The Construction of large-span Stations for underground Railways

Prof. Ing. P. Lunardi

1 Introduction

The construction of underground railways networks for large cities has become routine administration. The most delicate aspect of their construction is certainly the stations. These require large openings to be made underneath city centres where the ground is often of poor quality with very shallow overburdens and there are existing infrastructures of all types. All the characteristics of the construction must be accurately assessed beforehand and the design must be particularly thorough and optimised: the margins of error, the tolerances, are very small. Recourse to innovative construction methods is not rare.

What has been said above is illustrated particularly clearly by 2 projects completed in Italy over the last 10 years. The size and the construction systems adopted for these projects aroused enormous interest throughout the world (Fig. 1): the Venezia Station of the Milan Urban Link Line (a span of 30 m with an overburden of only 4 m sandy-gravelly terrain, under the water table) constructed using "cellular arch" technology which won the inventor a prestigious international award, and the Baldo degli Ubaldi Station on Line A of the Rome Metro (span of 22 m approx. and an overburden of more than 20 m, clayey soil with thin sandy levels) constructed using reinforcement of the advance core with fibre glass structural elements and mechanical precutting (performed for the first time in the world on a span of 21.5 m) combined with the "active arch" principle.

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2 The Milan Urban Link Line and the "Venezia" Station

The Milan Urban Link Line will connect the various railway networks present in the metropolitan area so that a single integrated transport system is formed consisting of the underground metro lines and the main-line routes on the surface. The mainline railway lines entering the city from the North West will be linked to those entering the city from the South East and at the same time, the transport system may be used at an underground metro and mainline level in the section between the Lancetti and Porta Vittoria stations. In order to achieve this, the Milan Urban Link Line will cross the entire city underground at an average depth of 20 m, with an overall length of approximately 18 km, comprising ten stations, 6 of which are underground. The Venezia Station, now already in operation, is strategically located in the central business district of the city and constitutes the largest underground work in the whole regional transport network.

It is a large tunnel with an overall diameter of approximately 30 m and a length of 215 m. It is a mined tunnel that passes through non-cohesive soil under the water table with an overburden of only 4 m beneath the foundations of 16th century buildings. Its construction was made possible by the adoption of a new construction system known as the „cellular arch" method which allows the final lining of the work to be placed before actual excavation itself is begun.

2.1 Features of the "Cellular arch" and why it was used

The tunnel for the station has a cross section of 440 m^2, 6 times larger than the twin-

Baldo degli Ubaldi Station during construction of the tunnel invert

Venezia Station during construction

track rail tunnel and almost twice the size of the largest tunnel constructed so far in Milan.

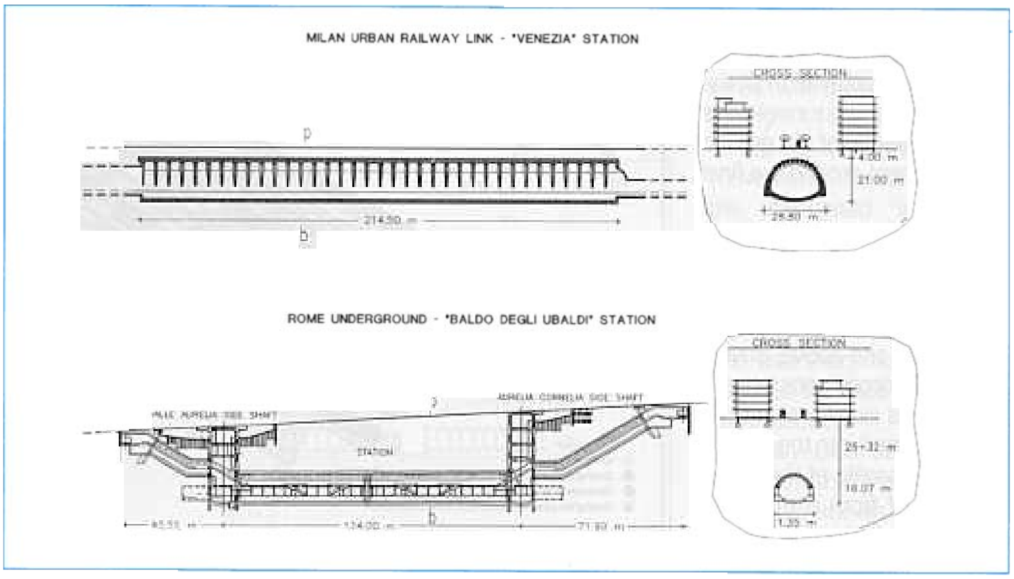
It was driven by boring through recent and non-cohesive soils. The overall diameter was approximately 30 m and the overburden under the foundations of ancient buildings was only 4–5 m.

Such a shallow overburden caused considerable doubt about what the results might be if traditional methods were employed based on advance in steps after first improving the ground with immediate placing of shotcrete and steel ribs (Fig. 2). It would in fact have been impossible to improve the ground over the arch of the tunnel before excavation began to a degree that would have been sufficient for the large dimensions of the tunnel cross-section. An analysis carried out using the finite element method also showed that the confinement structure of steel ribs and shotcrete would have been subject to excessive deformation and would not have been able, even temporarily, to contain surface subsidence within the limits required to safeguard nearby structures and utilities.

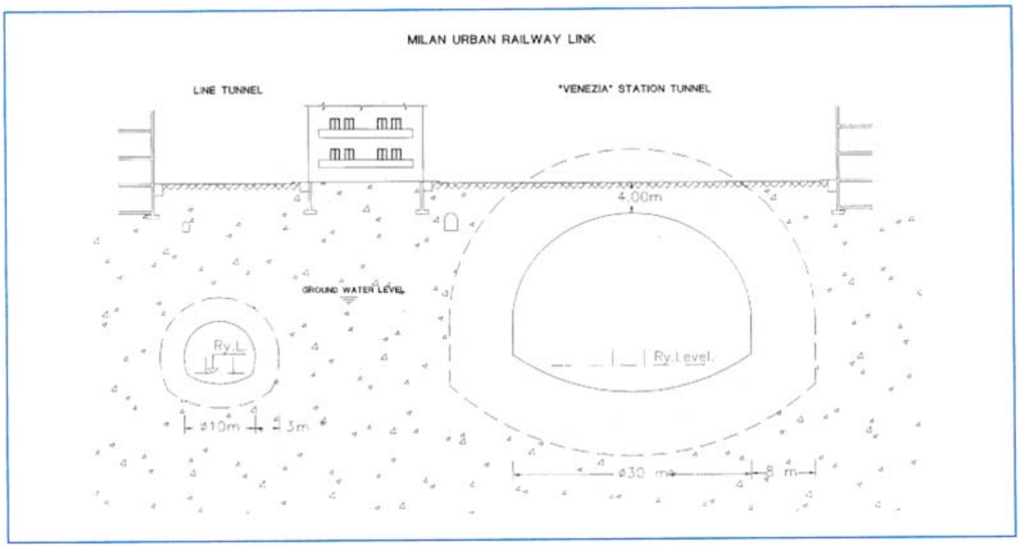
An alternative to the traditional method was sought that would provide a structure which was less subject to deformation with wide tunnel spans, which would become immediately active when excavated. The result was an innovative method called the "cellular arch" method, theoretically capable of opening a full face mined tunnel with a diameter as large as 60 m in non-cohesive or semi-cohesive soils under a water table and with overburdens shallower than the radius of the excavation.

The cellular arch consists of a composite structure similar to a trellis type framework with a semi-circular cross section. The longitudinal members (cells) consist of tubes in reinforced concrete joined together by a series of large transverse ribs (arches) (Fig. 3).

The advantage of this technique over traditional methods lies in the way the passage from the initial equilibrium condition of the undisturbed ground to the final con-



1 Profiles and cross sections of the Venezia and Baldo degli Ubaldi Stations

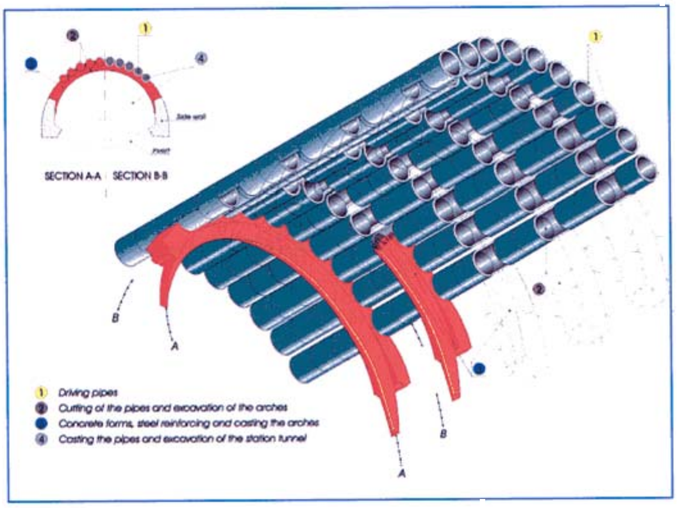


2 The overburden of theVenezia Station was not sufficient for construction using traditional method (based on advance improvement of an adequate band of ground around it)

dition of equilibrium of the finished tunnel is regulated to prevent the onset of decompression in the material and consequently also of surface subsidence.

Excavation is in fact performed when the very rigid load bearing structure has already been constructed and is able to furnish the ground with the indispensable confinement required without suffering any appreciable deformation.

In practice, cellular arch tunnel construction takes place in 5 main stages (Fig. 4)
1) half-face excavation of the side drifts for the tunnel walls and completion of the ground improvement around the final tunnel
2) completion of excavation of the tunnel wall side drifts and casting of the tunnel side walls and, in a completely independent site above, driving of ten reinforced concrete micro-tunnels side by side (2.10 m in diameter) into the ground along the profile of the future tunnel roof from a thrust pit (by the pipe jacking method)
3) excavation through the micro-tunnels of transverse tunnels to be used as formworl (the walls of this consisting o the ground itself) for the cast ing of the connecting arche: in reinforced concrete anc then placing of reinforcemen and casting of the arche: themselves
4) filling of the ten longitudinal micro-tunnels with concrete and then excavation o the actual final tunnel beneath the protection of the "cellular' arch already practically active
5) Casting of the tunnel inver in steps.



3 Structure of the cellular arch

2.2 Construction of the Cellular arch for the "Venezia" Station

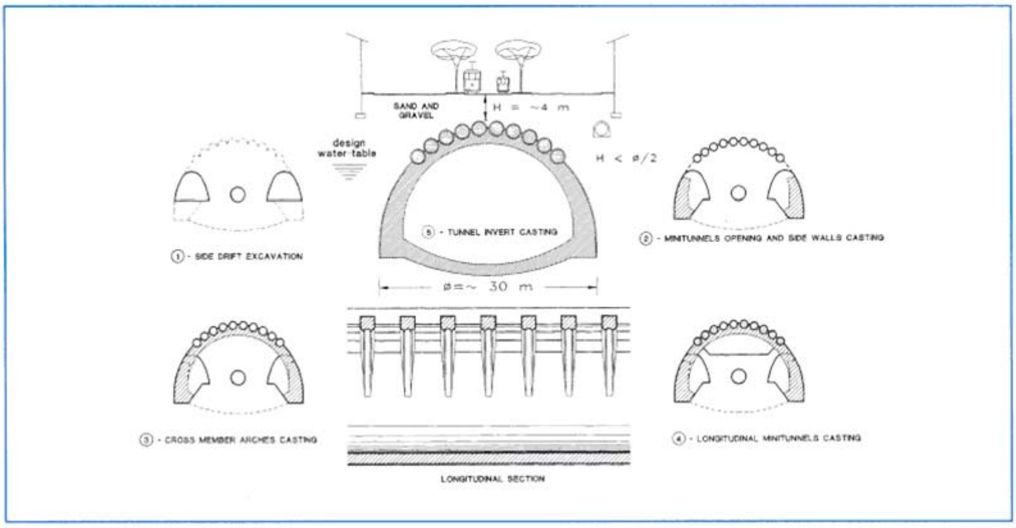
From an operational poin of view, the side drifts (which are the same length as the future station tunnel, 7.6 m in width and 11.0 m high giving a total excavated surface area of 60 m²) were constructed in two stages:
1) excavation of 40 m² down to the water table
2) ground improvement injections under the water table from the floor of the firs stage, under the future side walls of the tunnel and then subsequent deepening of the excavation down to the foot o the tunnel side walls.

The primary lining of these consisted of steel ribs, wire mesh reinforcement and shotcrete.

The side walls of the future station were then cast inside them. Average rate of progress was approximately 2 m per day of finished side wall, including the excavation work. It therefore took 11 months to complete the 430 m of side wall (215 m for each side), about the same time employed for pipe jacking which was performed simultaneously from a completely independent site.

The pipe jacking was for the excavation of 10 micro-tunnels along the profile of the crown as specified by the design for the tunnel. This involved driving 1,080 pipes for a total length of about 2,160 m. The pipes were prefabricated; manufactured using the radial pre-stress system and high strength cement mixes, and had an overall diameter of 2,100 mm, an internal diameter of 1,800 mm and a length of 2 m.

They were pipe jacked into the ground from a thrust pit (Fig. 5) using equipment consisting of a cylindrical metal shield with a diameter of 2,100 mm and a length of 7.7 m divided into two parts: the front part with a mobile head containing a computer-operated hydraulic cutter and a conveyor belt for mucking out and the rear part, 3.50 m long containing, motors, pumps and reservoirs for the hydraulic fluid. The thrust equipment included two longitudinal travel hydraulic long stroke jacks, the indispensable load distribution structures and a hydraulic pump operating at a pressure of 600 bar.



4 Construction stages of Cellular arch construction

Two sets of equipment were employed to obtain pipe advance rates of approximately 8–9 m per day. Topographic monitoring carried out during and after pipe jacking ensured and then confirmed that it was performed accurately with negligible deviations in direction and depth.

Once the side walls had been cast and all the pipes driven into place, construction of the load bearing cross members of the crown of the future tunnel started, undoubtedly the most characteristic part of the "cellular arch" technique.

The cross members consisted of a series of 35 intermediate arches placed at intervals of 6.00 m plus the 2 end pieces.

Construction was performed as follows (Fig. 6):

1) cutting and removal of the part of the pipe intersected by the arches and excavation of the arches mainly by hand down to the tunnel wall side drifts

2) assembly of the prefabricated steel forms inside the excavation, placing of the reinforcement for the pipes and the arches and casting of the latter on the side walls already in place

3) casting of the pipes.

Excavation in steps of the top heading in the crown and the bench of the large tunnel was then able to be undertaken in complete safety beneath the already active load bearing "cellular arch" structure. The lining was finally completed with an invert, varying from 1.5 to 2 m in thickness. It was cast in 5 m steps for a total length of 92 m with a total cross section of 38 m^2. Each 5 m advance took a 7-day working week to complete on average and work was co-ordinated so that the ring of the tunnel lining was left unclosed for only 3 days.

Average total production on the civil works of the Venezia Station using the cellular arch technique was 57 m^3 per day.

2.3 Monitoring System

The considerable dimensions of the cavity, the completely new and untried construction method and the delicate surface constraints meant that a vast monitoring programme had to be designed and implemented to measure:

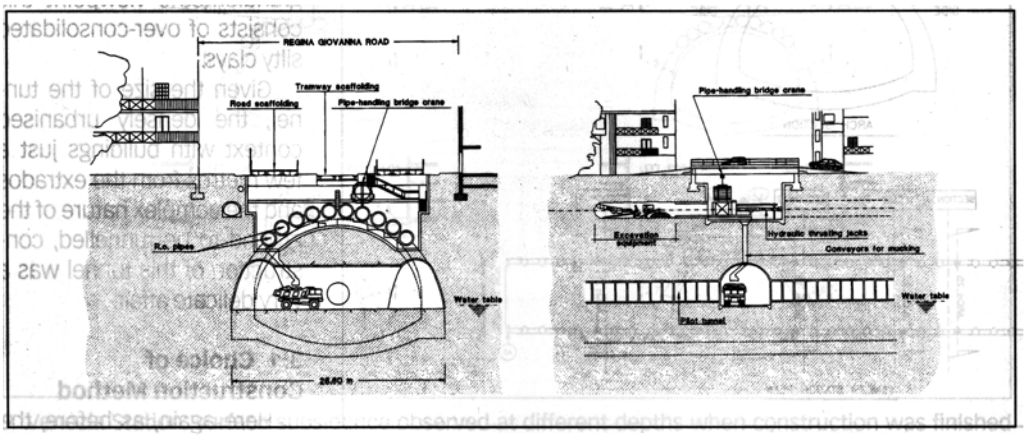
- subsidence, at the ground level of buildings in particular during all stages of the works
- deformation of the ground in the vicinity of the tunnels
- stresses and strains in the final lining of the tunnel.

The programme included (Fig. 7):

- topographic measurements
- levelling, deflectometer and inclinometer measures to monitor the development of deformation on existing buildings
- convergence measures in tunnels
- pressure and deformation measures on the lining structures.

Recording and processing of the measurements taken with each instrument furnished a sufficiently complete picture of the stress-strain conditions of the ground and the structure during the various stages of construction to provide a useful and constant comparison with both the design forecasts and the set limits within which existing structures will maintain their integrity.

As Fig. 8 shows, surface movements remained below the calculated values. Of course, the greatest subsidence occurred during excavation of the crown. The increase in deformation, slow at first and then more rapid as soon as the face passed the cross-section measured, gradually died down as the face moved further away. This behaviour shown from datum points at street level above the route of the tunnel (Fig. 9) was confirmed, though to a



5 Construction of the Venezia Station with the Cellular arch method: section at a thrust pit

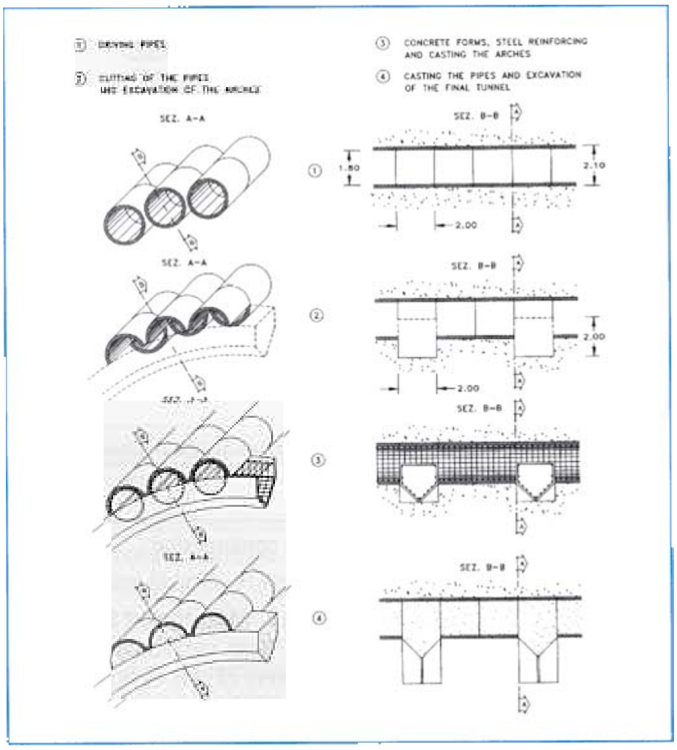
less marked extent, by those located on buildings for which maximum subsidence during the passage of the face did not exceed 1–2 mm.

This monitoring system guaranteed constant surveillance over actual conditions demonstrating the compatibility between the efficiency of the construction system and the urban environment, to provide a reassuring overall picture.

2.4 Possible Developments of the System

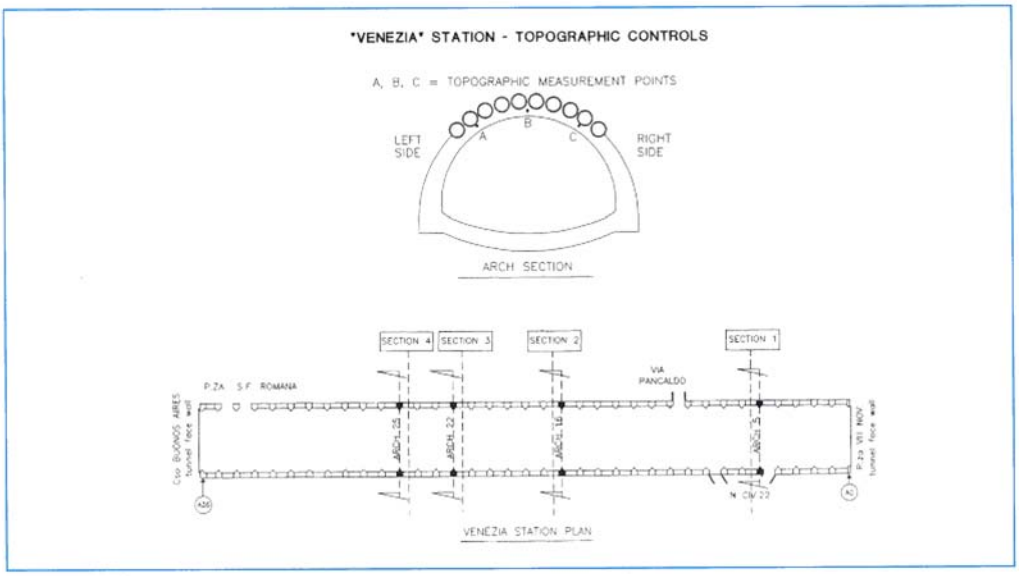
Studies were carried out to establish the limits of the "cellular arch" method for the construction of wide span tunnels in non-cohesive soils with shallow overburdens, under the water table.

Once a basic diagram of the problem had been constructed and the variables determined, approximate dimensions of the main construction elements were calculated using a one dimensional finite element model to simulate the behaviour of the structure and its interaction with the ground. 3 different geometries were considered with S:H ratios of 2.09, 1.73, and 1.5, with the span S varying up to 60 m.



6 Phases in the construction of the Cellular arch structure

The results of the calculation led to the production of tables giving the minimum thickness of the structural elements and surface subsidence as a function of the geometry, the overall diameter, the depth of the water table and the size of the overburden (see the example in Fig. 10). It would appear from the results that the "cellular arch" method could be employed with success for the mined tunnel construction of shallow tunnels with a span of over 60 m in non-cohesive ground, under the water table without any significant surface subsidence.



7 Venezia Station: location of the monitoring survey stations

3 The Baldo degli Ubaldi Station on the Rome Metro

The "Baldo degli Ubaldi" station is one of 5 new stations on the Ottaviano to Battistini extension of "line A" of the Rome Metro. It completes the connection of outlying districts in the north west of the city to the city centre and Vatican City.

The station has a span of 22 m and is situated in the centre of the city in prevalently clayey ground.

The numerous geological and geotechnical surveys carried out between 1987 and 1994 enabled a detailed picture to be drawn up of the stratigraphy of the ground affected by the project. Two categories of ground were identified (Fig. 11):

- a base formation consisting of Pliocene azure clays with sandy levels of a thickness measurable in centimetres and decimetres
- a formation closer to the surface consisting of sandy-silty ground which in places has very low consistency values.

The tunnel for the station is immersed in Pliocene clay under the water table. From a granulometric viewpoint this consists of over-consolidated silty clays.

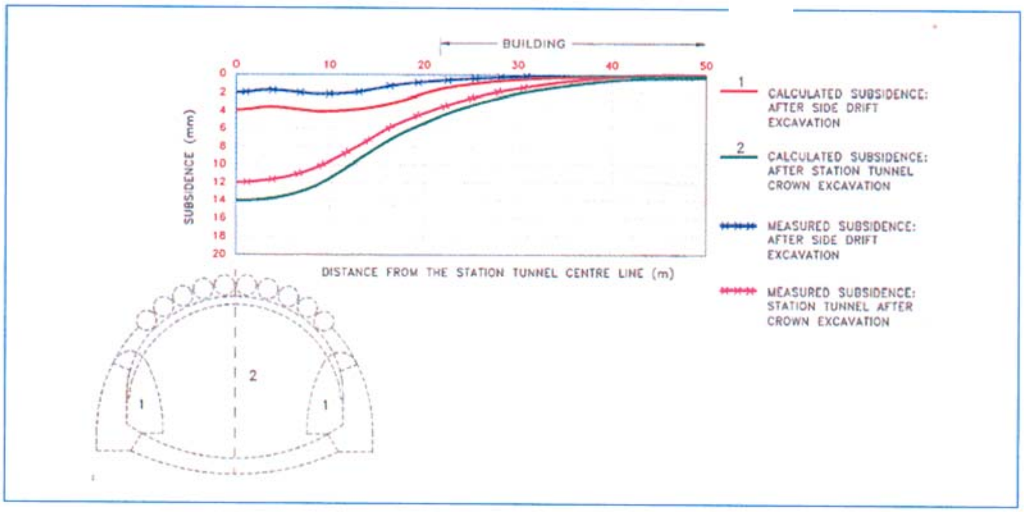
Given the size of the tunnel, the densely urbanised context with buildings just a few metres from the extrados and the complex nature of the ground to be tunnelled, construction of this tunnel was a very delicate affair.

3.1 Choice of Construction Method

Here again, as before, the proximity of numerous residential buildings brought with it the peremptory requirement to keep deformation well within the normal limits for tunnels driven through cohesive ground. In fact in the absence of preventative measures, the stress state induced by excavation would have produced extrusion at the face giving rise to considerable surface subsidence that would have been extremely dangerous for buildings above the tunnel.

The adoption of traditional construction methods, based on lining the tunnel in improved ground with steel ribs and shotcrete would not have kept deformation within the required limits, not even if multiple-drift excavation methods (side drift, top heading, top bench, and bottom bench) were employed.

Methods involving pre-confinement of the cavity were therefore studied. These were to act ahead of the face and would be able to maintain the advance core in the elastic range and consequently guarantee adequate control of deformation in the cavity during the various construction stages of the tunnel.



8 Venezia Station: surface subsidence actually measured compared to design calculation predictions

The advance system chosen for driving the two tunnels for the side walls of the station consisted of reinforcement of the advance core using fibre glass structural elements (in order to contain extrusion which would have translated immediately into surface subsidence) followed by full-face advance and a lining in fibre reinforced shotcrete, steel ribs with the foot in the tunnel invert and kickers in reinforced concrete.

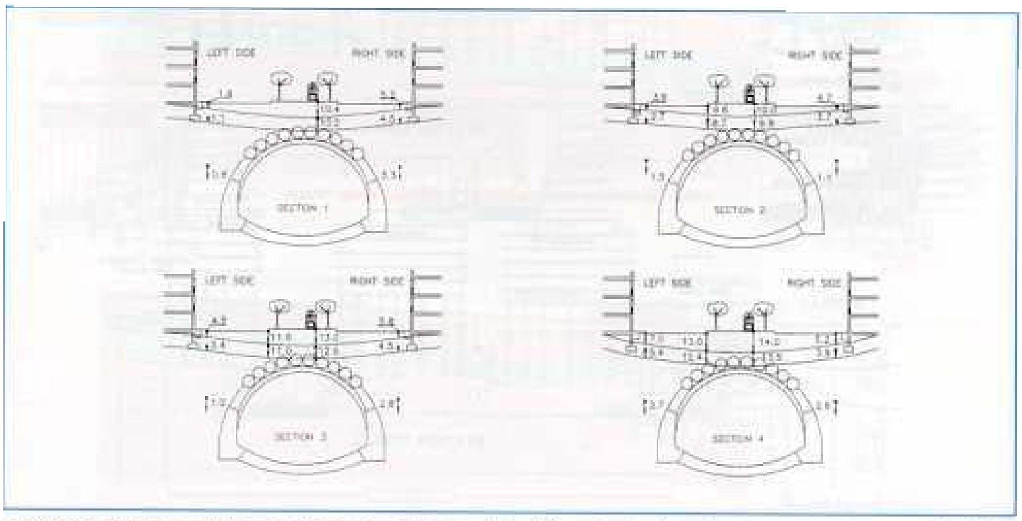
For the top heading, however, a new construction system was designed that combined reinforcement of the advance core with fibre glass structural elements and mechanical pre-cutting (performed for the first time in the world on a span of 21.5 m) with the "active arch" principle.

This technique allowed full control to be gained over deformation in the tunnel, an indispensable requirement for containing subsidence within the limits needed to avoid damage to residential buildings on the surface. This control was achieved by:

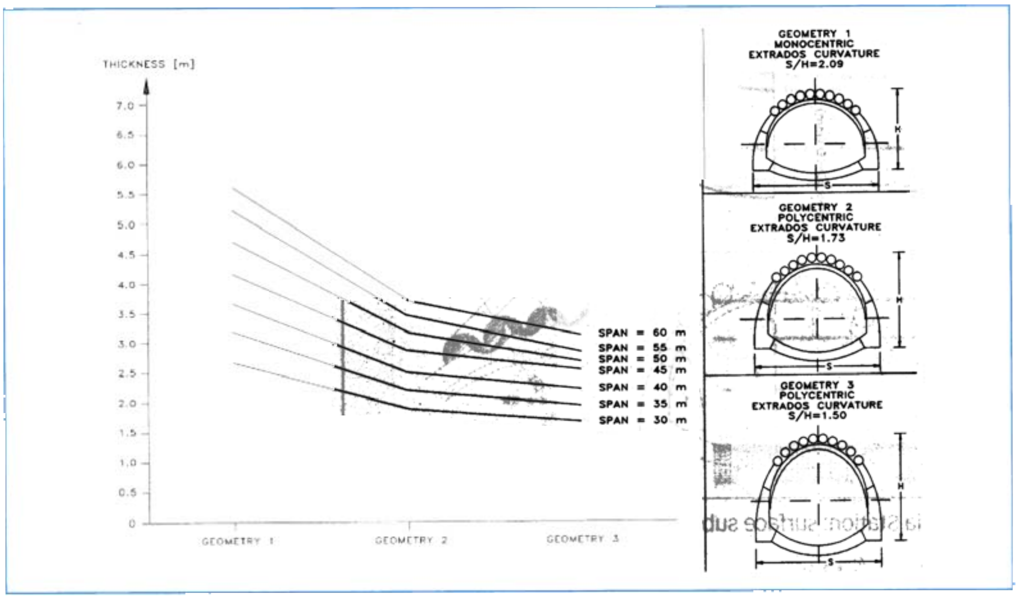
- reinforcement of the advance core with fibre glass structural elements to reduce extrusion at the face and act as a consequence to prevent pre-convergence and convergence of the cavity, which are the two primary causes of surface subsidence
- mechanical pre-cutting to produce pre-confinement of the cavity indispensable for eliminating short term deformation which normally commences before the arrival of the face and which can jeopardise the safety of the construction site both in the tunnel and on the surface
- the "active arch", consisting of a ring of the final lining in prefabricated segments placed at a distance of 2.7 m from the face and made "active" by the action of special jacks fitted in the key segments to produce immediate confinement action needed to control long term deformation around the cavity.

The main stages of the advance system are summarised in Fig. 12. Once the two access shafts of 200 m^2 cross section had been sunk (to house future services installations) at the two ends of the future station, put very briefly, construction proceeded as follows:

1a. 2 side drifts, 5 m wide and 9 m high were driven for the



9 Venezia Station: surface subsidence observed at different depths when construction was finished (for the ground improvement stage by means of traditional injections)



10 Examples of the potential of the cellular arch system

side walls of the tunnel, after first reinforcing the advance core with fibre glass structural elements and lining with fibre reinforced shotcrete further reinforced with double steel ribs (IPN 180 type) fitted with struts

1b. casting of the above side walls in reinforced concrete

2. excavation of the top heading of the station tunnel (21.5 m span, 8.5 m high with a cross section of 125 m²) after first improving the ground in the core with glass fibre structural elements and the creation of a shell by mechanical pre-cutting and then immediate lining of the crown with an "active arch" in prefabricated segments

3. excavation of the remaining bench below (cross section of 90 m²) and immediate casting of the tunnel invert in steps (7 m max.), after construction of the crown

4. completion of the station infrastructures with the construction of the platforms and mezzanine floor, access stairways and passageways.

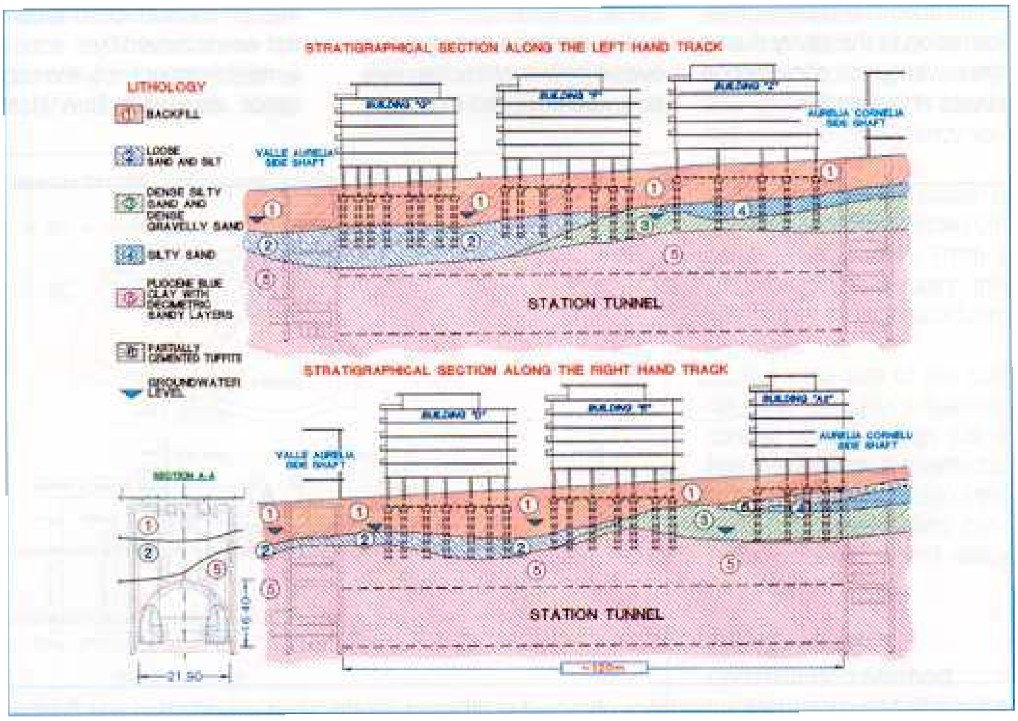
The advance and construction system, the dimensions and specifications for the stabilisation techniques in the various phases of the system were verified by numerous calculations performed on computers using non-linear finite element and also 3-dimensional models.

These calculations were also used to verify the ability of the system to guarantee the safety of buildings near the site.

3.2 The operational Stage

From an actual construction viewpoint, once the side drifts had been driven and the walls of the station cast in reinforced concrete had been completed, the main single arch tunnel was then driven in two stages, a top heading and bench, with the tunnel invert cast in steps. Tunnel advance proceeded from the Valle Aurelia shaft to the Aurelia Cornelia shaft. The first step (Fig. 13) was to stiffen the core of ground ahead of the face by inserting into it 47 fibre glass structural elements, 25 m in length (minimum overlap with subsequent lengths of 6.10 m). Then, every 2.7 m, a mechanically pre-cut shell was placed: 3.5 m long, 20 cm thick and a circumference of 28 m and a net span of 21.5 m

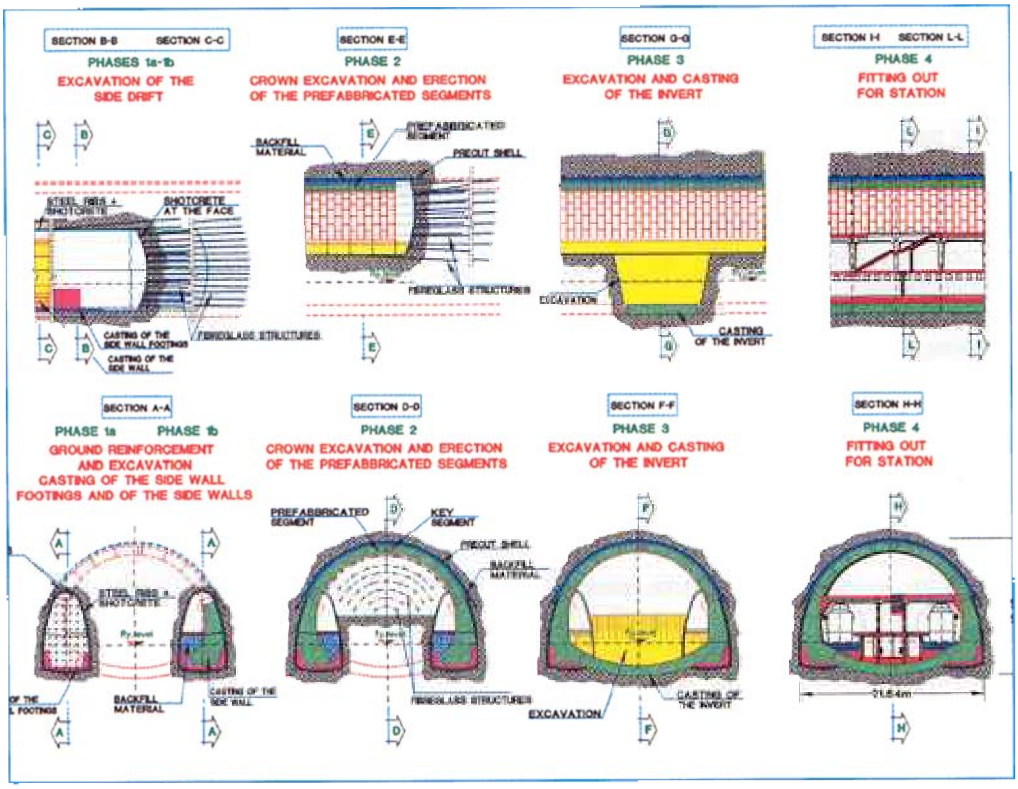
In order to obtain a particularly even and strong shell, the pre-cutting technique was modified to use pumped instead of sprayed concrete and to prevent concrete from spilling out of the cut during the filling stage, special tubular pneumatic forms were positioned along the edge of the cut behind the cutter with the diameter appropriate to the height of the cut.



11 Baldo degli Ubaldi Station: Geological and geotechnical situation

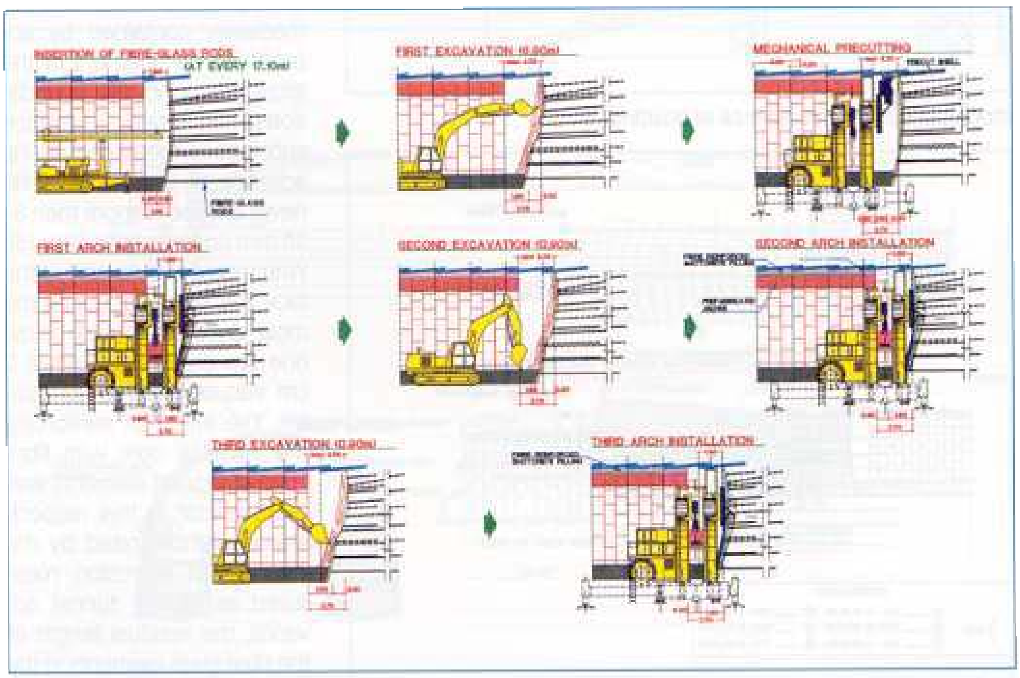
The placing of each shell was followed by excavation (in steps of 0.9 m) and immediate erection of the final lining at not more than 2.7 m from the face.

This consisted of 12 prefabricated concrete segments with an average weight of 6.5 t each: 2 rest on the tunnel side walls, 9 are standard segments and 1 is the key segment (Fig. 14). Once a lining arch had been erected, the space between it and the precut shell was filled with a sprayed concrete containing additives, while the arch still rested on the machines. Then the 360 t Freyssinet jacks (maximum travel of 3.5 cm) housed inside the key segments were used to put the whole arch under initial prestressing (40 t) making the lining immediately active and self-supporting, thereby preventing the onset of any deformation and even re-establishing elastic deformation that may have been suffered by the pre-cut shell.



12 Baldo degli Ubaldi Station: Construction phases of the tunnel

This method guaranteed the activation of the final lining of the tunnel at a very short distance from the face and reduced the risk of surface subsidence enormously. Average advance rates were 0.7–0.9 m/day of finished crown.



13 Baldo degli Ubaldi Station: Construction phases of the top heading using mechanical pre-cutting and the "Active Arch" technique

Once the crown of the tunnel was complete, the excavation of the bench below and casting of the tunnel invert was performed in steps. Finally the pre-stressing of the lining segments was completed stepping up the pressure to the full 360 t required to achieve the final centring of the stresses established in them.

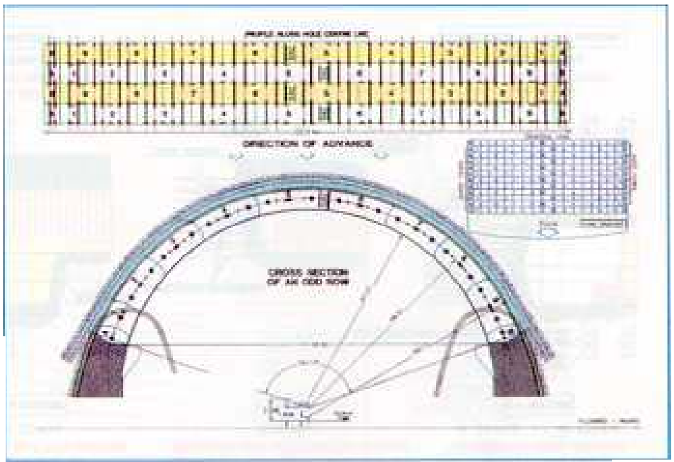
The arch constructed in this way received no facing and water proofing was obtained by properly sized neoprene joints between the segments and injections of water proofing mixes through special tubes in the segments themselves. Completion of the civil works for the Baldo degli Ubaldi Station took around a year and a half with average total progress of 59 m³/day.

3.3 Monitoring System

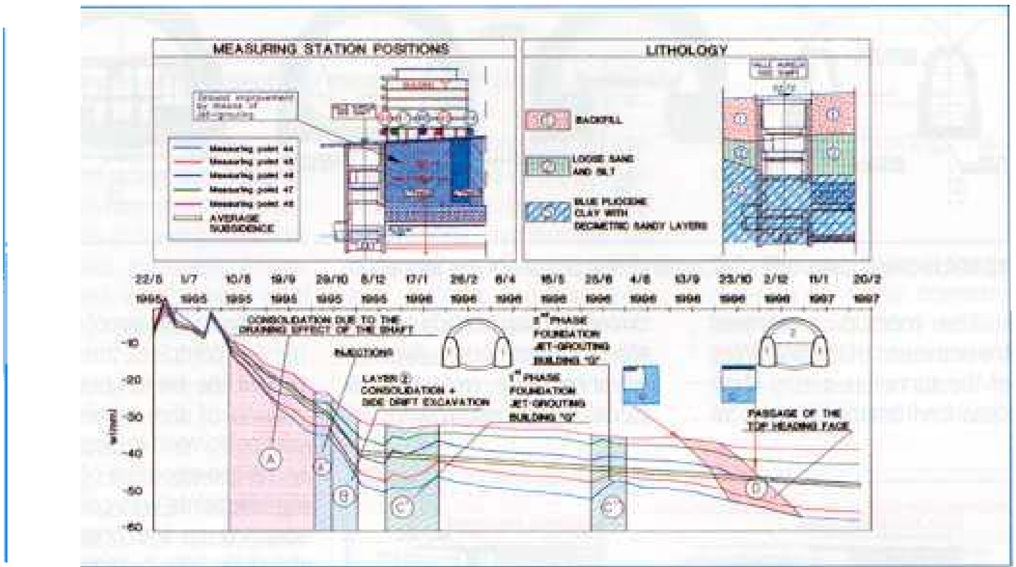
In addition to monitoring the behaviour of the tunnel itself, as has already been mentioned, the urban context in which the tunnel was driven required particular attention to be paid to monitoring surface subsidence effects of the works.

The following were subject to continuous and very careful monitoring:

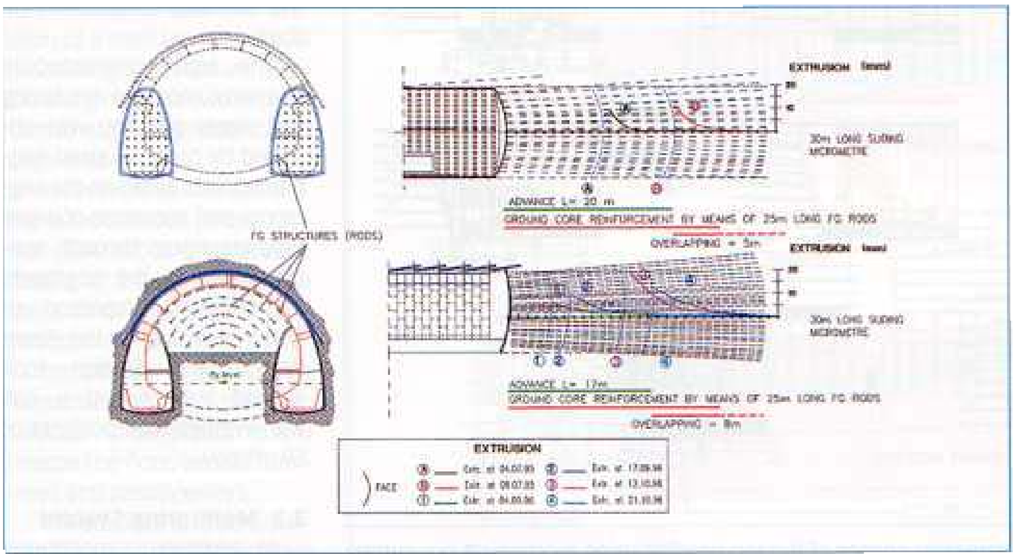
- movements of buildings in the area affected by the works
- subsidence of the ground in proximity of the foundations of the buildings



14 Baldo degli Ubaldi Station: Diagram of the "active arch" prefabricated segment lining



15 Baldo degli Ubaldi Station: Monitoring of surface subsidence at building "G"



16 Baldo degli Ubaldi Station: Monitoring of extrusion during advance of the side drifts

- changes in the level of the water table both at the surface and at depth
- extrusion of the ground in the core at the face and convergence around the walls of the tunnels
- changes in stress and deformation inside the prefabricated segments of the lining.

It was felt best to divide the issue of monitoring into 2 parts: The one performed during excavation of the access shafts and side drifts and the other performed during excavation of the top heading and bench.

3.3.1 Monitoring during Excavation of the access Shafts and side Drifts

The main purpose of monitoring during this stage was to measure the entity and effect of subsidence on buildings.

If exception is made for the local effect of accentuated consolidation of silty-sandy ground in the palaeoalveus adjacent to building G – due to changes in the hydrogeological equilibrium caused by the sinking of the shafts and immediately contained by appropriate confinement of the ground around the foundations concerned – surface subsidence measured during advance of the 2 side drifts never exceeded more than 8–10 mm on both sides (Fig. 15). With regard to extrusion at the face, this was kept during the most delicate phases below one cm on average, while 2 cm was considered admissible. The effect of reinforcing the advance core with fibre glass structural elements was fundamental in this respect. This is demonstrated by the increase in extrusion measured as, during tunnel advance, the residual length of the fibre glass elements in the core decreased (Fig. 16).

3.3.2. Monitoring during Excavation of the top Heading and Bench

The monitoring plan for the station tunnel involved:

- topographical extrusion measurements (with the face halted) and sliding micrometer measurements with a length of 30 m installed in the face
- incremental subsidence and inclinometers measurements to assess movements of the ground at depth
- piezometric measurements to monitor changes in the levels of the water tables.

At the same time surface subsidence and the integrity of overlying buildings was also monitored.

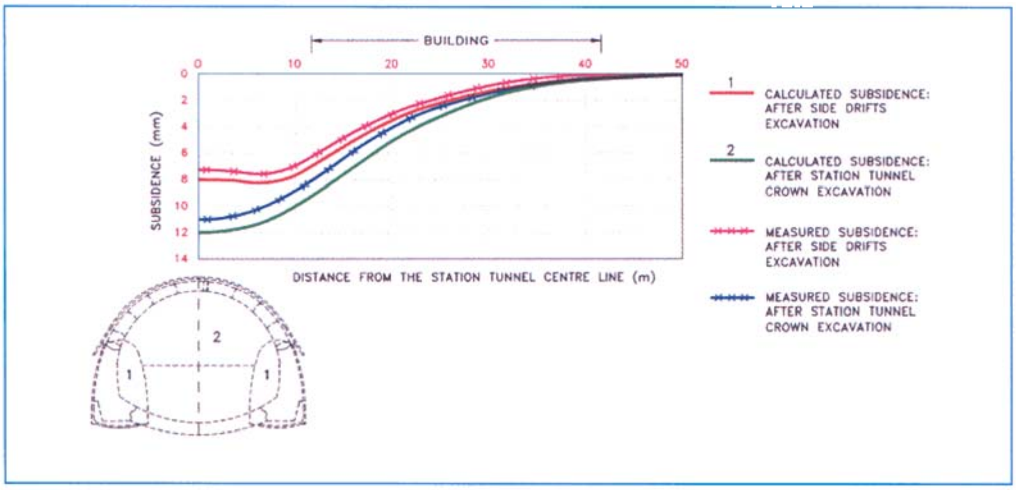
The results of measurements showed that (see Figs. 15, 16 and 17):

- accumulated extrusion remained on average between 10 mm and 15 mm depending on the residual length of ground reinforcement in the advance core at the face, changes in the stratigraphy of the overlying ground and in the local geotechnical characteristics of the material excavated
- the band of ground affected by movements extended vertically for around 3 m to 4 m above the crown of the tunnel, with maximum movements of 15 to 20 mm during the passage of the face
- the area in which surface subsidence occurred was very limited. Subsidence began to occur approximately 10 m before the arrival of the face. Movements close to buildings were uniform and in line with predictions at around 6 to 7 mm. Greater than average subsidence was recorded between 25 and 40 m and was due to residual consolidation of the levels of recent alluvia. An analysis of deformation in the tunnel seems to show a correlation between surface subsidence and extrusion: The greater the extrusion the greater the subsidence
- the subsidence measured was in line with the prior predictions of mathematical models remaining perhaps a little lower than the actual predictions.

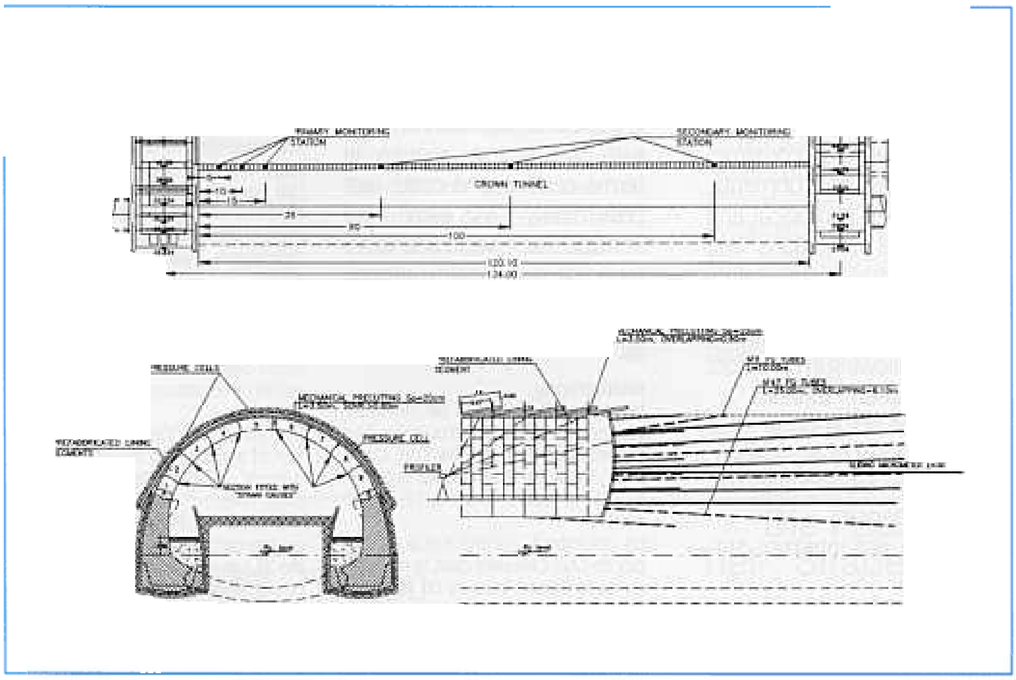
One of the purposes of monitoring was to "test" the construction system, since it was completely new and at the cutting edge of technology in the tunnelling field.

To this end convergence measurements of the pre-cut shell were taken and of deformation and stress in the arch of prefabricated segments. This was achieved by means of (Fig. 18):

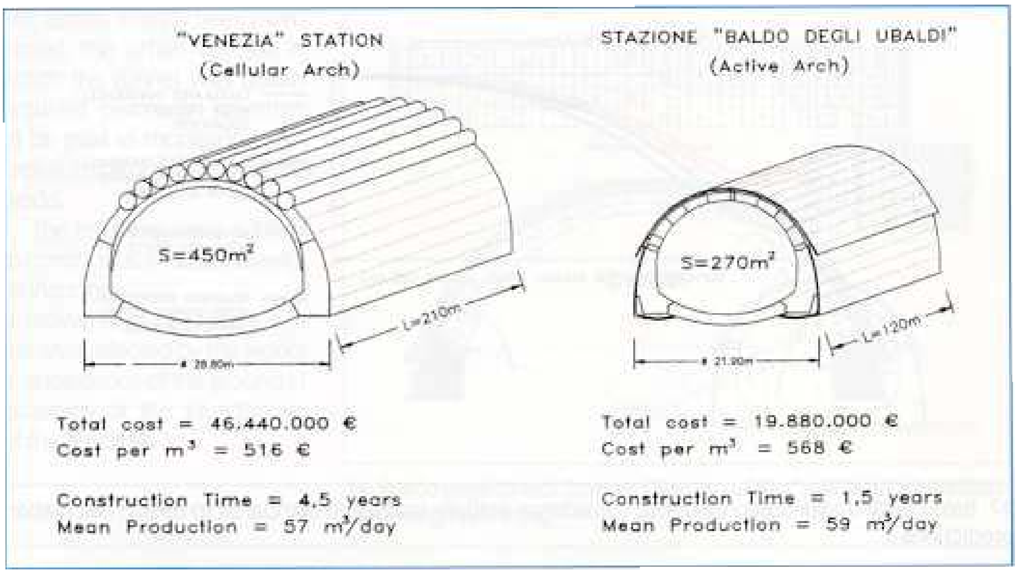
- 3 primary monitoring stations (located at 5, 10 and 15 m from the Valle Aurelia shaft) each station consisting of:
  - 3 acoustic strain gauges per segment, fitted on the nine standard segments, to monitor the state of stress in the structure and the way in which compression stress is transmitted;
  - 3 oil pressure cells fitted on segments 2, 5 and 8 at the extrados of the arch to measure pressures transmitted between the ground and tunnel structure
- 3 secondary monitoring stations (located at 36, 60 and 90 m from the same shaft) each station consisting of:



17 Baldo degli Ubaldi Station: Surface subsidence actually measured compared to design calculation predictions



18 Baldo degli Ubaldi Station: Location of the monitoring survey stations



19 Construction times and costs

– 3 acoustic strain gauges fitted on segments 2, 5 and 8 of the active arch
– 3 oil pressure cells fitted on segments 2, 5 and 8
■ targets set on segments to detect changes in position by means of laser measurements.

The results obtained from these stations showed:
■ maximum lowering of the pre-cut shell amounting to 1–1.5 mm
■ almost exclusively horizontal movements of the arch in the period of initial pre-stressing, varying between a minimum of a few mm and a maximum of 20 mm. As the face moved ahead away from the arch, settlement fell to less than 5 mm (both vertically and horizontally towards the centre of the tunnel cross-section)
■ tensile stress within the arch of prefabricated segments already reduced to zero after initial pre-stressing or if anything very slight values near the side walls of the tunnel.

During excavation of the bench, vertical and horizontal movements of the side walls were recorded. After the first two steps were excavated of 7 m and 5 m respectively, movements of a few mm were measured, lower than predicted by design calculations.

No significant variation was recorded in the other parameters measured (surface subsidence, level of the water table, etc.).

4 Conclusion

This paper has discussed two works of considerable importance, both constructed under similar conditions. Both projects involved construction in urban environments, under difficult geological and geotechnical conditions and to particularly tight safety specifications.

Briefly the two projects have the following in common:
■ large diameter tunnels
■ presence of the water table above the level of excavation
■ need for very reduced surface subsidence
■ need to not interrupt surface traffic.

It seems important to observe that faced with situations that can be classified as "not ordinary", it was possible to develop decidedly innovative "made-to-measure" construction technology such as the "cellular arch" and the already well known mechanical pre-cutting technique combined with the "active arch" method but for a span much larger than for normal applications, which allowed the multiple problems encountered to be solved with success.

Finally it is also important to state that innovative construction systems were adopted to tackle difficult ground and a difficult context with satisfactory results in terms of time and costs (approximately 516 €/m³ for Venezia Station and 568 €/m³ for Baldo degli Ubaldi Station), which were no higher than for more traditional systems (Fig. 19).

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