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# Tunnels and Metropolises

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# Mechanical pre-cutting for the construction of the 21.5 m span arch of the 'Baldo degli Ubaldi' Station on the Rome Underground

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ABSTRACT: The "Baldo degli Ubaldi" Station on the Rome Underground has a span of 21.5 m. and height of 16 m.. Due to the presence of multi-storey buildings on the surface with foundations as close as 2 m. from the extrados of the crown of the tunnel, the type of ground to be excavated and the contractual obligation to construct without any interruption to surface traffic flow, unusual design and construction methods were adopted.

## 1 INTRODUCTION

The "Baldo degli Ubaldi" station on the Rome Underground is located in the centre of the city at a depth of approximately 25 m. next to a major road route (Via Baldo degli Ubaldi) to Fiumicino Airport.

Unusual design and construction methods, which constitute the main theme of this report, were adopted due to the large dimensions of the station (a span of 21.5 m. and height of 16 m.), the presence of multi-storey buildings on the surface with foundations as close as 2 m. from the extrados of the crown of the tunnel, the type of ground to be excavated (Pliocene clays under the water table) and the contractual obligation to construct without any interruption to traffic flow along Via Baldo degli Ubaldi.

## 2. GEOLOGICAL AND GEOTECHNICAL CONDITIONS (SURVEY PHASE)

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 levels measurable in centimetres and decimetres;
- recent ground belonging to the upper band consisting of silty sands, not very compacted, and of paleoalveo soft sandy silts by the shaft on the Valle Aurelia side.

An intense geological survey campaign was carried out as part of the survey phase between 1987 and 1994. The results enabled thorough reconstruction of the stratigraphy to be performed and in particular of the paleoalveo bed by the Valle Aurelia shaft which touches the springline of the extrados of the crown.

From a hydrogeological viewpoint, numerous readings from piezometers installed in the area show the presence of a water table with a free surface not influenced by meteorological precipitation at a depth of 10 to 12 meters from the surface. Furthermore, a water table under pressure (2 bar approx.) was found inside the sandy levels of the Pliocene formation, in all probability contained within the sandy interstratifications.

From a geotechnical viewpoint, the Pliocene clays formation, the only one to be directly affected by the excavation of the station, was found to consist of overconsolidated and stiff clayey silts, characterized by the geomechanical properties given in table I below.

Table 1

| | |
|---|---|
| Unit weight | $\gamma = 20$ KN/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/sec |

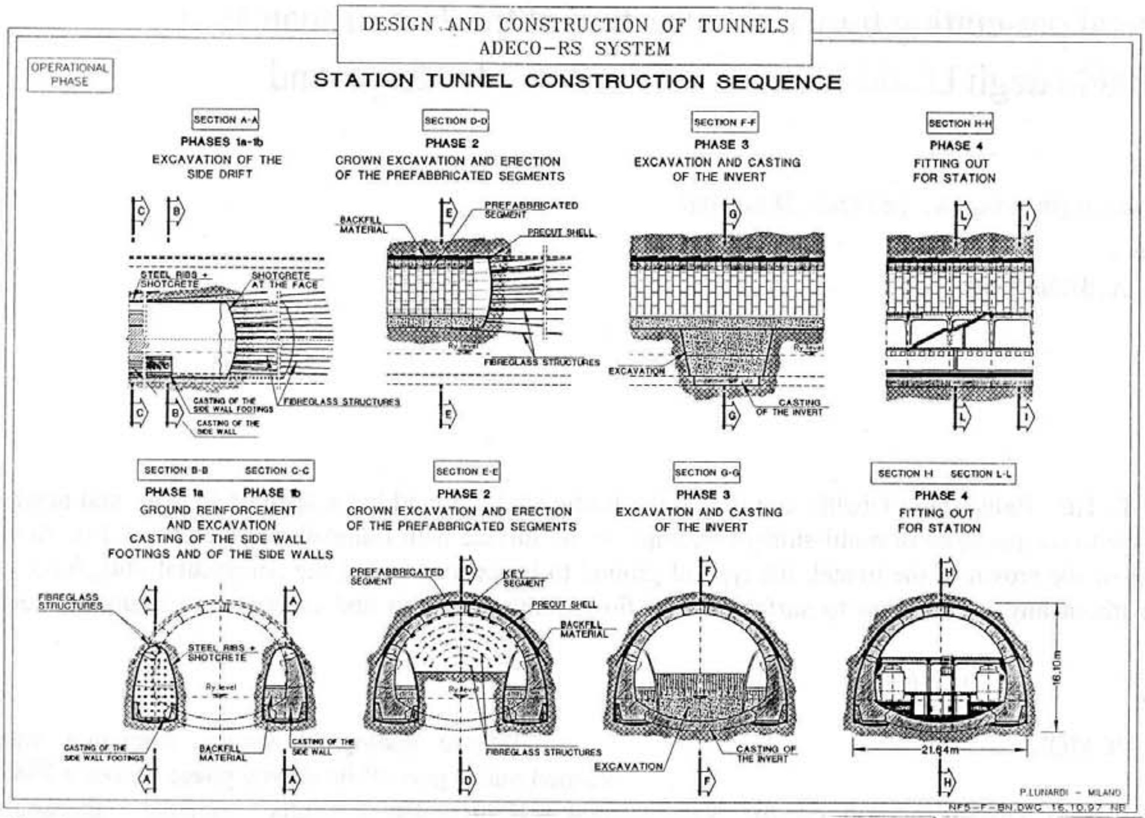
DESIGN AND CONSTRUCTION OF TUNNELS
ADECO-RS SYSTEM
OPERATIONAL PHASE
STATION TUNNEL CONSTRUCTION SEQUENCE
SECTION A-A
PHASES 1a-1b
EXCAVATION OF THE SIDE DRIFT
SECTION D-D
PHASE 2
CROWN EXCAVATION AND ERECTION OF THE PREFABBRICATED SEGMENTS
SECTION F-F
PHASE 3
EXCAVATION AND CASTING OF THE INVERT
SECTION H-H
PHASE 4
FITTING OUT FOR STATION
PREFABBRICATED SEGMENT
BACKFILL MATERIAL
PRECUT SHELL
STEEL RIBS + SHOTCRETE
SHOTCRETE AT THE FACE
FIBREGLASS STRUCTURES
EXCAVATION
CASTING OF THE INVERT
SECTION B-B
SECTION C-C
PHASE 1a
GROUND REINFORCEMENT AND EXCAVATION
PHASE 1b
CASTING OF THE SIDE WALL FOOTINGS AND OF THE SIDE WALLS
SECTION E-E
PHASE 2
CROWN EXCAVATION AND ERECTION OF THE PREFABBRICATED SEGMENTS
SECTION G-G
PHASE 3
EXCAVATION AND CASTING OF THE INVERT
SECTION H-H
SECTION L-L
PHASE 4
FITTING OUT FOR STATION
KEY SEGMENT
CASTING OF THE SIDE WALL FOOTINGS
CASTING OF THE SIDE WALL
16.10m
21.64m
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Fig. 1.

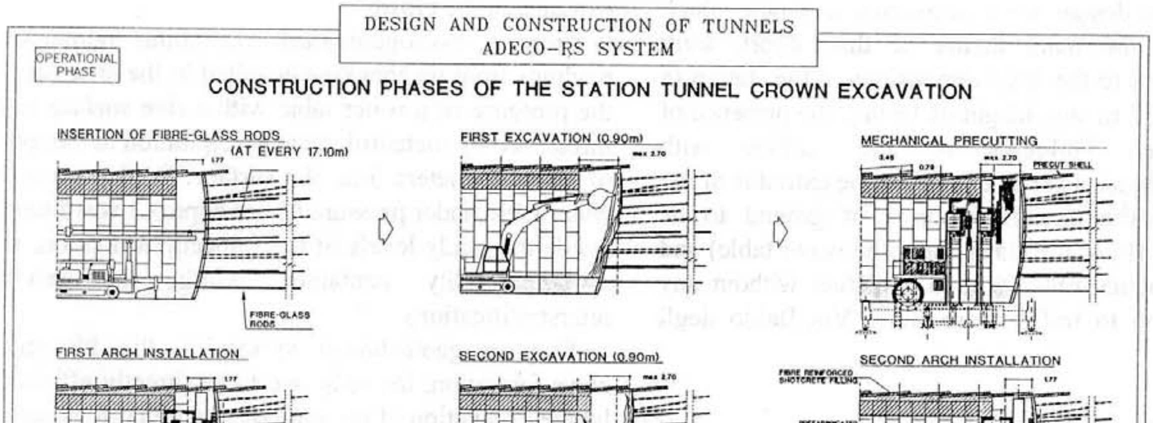
DESIGN AND CONSTRUCTION OF TUNNELS
ADECO-RS SYSTEM
OPERATIONAL PHASE
CONSTRUCTION PHASES OF THE STATION TUNNEL CROWN EXCAVATION
INSERTION OF FIBRE-GLASS RODS
(AT EVERY 17.10m)
FIBRE-GLASS RODS
FIRST EXCAVATION (0.90m)
MECHANICAL PRECUTTING
PRECUT SHELL
FIRST ARCH INSTALLATION
SECOND EXCAVATION (0.90m)
SECOND ARCH INSTALLATION
FIBRE REINFORCED SHOTCRETE FILLING
PREFABBRICATED ARCHES
THIRD EXCAVATION (0.90m)
THIRD ARCH INSTALLATION
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Fig. 2.

## 3 DESIGN ASPECTS (DIAGNOSIS AND THERAPY PHASES)

The design of the "Baldo degli Ubaldi" station tunnel was performed on the basis of the principles of the ADECO-RS (Analysis of COntrolled DEformation in Rocks and Soils) approach.

The studies carried out in the diagnosis phase and above all the interpretation of tri-axial cell extrusion test results showed that the tunnel to be constructed fell into behaviour category B (face stable in the short term).

It was immediately quite 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 requirement even if the face was split into separate headings: side drift, crown drift, bench and invert.

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

A tunnel advance system that involves reinforcement of the advance core (and thereby limits extrusion which would be immediately translated into surface subsidence) with structural elements in fibre glass was adopted for the side drifts of the tunnel, these being followed by full face excavation and lining with fibre reinforced shotcrete and steel ribs with struts for the tunnel invert and side walls in reinforced concrete.

A new construction system was designed for the crown drift combining reinforcement of the advance core with fibre glass structures and mechanical pre-cutting technology (used for the first time in the world on a span of 21.5 m.) with the "active arch" principle.

This decision was dictated by the absolute necessity of obtaining 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.

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 the companies Impregilo and Rodio and constructed by the firm Stac. It consists (Fig. 3) of a large metal portal with the same shape as the profile of the crown of the tunnel. It rests on stabilisers resting in turn 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 the prefabricated concrete segments for the final lining of the tunnel.

Once the two access shafts with a 200 $m^2$ cross section and a depth of 30 and 40 m. respectively had been excavated, at the ends of the tunnel to be constructed (once work is finished they will be used for housing service plant), construction commenced employing the following construction stages described very briefly here (Fig. 1):

1a excavation of two side drifts 5 m. in width and 9 m. in height where the side walls of the future tunnel would be after first reinforcing the advance core with fibre glass structures and lining with fibre reinforced shotcrete armoured with steel ribs fitted with struts;

1b casting of the side walls in reinforced concrete;

2 excavation of the crown of the tunnel (span of 21.5 m., height of 8.5 m with a cross section area of 125 $m^2$) after first reinforcing the advance core with fibre glass structures and placing a mechanically pre-cut shell. An "active arch" of prefabricated concrete segments was then placed immediately;

3 excavation of the remaining invert portion of the tunnel (cross section area of 90 $m^2$) and immediate casting of the invert in steps (max. of 7 m.) after construction of the crown;

4 completion of the station infrastructures with platforms and mezzanine floor and stairways to the passage ways.

## 4 CONSTRUCTION (OPERATIONAL PHASE)

After cordoning off the space required for the site and closing the two centre lanes of Via Baldo degli Ubaldi to traffic, excavation began on the two access shafts located at the ends of the future tunnel for the station (the Valle Aurelia shaft and the Aurelia Cornelia shaft) after first confining the ground around them with sheet piles Ø 1,200 mm and struts in reinforced concrete placed during excavation.

Once the start shaft was completed, the side drifts were excavated proceeding from the Aurelia Cornelia shaft to the Valle Aurelia shaft. As already mentioned, the characteristics and stress-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 to contain extrusion at the face. This was done by intense reinforcement of the advance core ahead of the face with fibre glass structures specially designed to obtain the maximum effect from the treatment. The walls of the tunnels, however, were stabilised by applying a fibre reinforced shotcrete lining, 20 cm. thick, reinforced with double IPN 180 steel ribs closed at the invert with a steel strut and by the casting of reinforced side walls. A strut was used at the height of the spring line to maintain convergence within 2 cm. (a value estimated as acceptable). The two tunnels were driven using these methods keeping the faces at a distance of at least 40 m. one behind the other without any particular problems with advance rates of about 2 m./day.

Once the side headings were finished, the side walls of the final tunnel were cast *in situ* in two stages.

The most interesting and particular part of the "Baldo degli Ubaldi" station then began, the construction of the large unsupported single arch tunnel.

Tunnel advance was by driving a crown drift followed by an invert drift and casting of the invert in steps. Work started from the Valle Aurelia shaft driving towards the Aurelia Cornelia shaft and began first of all (Fig. 2) by inserting 47 lengths of fibre glass structures, 25 m. long (minimum overlap with successive lengths of 6.10 m.) into the face to make the ground ahead of it more rigid. A shell was then placed ahead of the face in a mechanical cut (mechanically pre-cut shell) every 2.70 m, with a length of 3.50 m. and thickness of 20 cm along a 28 m. profile given the 21.5 m. net span of the tunnel.

In order to obtain a particularly strong and uniform shell, the pre-cutting technique was specially modified so that pumped instead of sprayed concrete could be used.

To do this 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 squeeze out of the cut while it was being filled.

The casting of each shell was followed by excavation (in steps of 0.90 m.) and immediate erection of the final lining at a distance of not more than 2.70 m. from the face.

This operation consisted of placing twelve prefabricated segments each weighing 6.5 tons: two segments resting on the side walls of the tunnel, 9 standard segments and a key segment. Once the arch was in position the space between it and the mechanically pre-cut shell was filled with a sprayed concrete containing additives while the arch was still resting on the machine. Initial prestressing (40 ton) of the entire arch was then performed using two 360 ton Freyssinet jacks (maximum travel of 3.5 cm.) housed in the key segment. This resulted in making the arch immediately active and self supporting, capable of halting any deformation phenomena that may have started and even of correcting elastic deformation already suffered by the pre-cut shell.

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 and thereby reduced the risk of surface subsidence enormously, while maintaining advance rates of 0.7 to 0.9 metres of finished crown heading per day.

Once the crown of the tunnel was completed, excavation and casting of the invert was carried out in steps and this will be followed by full prestressing of the lining arches to 360 tons needed to obtain the final centring of the stresses produced in them.

The arch thus produced will need no further lining and impermeability is guaranteed by the carefully designed neoprene seals and by injections of a waterproofing mixture into tubes provided inside the segments.

## 5 MONITORING DURING CONSTRUCTION

The particular location of the "Baldo degli Ubaldi" station in an urban environment meant that it was of fundamental importance not only to monitor the usual stress strain behaviour of the tunnel itself but also to continuously monitor the effects of the works in terms of surface subsidence.

Consequently the following was carefully and continuously monitored:

- movements of buildings located in the area affected by the works;
- subsidence of the foundations of the buildings;

- changes in the levels of the surface and deep water tables;
- extrusion of the ground core at the face and convergence of the cavity;
- the development of stress and strain inside the lining of prefabricated concrete segments.

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

### 5.1 *Monitoring during excavation of the access shafts and side drifts*

During this phase the main purpose of monitoring was to ascertain the size and effect of subsidence on buildings.

If exception is made for the local effect of a marked consolidation phenomenon of the paleoalveo silt-sandy ground close to building G - due to changes in the hydrogeological equilibrium caused by the excavation of the shaft - and promptly halted by means of a suitable intervention of confinement of the foundation ground concerned, the subsidence values measured on the surface during the excavation of the two side drifts never exceeded 8 to 10 mm for both headings (Fig. 3). As far as extrusion at the face is concerned, this remained on average, during the more delicate passages, below one centimetre while two centimetres 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 lengths of fibre glass inserted in the core decreased with tunnel advanced (see Fig. 4).

### 5.2 *Monitoring during excavation of the crown and invert headings of the Station tunnel*

The plan for monitoring the tunnel for the station involved the following:
- topographical extrusion measurements (with the face halted) and 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 buildings on the surface was monitored at the same time. The measurements showed that (Fig. 3 and Fig. 4):
- cumulative subsidence remained on average within 10 to 15 mm 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 to 4 metres above the crown of the tunnel with maximum movements of 15 to 20 mm during the passage of the face;
- the subsidence basin on the surface was very small. Subsidence began to occur 10 m. before the arrival of the face. Movements near buildings were uniform and corresponded to those forecast, being in the order of 6 to 7 mm. Values greater than average observed at metre 25 to metre 40 are to be attributed to residual consolidation of recent alluvial levels. An 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 new construction system employed, since this was absolutely new and innovative in the field of underground works.

Convergence of the pre-cut shell and deformation and stress measurements of the arch of prefabricated segments were therefore taken by setting up the following:
- 3 primary stations (located at a distance of 5, 10 and 15 m. from the Valle Aurelia shaft) each consisting of:
    - 3 acoustic strain gauges fitted on the nine standard segments to measure the stress state in the structure and how the compression stress is transmitted;
    - 3 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.
- 3 secondary stations (located at a distance of 36, 60 and 90 m. from the Valle Aurelia shaft) each consisting of:
    - 3 acoustic strain gauges, fitted on segments 2, 5 and 8 of the active arch;

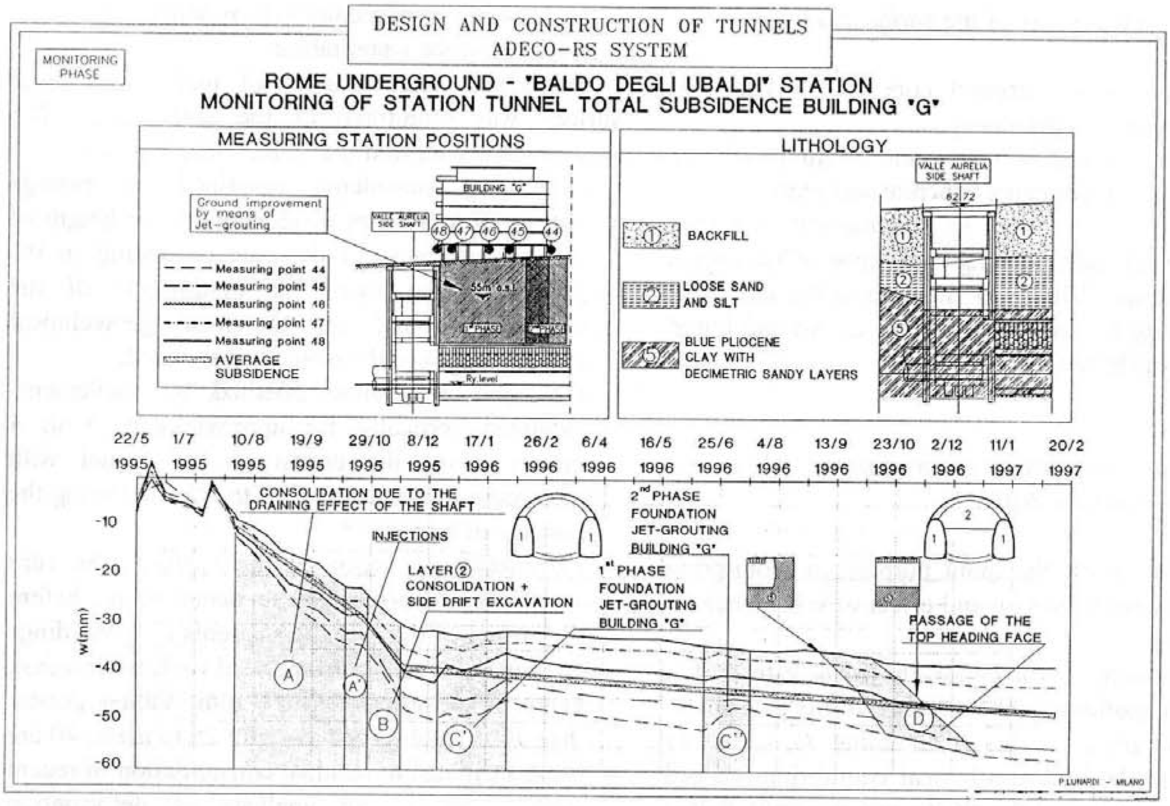
DESIGN AND CONSTRUCTION OF TUNNELS
ADECO-RS SYSTEM
MONITORING PHASE
ROME UNDERGROUND - "BALDO DEGLI UBALDI" STATION
MONITORING OF STATION TUNNEL TOTAL SUBSIDENCE BUILDING "G"
MEASURING STATION POSITIONS
Ground improvement by means of Jet-grouting
BUILDING "G"
VALLE AURELIA SIDE SHAFT
Measuring point 44
Measuring point 45
Measuring point 46
Measuring point 47
Measuring point 48
AVERAGE SUBSIDENCE
LITHOLOGY
BACKFILL
LOOSE SAND AND SILT
BLUE PLIOCENE CLAY WITH DECIMETRIC SANDY LAYERS
22/5 1995
1/7 1995
10/8 1995
19/9 1995
29/10 1995
8/12 1995
17/1 1996
26/2 1996
6/4 1996
16/5 1996
25/6 1996
4/8 1996
13/9 1996
23/10 1996
2/12 1996
11/1 1997
20/2 1997
w(mm)
CONSOLIDATION DUE TO THE DRAINING EFFECT OF THE SHAFT
INJECTIONS
LAYER② CONSOLIDATION + SIDE DRIFT EXCAVATION
1st PHASE FOUNDATION JET-GROUTING BUILDING "G"
2nd PHASE FOUNDATION JET-GROUTING BUILDING "G"
PASSAGE OF THE TOP HEADING FACE
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Fig. 3.

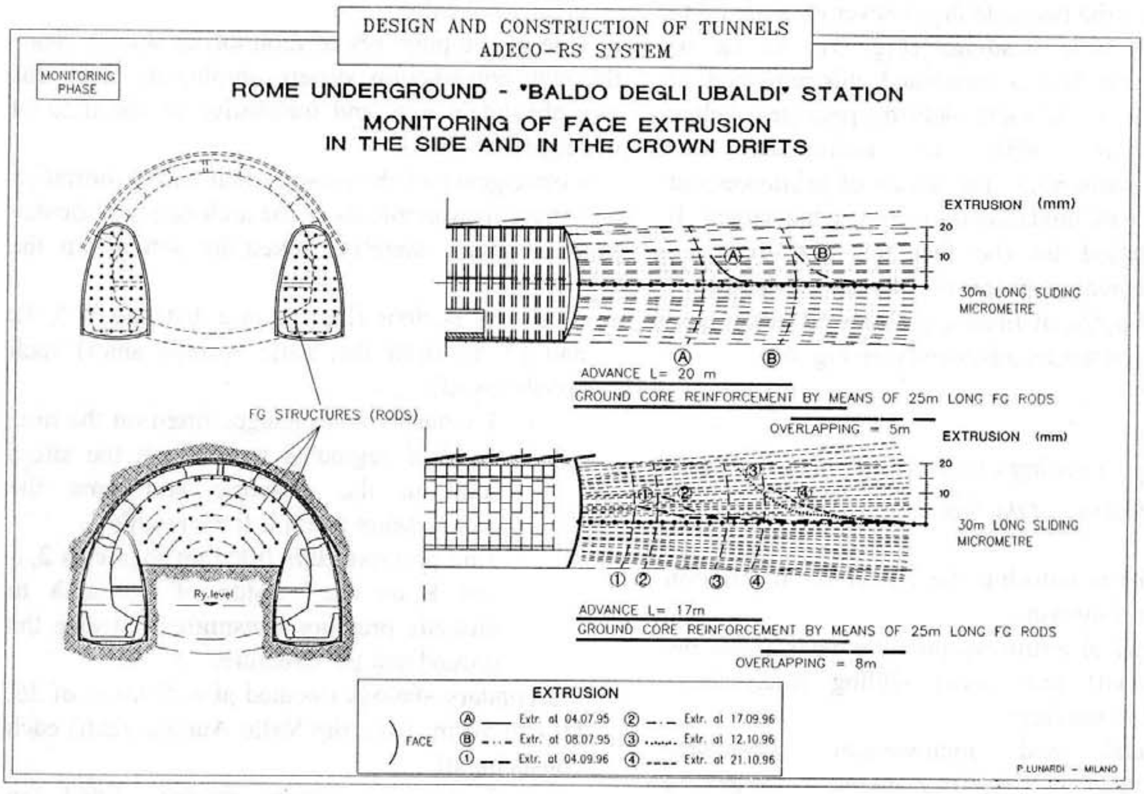
DESIGN AND CONSTRUCTION OF TUNNELS
ADECO-RS SYSTEM
MONITORING PHASE
ROME UNDERGROUND - "BALDO DEGLI UBALDI" STATION
MONITORING OF FACE EXTRUSION
IN THE SIDE AND IN THE CROWN DRIFTS
EXTRUSION (mm)
30m LONG SLIDING MICROMETRE
ADVANCE L= 20 m
GROUND CORE REINFORCEMENT BY MEANS OF 25m LONG FG RODS
OVERLAPPING = 5m
FG STRUCTURES (RODS)
Ry.level
EXTRUSION (mm)
30m LONG SLIDING MICROMETRE
ADVANCE L= 17m
GROUND CORE REINFORCEMENT BY MEANS OF 25m LONG FG RODS
OVERLAPPING = 8m
EXTRUSION
FACE
Ⓐ Extr. at 04.07.95
Ⓑ Extr. at 08.07.95
① Extr. at 04.09.96
② Extr. at 17.09.96
③ Extr. at 12.10.96
④ Extr. at 21.10.96
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Fig. 4.

- 3 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 pre-cut shell were between 1 and 1.5 millimetres;

· 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 20 mm. At a distance from the face after tunnel advance, settling movement was less than 5 mm. (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 side walls.

As far as the excavation of the tunnel invert is concerned (currently underway), vertical and horizontal movements of the tunnel side walls are measured. After the first few sections, 7 and 5 m. in length respectively, values measurable in millimetres were obtained, less than forecast.

For the time being, no significant changes have been observed in the other values monitored (surface subsidence, level of the water tables, etc.).

## 6. CONCLUSIONS

Design and construction problems concerning the "Baldo degli Ubaldi" underground station currently under construction for the extension of line A of the Rome Underground have been illustrated. It is a large tunnel with a 21.5 m. span single arch, 16 m. in height at a depth of 25 m. under construction in difficult stress-strain conditions close to residential buildings and the design and construction constraints are particularly strict.

To build the station, a new construction system was designed which combines reinforcement of the advance core with fibre glass structures and mechanical pre-cutting technology (used for the first time in the world on a span of 21.5 m.) with the "active arch" principle in order to activate the final lining of the tunnel at a distance of less than 3 m. from the face thereby reducing the risk of surface subsidence enormously.

The works, begun in 1992, are at an advanced stage: the system functions excellently and so far has furnished higher than average advance rates for this type of project and ground If exception is made for the subsidence resulting from the consolidation of the ground at the Valle Aurelia shaft, which was promptly halted, surface subsidence values have so far been minimal and less than those forecast by design calculations.

## ACKNOWLEDGEMENT

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## REFERENCES

Lunardi, P. 1994. "Progetto e costruzione di gallerie secondo il metodo basato sull'analisi delle deformazioni controllate nelle rocce e nei suoli - Parte prima: Presostegno e precontenimento". *Quarry and Construction*, 3

Lunardi, P. 1995. "Progetto e costruzione di gallerie secondo il metodo basato sull'analisi delle deformazioni controllate nelle rocce e nei suoli - Parte seconda: Ruolo e risultati della ricerca" sperimentale". *Quarry and Construction*, 3

Lunardi, P. 1995, "L'importanza del precontenimento del cavo in relazione ai nuovi orientamenti in tema di progetto e costruzione di gallerie". *Gallerie e grandi opere in sotterraneo*, 45

Lunardi, P. 1996. "Progetto e costruzione di gallerie secondo il metodo basato sull'analisi delle deformazioni controllate nelle rocce e nei suoli" - Parte terza: Proposta del nuovo approccio". *Quarry and Construction*, 4

TECHNICAL DATA CARD
Work: Line A of Rome Underground
Owner: Municipality of Rome
Concessionary: INTERMETRO S.p.A.
General Contractor: IMPREGILO S.p.A.
Special Contractor: RODIO S.p.A.
Design: ROCKSOIL S.p.A. (Milan)