, which touches the springline of the extrados of the crown (Fig 2, p28).

Piezometer readings showed the presence of a water table with a free surface not influenced by meteorological precipitation at a depth of 10-12m below surface. Furthermore, a water table under a pressure of approximately 2 bar was found inside the sandy levels of the Pliocene formation, which was probably contained within the sandy layers. The various upper levels and the Pliocene clays, the only formation to be affected directly by station excavation, were carefully investigated. The latter were found to consist of overconsolidated stiff clayey silts. Laboratory tests conducted on borehole samples provided the geomechanical properties given in Table I (below).

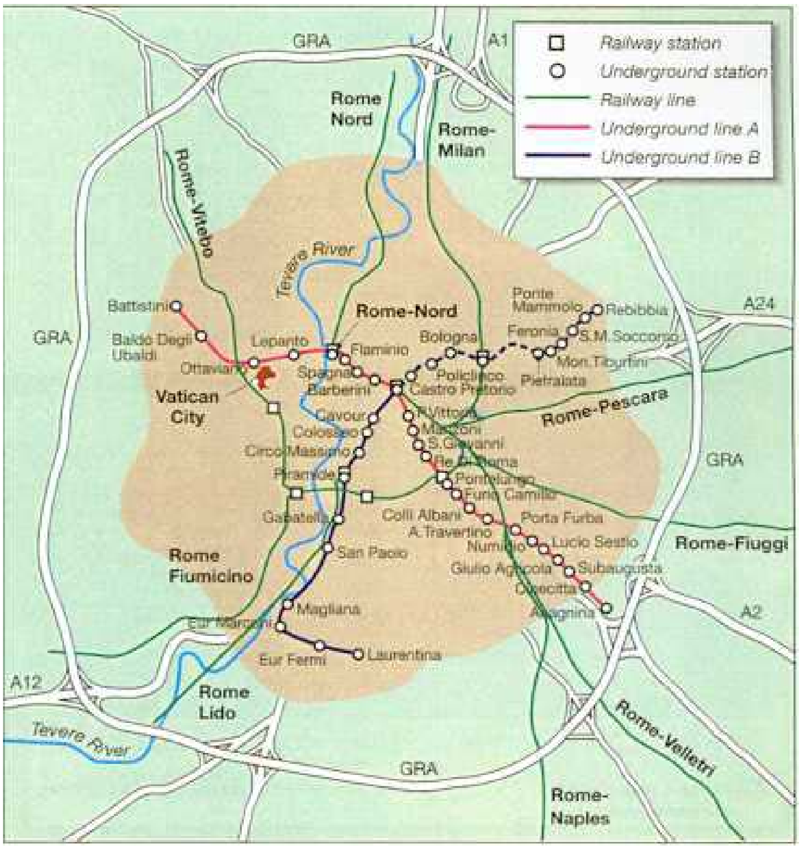
Table1. Geomechanical properties of borehole samples

Unit weight	$\gamma = 2.0\ t/m^3$
Angle of friction	$\varphi = 24° \div 33°$
CD cohesion	$c' = 0.015 \div 0.041 MPa$
UU cohesion	$c_u = 0.20 \div 0.57 MPa$
Elastic modulus	$E = 100 \div 250 MPa$
Permeability	$K = 10^{-6} cm/s$

Design aspects

Design of the Baldo degli Ubaldi station tunnel was performed according to the principles of the Analysis of Controlled Deformation in Rocks and Soils (ADECO-RS) approach, which divides the actual design process into two phases as follows:

- the Diagnosis Phase. Here, the design engineer uses the information gathered during the Survey Phase to make reliable predictions, employing theoretical tools, concerning the deformation response of the ground to the excavation procedure until he is able to divide the tunnel into sections, each having a uniform deformation behaviour in terms of the three basic categories of deformation behaviour:



Category A: face stable
Category B: face stable in the short term
Category C: face unstable

■ the Therapy Phase. After the Diagnosis Phase, the design engineer decides the type of action to be exerted (preconfinement or simple confinement) and the works required in terms of the three behaviour categories A, B and C to obtain complete stabilisation of the tunnel. He perfects the design in terms of systems, schedules and excavation steps, designing typical longitudinal and transverse sections which are then analysed using mathematical tools.

In this case, the studies carried out in the diagnosis phase and, above all, the interpretation of tri-axial cell extrusion test results, showed that the tunnel fell into Category B (face stable in the short term), corresponding to situations in which, after hypothetical tunnel advance and in the absence of intervention to stabilise the tunnel, the stress state at the face and around the tunnel is in the elastic range and greater than the tunnel's ability to resist the stresses; these however do not develop immediately into the failure range.

In this situation the 'arch effect' is not created immediately around the cavity but at a distance from it that depends on the thickness of the band of ground in which plasticisation occurs.

Deformation which develops in the elastic/plastic range is deferred and measurable in decimetres. At normal advance rates the face is stable in the short term and its stability increases or decreases with increases or decreases in the speed of tunnel advance, independently of the width of the face.

Deformation of the advance core in the form of extrusion does not affect the stability of the tunnel because the ground is still able to mobilise sufficient residual strength. Instability occurs in the form of widespread spalling at the face and around the cavity. The presence of water can encourage the extension of plasticisation of the ground and, therefore, of instability phenomena if it is not adequately controlled.

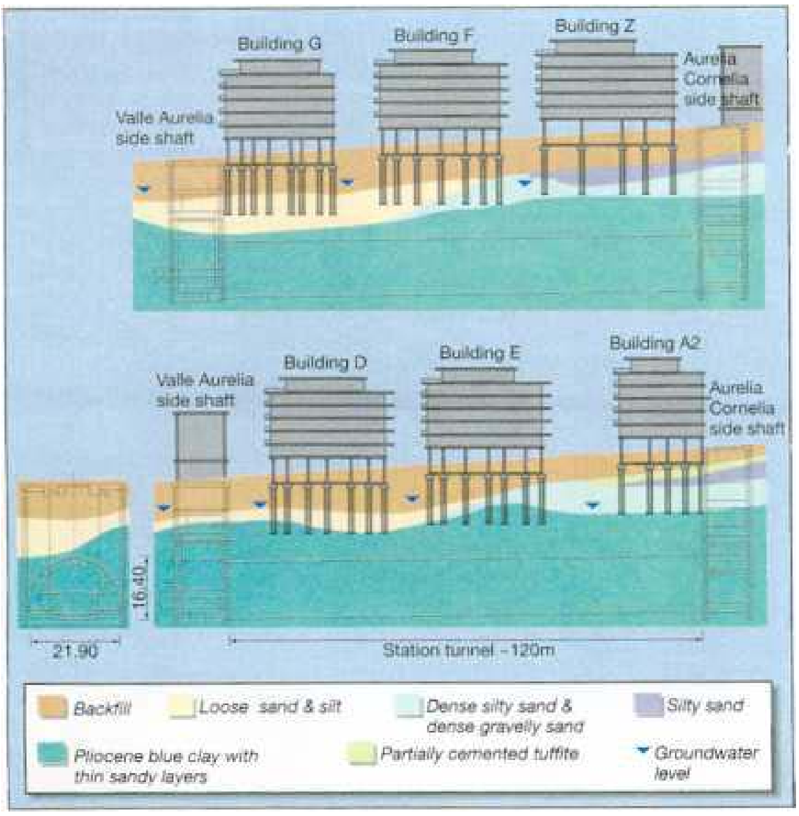


Fig 2. Reconstruction of the stratigraphy, especially of the Paleoalveo bed by the Valle Aurelia Shaft

It was immediately clear in the Therapy Phase that, given these forecasts, keeping deformation within low minimum values well below those normally admissible for tunnels excavated in cohesive soils would be an essential requirement, since the tunnel was to pass close to residential buildings. The adoption of traditional construction methods based on lining the tunnel with steel ribs and shotcrete would not have achieved this aim even if the face was split into separate headings.

Methods of creating preconfinement of the core at the face and of the cavity were therefore studied. By acting ahead of the face it would be possible to keep the advance core in the elastic range and consequently guarantee adequate control of deformation of the cavity during the station's various construction phases.

A tunnel advance system that involved reinforcement of the advance core (and thereby limited extrusion which would be immediately translated into surface subsidence) with structural elements in fibreglass was adopted for the side drifts of the tunnel. These were to be followed by full face excavation and lining with fibre reinforced shotcrete and steel ribs, with struts for the tunnel invert and sidewalls in reinforced concrete.

New construction system

A new construction system was designed for the crown drift which combined reinforcement of the advance core with fibreglass structures and mechanical precutting technology (used for the first time in the world on a span of 21.5m) with the 'active arch' principle. This decision was dictated by the absolute necessity of obtaining the fullest possible control over the deformation behaviour of the tunnel, an indispensable requirement if minimum subsidence limits imposed by residential buildings on the surface were to be achieved. It functions as follows:

■ reinforcement of the core ahead of the face with fibreglass structures reduces extrusion at the face and, as a consequence, helps prevent triggering of preconvergence and convergence of the cavity - the primary causes of surface subsidence

■ mechanical precutting provides a preconfinement effect that is indispensable for short-term prevention of deformation, which normally starts before the arrival of the face and can jeopardise the safety of the site in the tunnel and on the surface

■ the 'active arch', which consists of a final lining of prefabricated concrete segments which are placed a very short distance from the face and made 'active' by employment of special jacks inserted in the key segment, produces the immediate confinement action required to control long-term deformation around the cavity

In order to combine these technologies, all fairly recent in conception, in a single and highly industrialised construction system, a special machine was designed with the help of engineers from Impregilo and Rodio and constructed by the company Stac. It consists (see photo on page 30) of a large metal portal with the same shape as the profile of the crown of the tunnel. It rests on stabilisers, which in turn rest on longitudinal members placed in the side drifts, allowing it to move backwards and forwards. The portal contains the equipment needed not only for mechanical pre-cutting but also for handling and placing of the prefabricated concrete segments for the final lining of the tunnel.

First, the two access shafts with a $200m^2$ cross section and a depth of 30m and 40m respectively were excavated. Then, construction started at each end of the future tunnel employing the following construction stages:

■ 1a) Excavation of two 5m wide, 9m high side drifts after first reinforcing the advance core with fibreglass structures and lining it with fibre reinforced shotcrete and steel ribs fitted with struts

■ 1b) Casting the sidewalls in reinforced concrete

■ 2) Excavation of the tunnel crown, which has a span of 21.5m, a height of 8.5m and a cross section of 125m^2, after first reinforcing the advance core with fibreglass structures and placing a mechanically precut shell. An 'active arch' of prefabricated concrete segments was then placed immediately

■ 3) Excavation of the remaining invert portion of the tunnel (cross section 90m^2) and immediate casting of the invert in steps of maximum 7m after construction of the crown

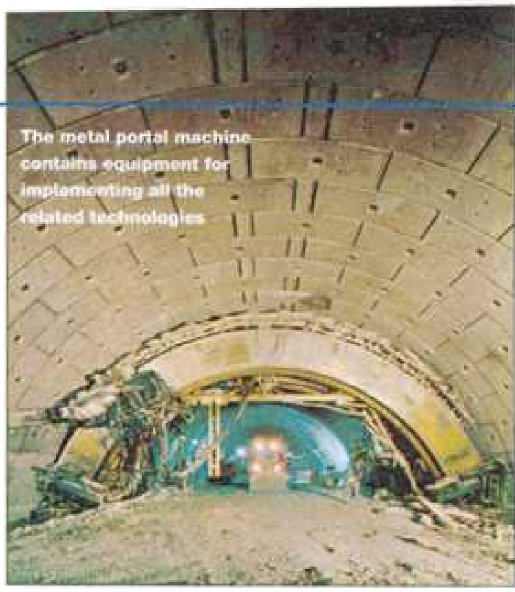
■ 4) Completion of the station infrastructure with platforms and mezzanine floor and stairways to the passage ways

The excavation system and the design of the stabilisation works was tested for each stage of the operations on finite element models. The calculations were used to test the system's effectiveness in guaranteeing the safety of buildings near the site. The maximum surface subsidence forecast as a result of tunnel construction was 14mm at the centreline of the tunnel and about 10mm next to the buildings.

Construction (Operational Phase)

The sequence of operations is shown in Fig 3 (below). After closing the two centre lanes of Via Baldo degli Ubaldi to traffic, excavation began on the two access shafts - the Valle Aurelia Shaft and the Aurelia Cornelia Shaft - after first confining the ground around them with sheet piles 1.2m in diameter and placing struts in reinforced concrete during excavation.

Once the start shaft was completed, the side drifts were excavated from the Aurelia Cornelia Shaft to the Valle Aurelia Shaft. The characteristics and stress-



The metal portal machine contains equipment for implementing all the related technologies

strain conditions of the ground and the dimensions and deep, elongated shape of the excavation, together with the requirement to keep surface subsidence within admissible levels, meant that severe preventative stabilisation measures had to be taken.

This was achieved by means of intensive reinforcement of the advance core ahead of the face with fibreglass structures specially designed to obtain the maximum effect from the treatment (Fig 4). The walls of the tunnels were stabilised by applying a fibre reinforced shotcrete lining, 200mm thick, reinforced with double IPN 180 steel ribs closed at the invert with a steel strut and by the casting of reinforced sidewalls.

A strut was used at the height of the springline to maintain convergence within 20mm (estimated as acceptable). The two tunnels were driven by these methods one behind the other, keeping the faces at least 400mm apart, without any particular problems. Advance rates averaged 2m/day. Once the side headings were finished, the sidewalls of the final tunnel were cast in situ in two stages.

The most interesting part of the excavation of Baldo degli Ubaldi Station then began, i.e., construction of

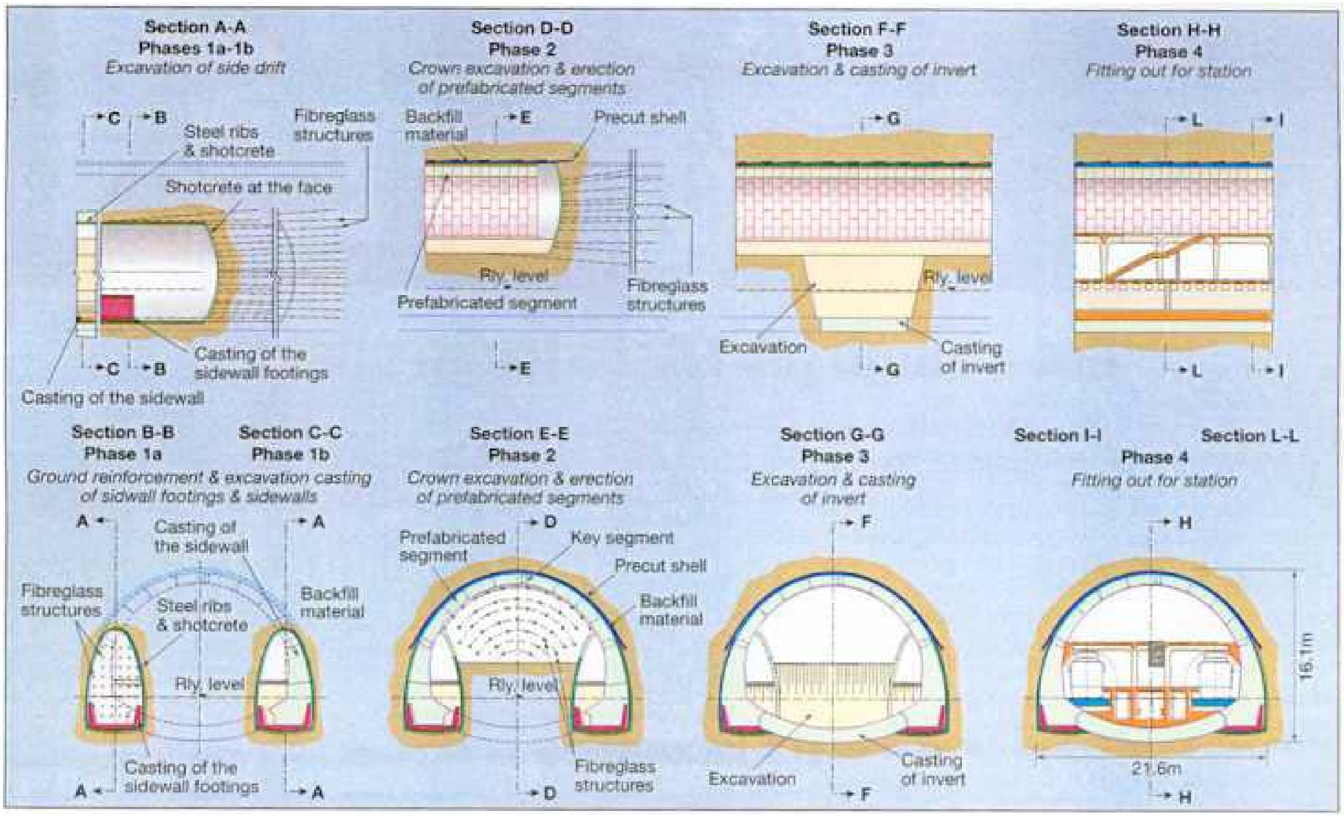


Fig 3. Operational Phase: station tunnel construction sequence

the large unsupported single arch tunnel. The tunnel was advanced by driving a crown drift followed by an invert drift and the casting of the invert in steps. Work started from the Valle Aurelia Shaft towards the Aurelia Cornelia Shaft. First, 47 lengths of 25m long (minimum overlap with successive lengths of 6.1m) fibreglass structures were inserted into the face to make the ground ahead more rigid.

A 3.5m long, 200mm thick mechanically precut shell was constructed ahead of the face every 2.7m along a 28m profile, given the 21.5m net span of the tunnel.

In order to obtain a particularly strong and uniform shell, the precutting technique was specially modified so that pumped instead of sprayed concrete could be used: special tubular pneumatic forms of a diameter appropriate to the height of the cut to be filled were positioned along the edge of the cut behind the blade so that wet concrete would not extrude out of the cut while it was being filled. The casting of each shell was followed by excavation (in steps of 900mm) and immediate erection of the final lining at a distance of not more than 2.7m from the face.

This operation consisted of placing 12 prefabricated segments each weighing 6.5 tonnes: two segments resting on the sidewalls of the tunnel, nine standard segments and a key segment (see photo below). Once the arch was in position, the space between it and the mechanically precut shell was filled with sprayed concrete containing additives while the arch was still resting on the machine. Initial prestressing (40 tonnes) of the entire arch was then performed using two 360 tonne Freyssinet jacks (maximum travel of 35mm) housed in the key segment. This rendered the arch immediately active and self supporting, capable of halting any deformation phenomena that may have started and even of correcting any elastic deformation already suffered by the precut shell.

Tunnel advance using this procedure allowed the final lining of the tunnel to be placed and made active at a very short distance from the face, thereby reducing the risk of surface subsidence enormously while maintaining advance rates of 0.7-0.9m of finished crown heading/day. Once the tunnel crown was completed, excavation and casting of the invert was carried out in steps (see photo on page 32) and this will be followed by full prestressing of the lining arches to the 360 tonnes needed to obtain the final centring of the stresses produced. The arch thus produced will need no further lining and impermeability is guaranteed by the neoprene seals and by injections of a waterproofing mixture into tubes provided inside the segments.

Monitoring during construction

This phase is of great importance since this is the time when the validity of forecasts made during the Diagnosis and Therapy Phases are checked to assess the appropriateness of the design as a whole and when fine tuning and perfection of the design is performed. Consequently, the following factors were continuously monitored:

- movements of buildings located in the area affected by the works
- subsidence of buildings foundations
- changes in the levels of the surface and deep water tables
- extrusion of the ground core at the face and convergence of the cavity
- development of stress and strain inside the lining of prefabricated concrete segments

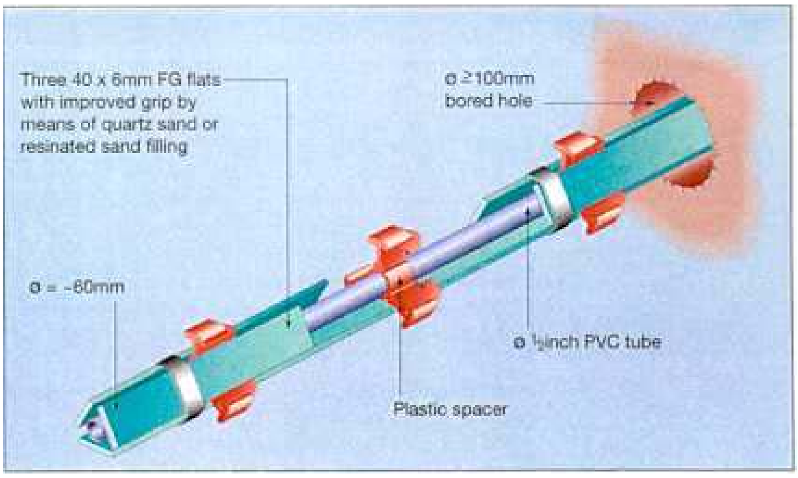


Fig 4. Fibreglass structural elements were used to reinforce the ground core at the face

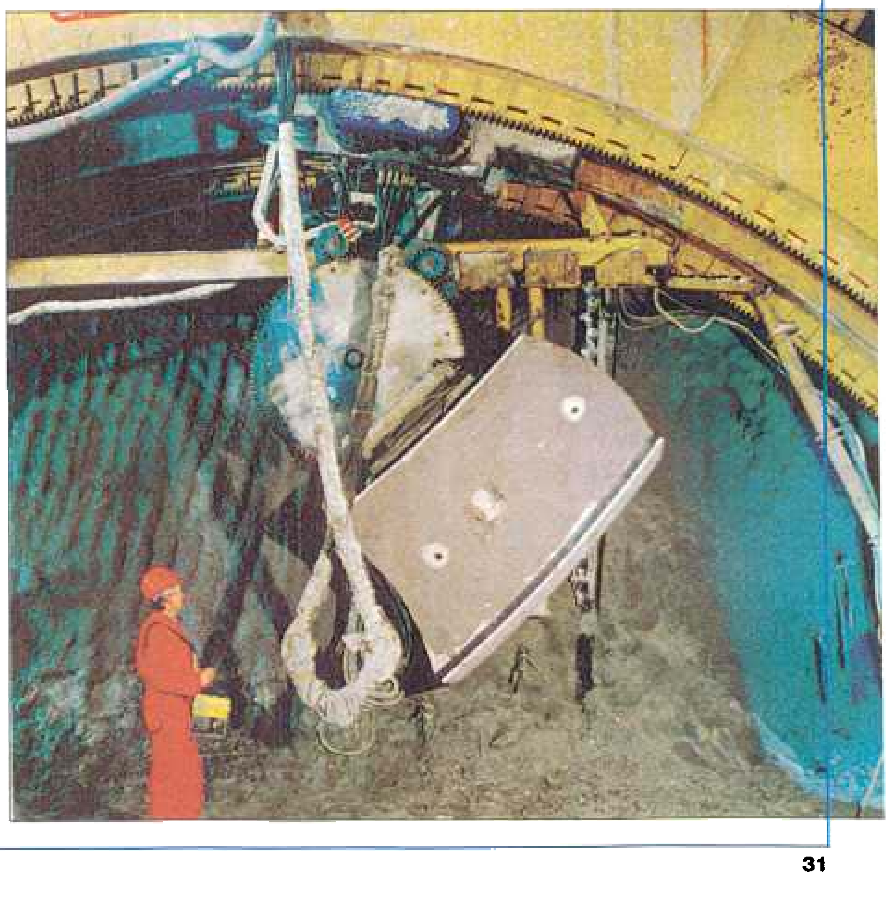
It was thought best to distinguish between measurements taken during excavation of the access shafts and driving of the side drifts and those taken during excavation of the crown and invert headings.

Monitoring of access shafts & side drifts

During this phase, the main purpose of monitoring was to ascertain the size and effect of subsidence on buildings and to correlate them with the advance of the works over time so that the reliability of design forecasts could be verified and the causes of the phenomena observed could be investigated and remedied. The measurements so obtained made it possible to identify the onset of a worrying subsidence phenomenon in good time.

It occurred on the centreline of the future left-hand track close to Building G next to the Valle Aurelia Shaft when the face of the left-hand side drift was still 50m from the building and the shaft was still under construction.

An analysis of the available data - extrusion and convergence measurements taken in the tunnel, subsidence, inclinometer and piezometer measurements



Placing of the final lining during the Operational Phase from the surface - resulted in the phenomenon being attributed with reasonable certainty to consolidation of the Paleoalveo silty-sandy ground due to changes in the hydrogeological equilibrium caused by the excavation of the shaft, and in the most suitable measures to be adopted.

In the end, it was decided to intervene with ground confinement of foundations of the buildings consisting of two lines of columns of ground improved by jet grouting (approximately 250 columns of 600mm diameter, with an average distance between centres of 600mm). The dual purpose of attenuating subsidence of buildings near the left-hand track and providing adequate confinement to the ground around the foundations of the buildings during excavation of the large tunnel arch was thereby attained.

If this consolidation phenomenon is excluded, subsidence values measured on the surface during excavation of the two side drifts did not exceed 8-10 mm for both headings. Extrusion at the face remained on average during the more delicate passages less than 10mm, while 20mm was considered admissible. The effect of reinforcement of the core was fundamental to this achievement. It is demonstrated by the fact that the extrusion measured increased proportionally as the length of remaining pieces of fibreglass inserted in the core decreased with the tunnel advance.

ON SITE

- **OWNER:** Rome Municipality
- **CONCESSIONARY:** INTERMETRO SpA
- **GENERAL CONTRACTOR:** IMPREGILO SpA
- **SPECIALIST CONTRACTOR:** RODIO SpA
- **DESIGNER:** ROCKSOIL SpA (Milan)

Monitoring of the access shafts and side drifts

The plan for monitoring the station tunnel involved:

- topographical extrusion measurements (with the face halted) using sliding micrometers installed in the face
- incremental and inclinometer subsidence measurements to assess movements of the ground at depth
- piezometric measurements to monitor changes in the level of the water tables. Subsidence and integrity of the buildings on the surface was monitored at the same time. The measurements showed that:
- cumulative subsidence remained on average within 10-15mm depending on the length of the reinforcement of the core remaining in the ground at the face, the stratigraphy of the overlying ground and the local geotechnical characteristics of the material excavated
- the band of ground affected by movements extended vertically for approximately 3-4m above the tunnel crown, with maximum movements of 15-20mm during the passage of the face
- the subsidence basin on the surface was very small. Subsidence began to occur 10m before the arrival of the face. Movements near buildings were uniform and corresponded to those forecast - in the order of 6-7mm. Values greater than average observed at metre 25 to metre 40 are attributed to residual consolidation of recent alluvial levels. Analysis of deformation measured in the tunnel shows that surface subsidence seems to correlate with extrusion. Greater subsidence did in fact coincide with greater extrusion.

One of the purposes of monitoring was to 'test' the construction system employed, since this was absolutely new and innovative in the field of underground works. Convergence of the precut shell, and deformation and stress measurements of the arch of prefabricated segments were therefore taken by setting up the following:

Three primary stations (located at a distance of 5m, 10m and 15m from the Valle Aurelia Shaft, each consisting of:

- three strain gauges fitted on the nine standard segments to measure the stress state in the structure and how the compression stress was transmitted
- three oil pressure cells fitted on segments 2, 5 and 8 on the outside of the arch to measure pressure transmitted between the ground and the structure.

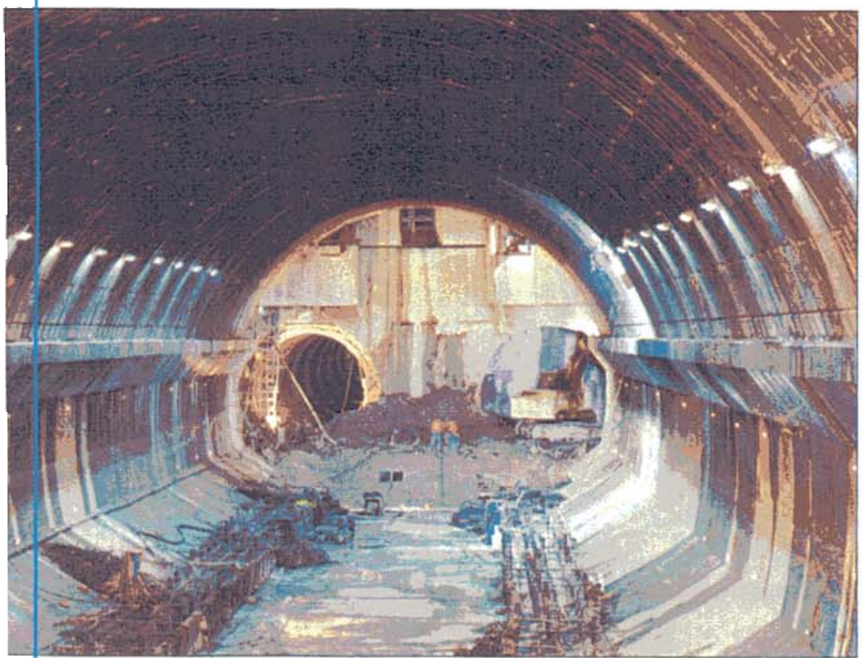
Three secondary stations, located at a distance of 36m, 60m and 90m from the Valle Aurelia Shaft, each consisting of:

- three strain gauges, fitted on segments 2, 5 and 8 of the active arch
- three oil pressure cells fitted on segments 2, 5 and 8
- targets fitted on segments to assess changes in the position of the segments using laser measurements.

The results obtained from this instrumentation showed:

- that the maximum values for lowering of the precut shell were 1-1.5mm
- movements of the arch in the initial prestressing stage were almost exclusively horizontal and varied between a minimum of a few millimetres to a maximum of 20mm. At a distance from the face after tunnel advance, settlement was less than 5mm both vertically and horizontally towards the centre of the tunnel cross section
- tensile stress inside the prefabricated segment arch was already zero after the initial prestressing and remained so apart from some minimal stress near the tunnel sidewalls

As far as excavation of the tunnel invert was concerned, vertical and horizontal movements of the tunnel sidewalls were measured. After the first few sections, 7m and 5m in length respectively, values measurable in millimetres were obtained, which were less than forecast.



Excavation and casting of the invert was performed in steps

Conclusions

The works, started in 1992, are now complete. The system functions extremely well and furnished higher than average advance rates for this type of project in this type of ground. If exception is made for the subsidence resulting from consolidation of the ground at the Valle Aurelia Shaft, which was promptly halted, surface subsidence values were minimal and less than those forecast by design calculations.

A list of references in Italian, French and English is available by request from *Tunnels & Tunnelling International*.