Title: Design and construction of an underground station tunnel with interconnected galleries for achieving high advance rates and controlling settlements

Authors' identification: Spiros Massinas, Omikron Kappa Consulting Ltd, Athens, Greece
Nikos Koronakis, Omikron Kappa Consulting Ltd, Athens, Greece
Panayiotis Kontothanassis, Omikron Kappa Consulting Ltd, Athens, Greece

Summary: The paper describes the detailed engineering and construction sequence of Eleonas station tunnel and the associated complex of interconnected underground openings and relative civil works, which is considered to be among the most complicated stations of Athens Metro. The station tunnel alignment underpasses a significant Athens avenue with heavy traffic and the influence zone of the complex includes several commercial buildings and manufacturing sites. Specific problems encountered during the design refer to the four big cuts in the temporary shell of the station tunnel for starting the excavation of the inclined galleries up to the upper part of the main building, as well as to the construction of the cross gallery just above the crown of the station tunnel. Important design issues for controlling displacements of the underground structures and surface settlements were anticipated, due to the close proximity of the interconnected openings and their vicinity with the building pit.

GENERAL DESCRIPTION OF ELEONAS UNDEGROUND COMPLEX

PROJECT LAYOUT

Eleonas station (ex Agios Savas) underground complex is a part of the new LINE 3 extension of Athens Metro. The project is considered to be very complicated since it contains an underground station cavern of 110m in length, the main building almost adjacent to the station tunnel and a cut & cover dome (at the other side of the station tunnel) which will be connected with the main building via an underground cross gallery above the station's tunnel (Figures 1 & 2). The whole complex is completed by the presence of four underground inclined stair galleries (A,B,C & D) which provide access to the station tunnel (Figure 1).

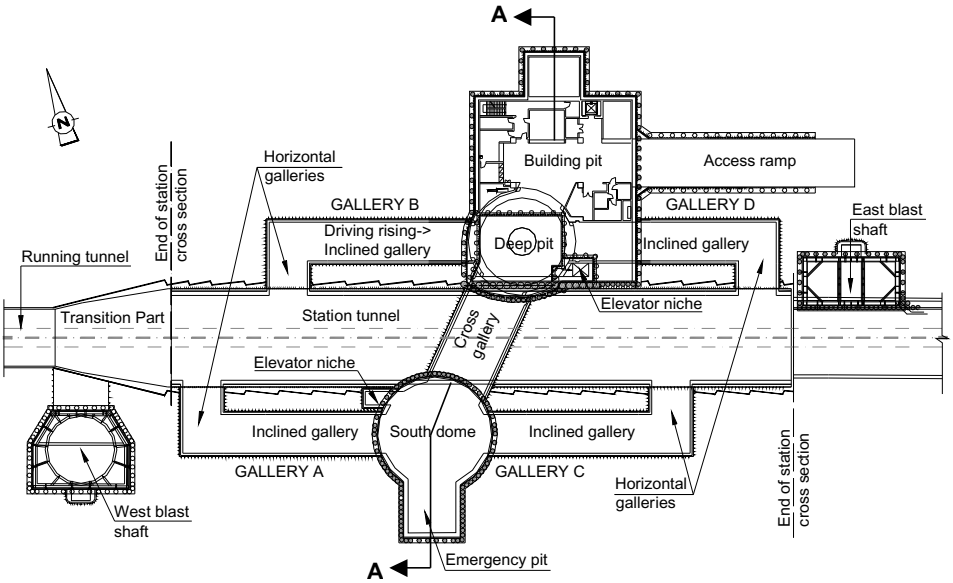
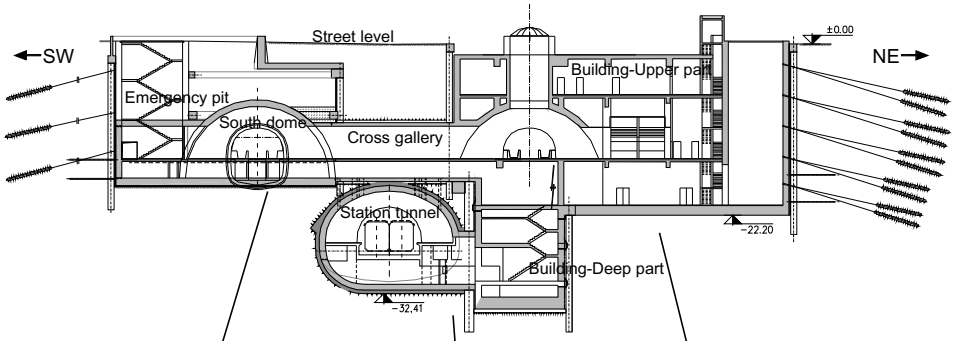


Figure 1: Plan view of Eleonas underground complex at the final construction stage.

Figure 2: Eleonas station underground complex at the final construction stage (section A-A).



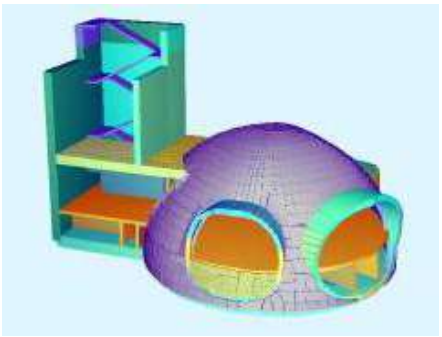


Figure 3: South dome with emergency exit (3D model used for final lining analysis).

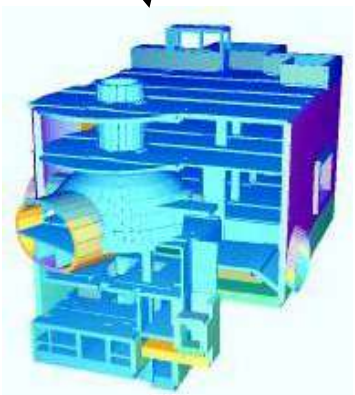


Figure 4: Main building (3D model used for final lining analysis).

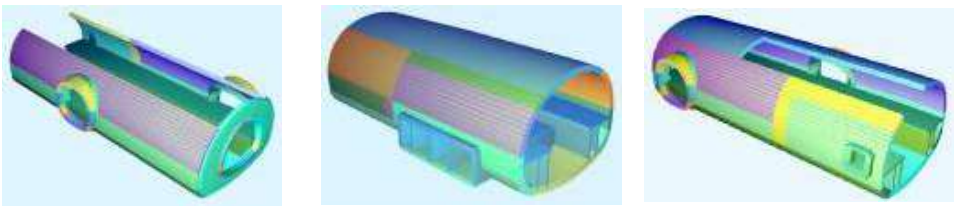


Figure 5: Station tunnel final lining (3D model used for final lining analysis).

The piling work in the area of Eleonas Station building pit started at January 2003 and the contractor (J/V AKTOR SA-IMPREGILO SpA) will fulfil the civil works during next year.
According to the construction sequence prescribed by the design, the following discrete stages are foreseen:

- Installation of the retaining system of the building pit and south dome (reinforced concrete piles and prestressed anchors) and partial excavation of the building pit.
- Excavation of the station tunnel with forepoling method and top heading and bench.
- Increase of the stiffness of the temporary shell of the station in the areas before and after the four big cuts, for starting the excavation of the horizontal part of the galleries.
- Excavation of the first part (horizontal) of the galleries and installation of the final lining of the station tunnel.

- Excavation of the deep part of the building pit with special application of a top-down method.
- Concreting works of the building (up to a certain level) and the dome.
- Construction of the remaining underground parts (inclined galleries and cross gallery).
- Concreting works of the remaining part of the building.

EXCAVATION AND TEMPORARY SUPPORT OF STATION TUNNEL

The overburden thickness of the station's tunnel is approx. 18m. The geological formation at the depth of the station tunnel consists of conglomerates and marls with small intercalations of sand and clay.

The station tunnel design and construction is based on the application of NATM tunnelling, in two discrete stages (top heading and bench) and on the systematic use of grouted forepoling umbrellas consisted of tubes St37, Φ193.7/179.5mm, 12 m long, placed at average axial distances of 0.60m per 6 round lengths of top heading (every 6m) and fiberglass bolts in the face of the tunnel. The temporary shell consists of 40cm C25/30 shotcrete (with wire mesh and steel sets) and in the junction areas of temporary invert and elephant feet the structural thickness requirements increase for providing a more rigid structural system with smooth geometrical corners and for avoiding stress concentrations.
Excavation is performed by the use of a hydraulic hammer.

The excavated cross section of the station's tunnel ranges between 195m^2 (at the minimum excavation) to 215m^2 (at the maximum excavation enlargement due to forepoling). The width of the top heading and bench is 20.2m, the total height of the tunnel 14.25m (in the maximum enlargement), while the excavated height of the top heading exceeds 8m.

In order to implement the first series of forepoles, it was necessary to enlarge the running tunnel's cross section, thus creating the required space for installing the forepole tubes at the station's cross section (Figure 1). The enlargement was gradually increased from the running tunnel's smaller cross section to the station's cross section, creating a stable and statically acceptable excavation. A transition part of the running tunnel was constructed from the running tunnel to the station, 20m long, with minimum and maximum excavated cross section of 91m^2 and 213m^2, respectively.

The excavation of the A phase of the station tunnel began at middle of March 2004 and ended at the end of October 2004. The total excavation of the station was fulfilled at January 2005.

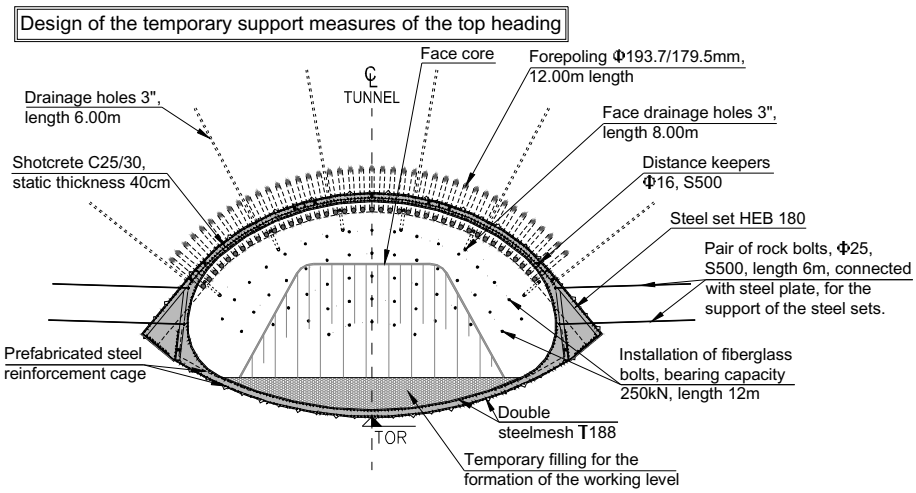


Figure 6: Temporary support measures of the station tunnel's top heading.

Photo 1: Bench excavation of the station tunnel.

Photo 2: Final excavation geometry of the station tunnel.

HORIZONTAL AND INCLINED GALLERIES

GEOMETRICAL DESCRIPTION OF GALLERIES

According to the general design layout of Eleonas underground complex, four galleries will be constructed, two on west (gallery A) and east (gallery C) side of the south dome and two on the west (gallery B) and east (gallery D) side of the building (Figures 1 & 9).
Each gallery consists of horizontal and inclined parts, as presented in figures 10, 11 and 12.

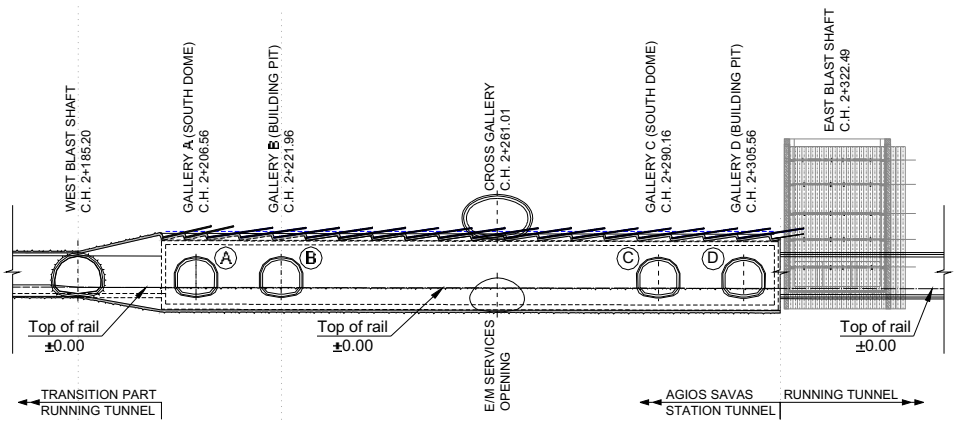


Figure 7: Positions of inclined galleries in relation to the longitudinal section of the station tunnel.

The axis of the horizontal parts 1 and 2 is perpendicular to the station tunnel's axis, while the axis of horizontal parts 3 and 5 is parallel. Part 4 is the inclined part of the gallery with its axis parallel to the station tunnel's axis. The gallery D is the only one which does not include part 5 (see Figure 10). The inclined part of each gallery is 30^{o} steep with a horizontal length of approx. 18.8m for galleries A, B and C and 13.6m for D.

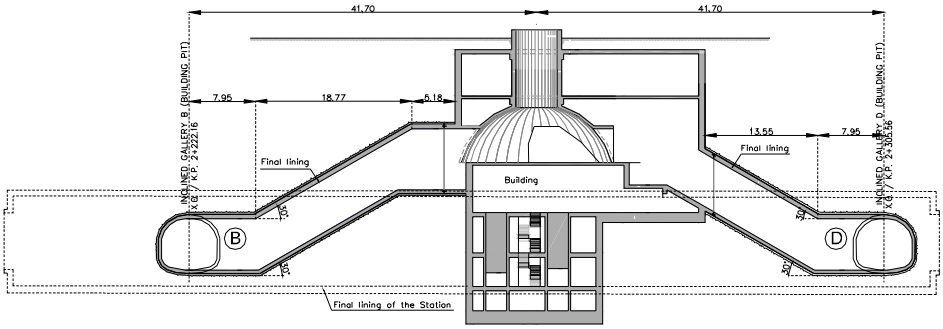


Figure 8: Longitudinal section of galleries B, D in relation to the station building.

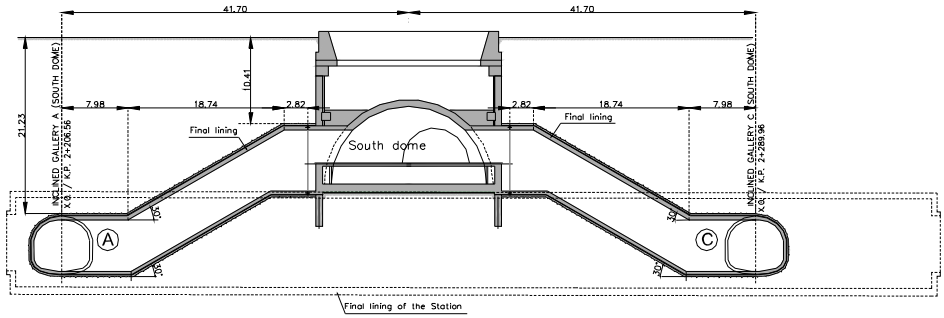


Figure 9: Longitudinal section of galleries A, C in relation to the south dome.

The overburden thickness of the galleries varies from 22m for deeper parts (1, 2 and 3) to approx. 11m (for part 5). The geological formation at the depth of parts 1, 2 and 3 consists of conglomerates and marls with small layers of sand and clay. For shallow part 5 the main geological formation is sand and clay.

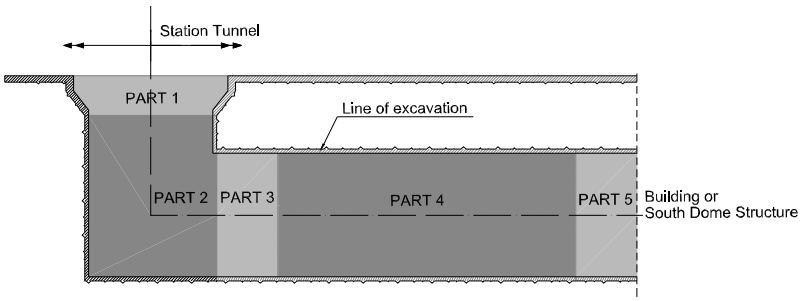


Figure 10: Positions of defined parts 1 to 5 in each gallery.

CONSTRUCTION OF BIG CUTS IN STATION TUNNEL'S TEMPORARY SHELL (EXCAVATION OF PART 1)

For starting the excavation of the galleries, four big cuts (approx. 10m in width) should be constructed in the temporary shell of the station tunnel. In order to provide an adequate support system (since the demolition of part of the temporary shell of the station tunnel and

the excavation of the galleries would reduce the local stiffness and bearing capacity of the temporary shell of the station) for controlling displacements of the underground works and surface settlements, the construction of a stiffening ring, in each side of the galleries entrances, was considered necessary. Consequently the loads would be redistributed on the side areas of the galleries entrances, where the stiffening rings had already been implemented.

The forepole umbrellas Φ193.7/179.5mm, 12m long, installed every 6m during the excavation of the station tunnel, provided a stiff system capable to bridge the 10m span of galleries entrances and to transfer the redistributed loads on the side area of galleries entrances where the stiffening rings had already been implemented. The stiffening rings were installed at the end of construction phase A due to the geometrical limitations of the mechanical equipment. An additional stiffening system at the end of the station tunnel was required for the excavation of gallery D.

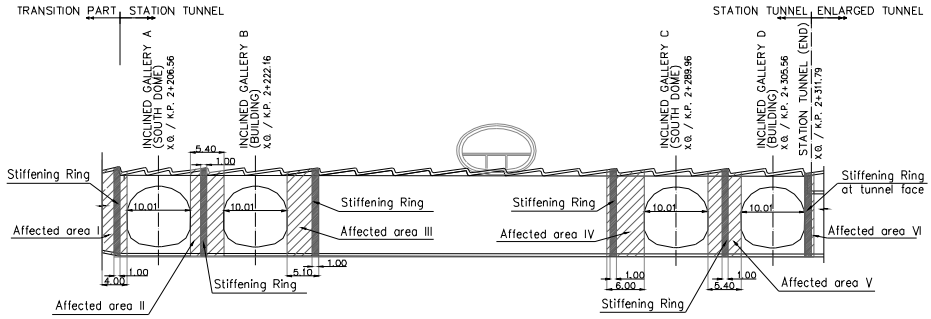


Figure 11: Arrangement of the stiffening rings in station tunnel.

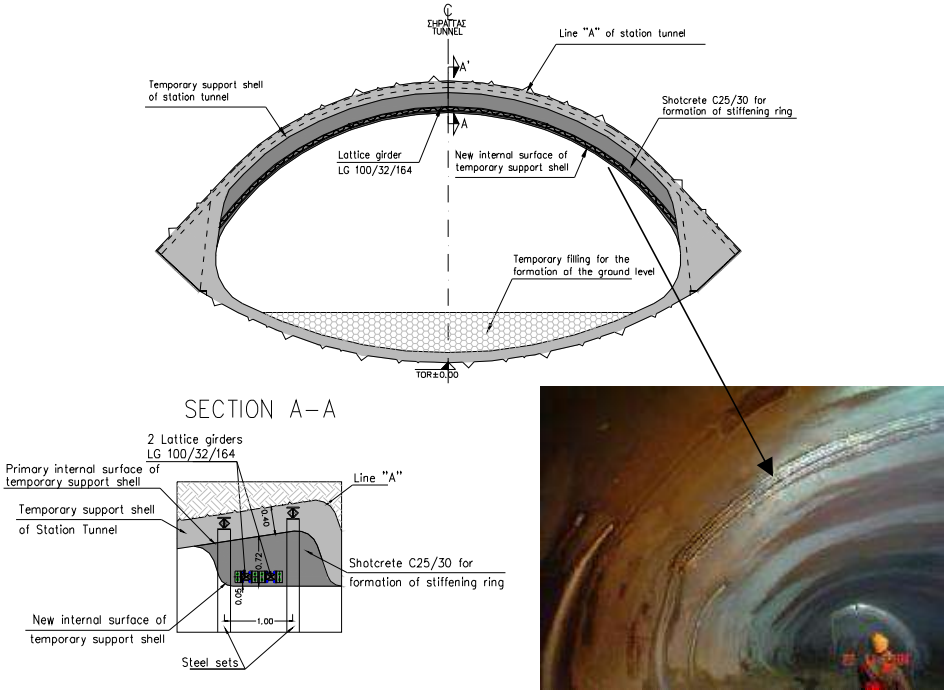


Figure 12: View and detail (section A-A) of the stiffening rings.

Photo 3: Installation of the stiffening rings.

After the completion of construction phase B of the station tunnel, the parts 1 (3m length) of galleries A and D were excavated and temporarily supported and then the excavation of part 1 of galleries B and C followed.

The excavated cross section of part 1 of the galleries ranged from 88m^2 (at the maximum excavation) to 53m^2 (at the minimum excavation). The enlargement at the beginning of part 1 was necessary due to geometrical limitations of the final lining of the station tunnel (figure 13). The excavation and temporary support system was based on the application of NATM tunneling in one stage (top heading and final invert). The temporary shell consisted of 40cm C25/30 shotcrete (with wire mesh) and in the junction areas of final invert and elephant feet the structural thickness requirements were increased for providing a more rigid structural system. In the face of the galleries, fiberglass bolts were implemented along with drainage holes for water pressure relief. Steel sets HEB140 were placed every 1m and fully grouted rockbolts. Finally the construction of part 1 was executed under the protection of one row of self drilling spiles.

The stiffening rings installed prior to the execution of the big cuts, secured the temporary shell of the station tunnel. It is noted that no additional displacements in the temporary shell of the station tunnel or surface settlements were measured during the excavation of part 1 of the galleries. Thus, the application of such a stiff system proved to be very efficient for the safety of the underground works as long as for the surface structures.

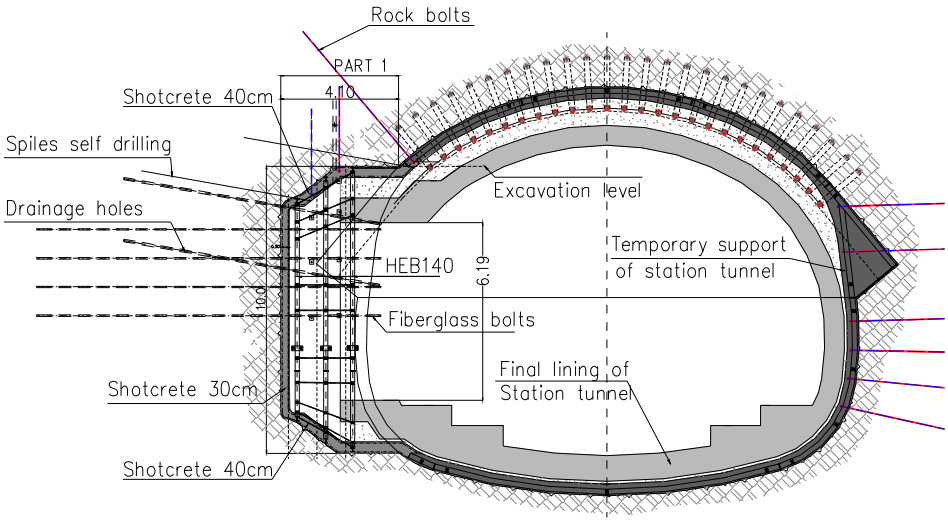


Figure 13: Temporary support measures for excavation of part 1 of galleries.

Photo 4: Demolition of station tunnel's shotcrete shell.

Photo 5: Installation of the second steel set HEB140.

The excavation and temporary support of part 1 of the galleries was necessary in order to facilitate the installation of the final lining of the station tunnel up to the construction joint, which was foreseen at a 2m distance from the galleries entrances. The specific geometrical dimensions of the final lining had been derived by the structural analysis requirements in order to withstand all the design loads in the final stage.

Photo 6: Protective measures on final excavation face of part 1.

Photo 7: Installation of final row of self drilling spiles for future excavation of part 2. Gallery's face is secured with fibreglass bolts and 30cm shotcrete.

INSTALLATION OF STATION TUNNEL'S FINAL LINING – EXCAVATION AND TEMPORARY SUPPORT OF PARTS 2 TO 5 OF GALLERIES

In order to secure the already constructed underground station tunnel, the implementation of the final lining of the station tunnel was necessary in order to withstand all the additional loads due to the construction of the deep part of the building (Figures 2, 4 & 8), the excavation and temporary support of parts 2 to 5 of the galleries and finally the construction of the cross gallery above the crown of the station tunnel.

Photo 8: Installation of steel reinforcement in the final invert of the station tunnel.

Photo 9: Completed final invert of station tunnel.

Photo 10: Installation of waterproofing membrane in the crown of the station tunnel.

After the completion of the station tunnel's final lining, the excavation and temporary works should proceed only in gallery A, up to the south dome piles. The reason was that gallery A was not affected by the presence of the prestressed anchors of the building pit (Figure 14).

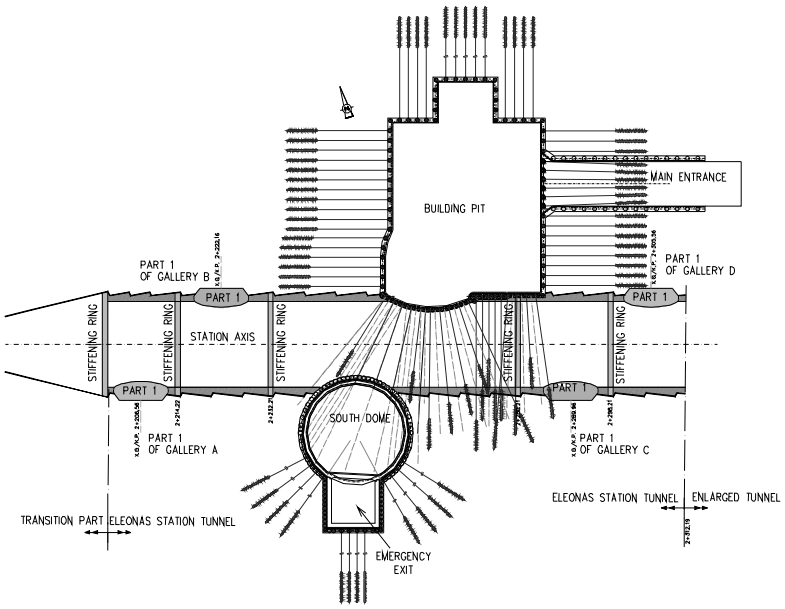


Figure 14: Plan view of Eleonas station underground complex at the stage of station tunnel's final lining installation.

The excavation works on galleries B, C and D should not initiate before the partial concreting of building had already been finished. Specifically, the perimetric walls of building should have been constructed up to elevation -7m and the relevant stiffening slabs sould have been built up to elevation -15m. The permanent support of the partial concrete structure of building would allow the unlocking of the relevant prestressed anchors, which lie within the surrounding area of galleries B, C and D. After the unlocking procedure is assured, the excavation and temporary support of galleries B, C and D can be safely executed.

EXCAVATION AND TEMPORARY SUPPORT OF CROSS GALLERY

According to the general design layout of Eleonas station complex, the final underground construction step will be the excavation and temporary support of the cross gallery (Figures 1, 2), which connects the main building (Figure 4) with the south dome (Figure 3). The construction of the cross gallery is in accordance with the timetable of the Eleonas station's complex construction works. Thus, the excavation works concerning the cross gallery should start after the construction of the final lining of the station's tunnel (in order to withstand the additional loads), the partial concreting of the main building (in order to unlock the prestressed anchors which are in the vicinity of the cross gallery - Figure 14) and the final lining of the south dome (in order to cut the piles of the south dome and start the excavation (Figure 15).

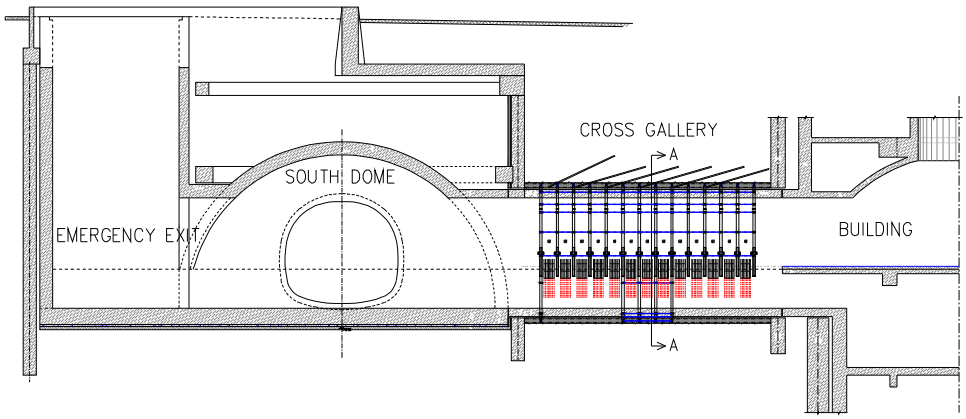


Figure 15: Longitudinal section of the cross gallery.

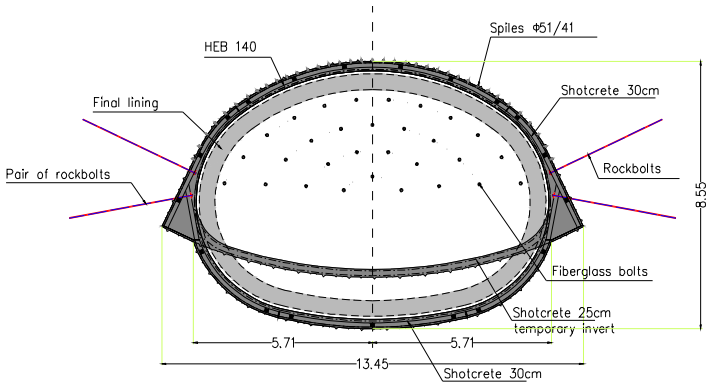


Figure 16: Temporary support measures of the cross gallery (section A-A).

The overburden thickness of the cross gallery is approximately 10m and the geological formation consisted of sand and clay. The excavation cross section is 83m^2 and the temporary support consists of shotcrete, rockbolts, spiles, steel sets and fibreglass anchors placed in the tunnel's face.

The cross gallery will be excavated in two discrete phases (top heading and bench) between the partially concreted south dome and the main building, as well as, over the fully concreted station tunnel. Thus, the cross gallery's temporary shell is not subjected to any

significant displacements, due to the stiff existing sub-base, which consists of the final lining of the station tunnel. However, due to the soil-like formations at the gallery's face and the low overburden, surface settlements are expected to be developed mainly due to the relaxation of the excavated face. The application of a heavy spilling umbrella (Φ51/41, 35cm axial distance, 4.5m length) in accordance with the installation of fiberglass bolts in the gallery's face, would constrain the surface settlements and angular distortion to their minimum values.

According to the design estimations, the excavation of the cross gallery will cause additional settlements of 15mm, at the midpoint of the total length of the cross gallery, only in a small area in the surface, due to the fact that the heavy spilling umbrella, the fiberglass bolts as long as the presence of the perimetric wall of the building, the final lining of the south dome and the final lining of the station tunnel, stiffen the soil mass system and delimit its relaxation.

CONCLUSIONS

The design and construction of the station tunnel, the horizontal and inclined parts of galleries A, B, C and D as long as the cross gallery are based on the application of NATM tunnelling. Special problems encountered during the design process refer to the four big cuts in the temporary shell of the station tunnel for starting the excavation of the galleries, as well as to the construction of the cross gallery just above the crown of the station tunnel.

The whole alignment underpasses a significant Athens avenue with heavy traffic and the influence zone of the underground complex includes several commercial buildings and manufacturing sites. The Eleonas station complex is considered to be among the most complicated stations of Athens Metro.

The choice of the installation of the stiffening rings in the temporary shell of the station tunnel has proven to be successful for the project, since the construction of the four big cuts did not affect the stability of the underground constructions and the surface structures. Due to the application of such a stiff system no additional surface settlements were measured during the excavation of the first part of galleries.

Furthermore the installation of the final lining of the station tunnel proved to be a rational and safe decision:

- providing controllable surface settlements when the excavation and temporary support of the cross gallery will start,
- withstanding all the additional loads, due to the construction of the deep part of building (by top down method) and due to the excavation and temporary support of parts 2 to 5 of the galleries.

It is noted that the application of a significantly heavy spilling umbrella in accordance with the installation of fiberglass bolts in cross gallery's face, would constrain the surface settlements and angular distortion to their minimum values.

The contractor (J/V AKTOR S.A. – IMPREGILO S.p.A.) and the designer (Omikron Kappa Consulting Ltd – Ingenieurburo EDR GmbH), in order to confront the complexity of the design and the increased requirements for premium quality of construction, created a close contact system of information exchange.

The main feature of this system was the systematic involvement of the Designer on Site team. The presence of such a team was necessary for all the revealing issues of the whole metro line under construction by J/V, as it provided the ability of immediate and efficient response to the upcoming difficulties of the project.

Thus, the daily contact between the Designer and the Contractor, as well as the accurate, fast and fully informing of the Designer, made the implementation of changes and minor or more extensive modifications of the design during execution, possible.

Finally, the development of an extensive and close to the tunnel advance geotechnical monitoring program, provided the necessary data for evaluation of the design-construction coupled system.

REFERENCES

(1) Omikron Kappa Consulting Ltd and Ingenieurburo EDR GmbH, March 2004, Excavation and temporary support of the Station tunnel, KP 2+200.32 to KP 2+312.19 (Detailed Final Design 1).
(2) Omikron Kappa Consulting Ltd and Ingenieurburo EDR GmbH, December 2004, Excavation and temporary support of the horizontal and inclined galleries of the Station tunnel (Detailed Final Design 1).
(3) Omikron Kappa Consulting Ltd and Ingenieurburo EDR GmbH, March 2005, Excavation and temporary support of the Cross Gallery (Detailed Final Design 1).
(4) Omikron Kappa Consulting Ltd and Ingenieurburo EDR GmbH, January 2005, Final lining of the Station tunnel, KP 2+200.32 to KP 2+312.19 (Detailed Final Design 2).
(5) Omikron Kappa Consulting Ltd and Ingenieurburo EDR GmbH, January 2005, Final lining of Building (Detailed Final Design 2).
(6) Omikron Kappa Consulting Ltd, Daily Reports from the Designer on Site, December 2004, January-February 2005.

UNDERGROUND CONSTRUCTION 2005

London, 26-27 October 2005

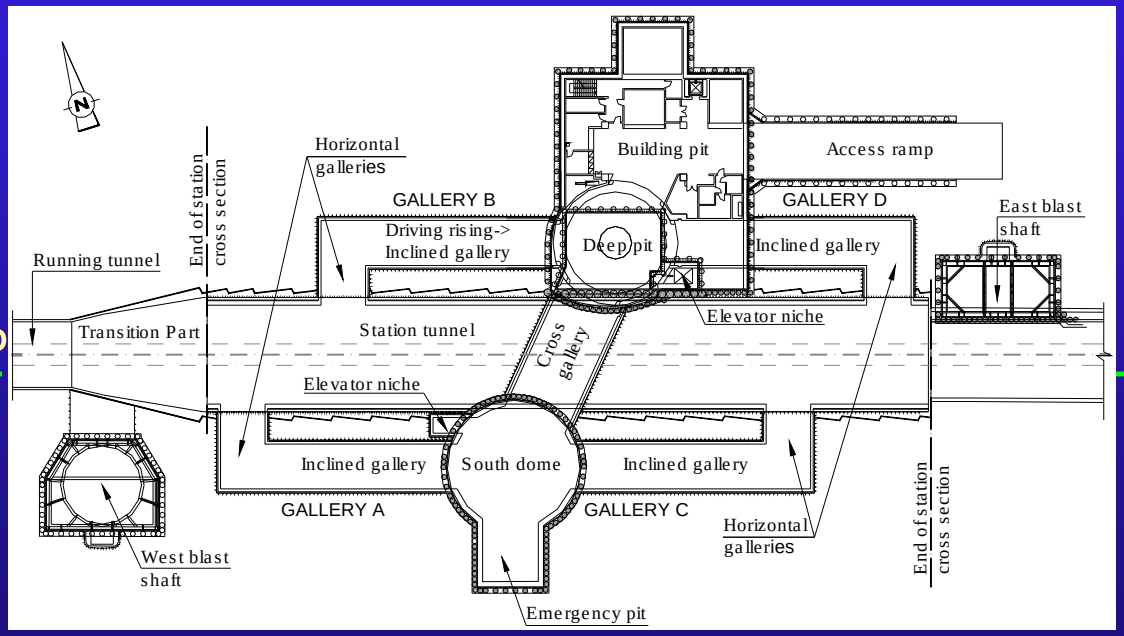
DESIGN AND CONSTRUCTION OF AN UNDERGROUND STATION TUNNEL WITH INTERCONNECTED GALERIES IN ORDER TO ACHIEVE HIGH ADVANCE RATES AND TO CONTROL SETTLEMENTS

Authors:

- S. MASSINAS – OMIKRON KAPPA CONSULTING Ltd
- N. KORONAKIS – OMIKRON KAPPA CONSULTING Ltd
- P. KONTOTHANASSIS – OMIKRON KAPPA CONSULTING Ltd

GENERAL DESCRIPTION

- Athens Metro
- New Line 3 extension from Monastiraki to Egaleo
- Eleonas Station underground complex

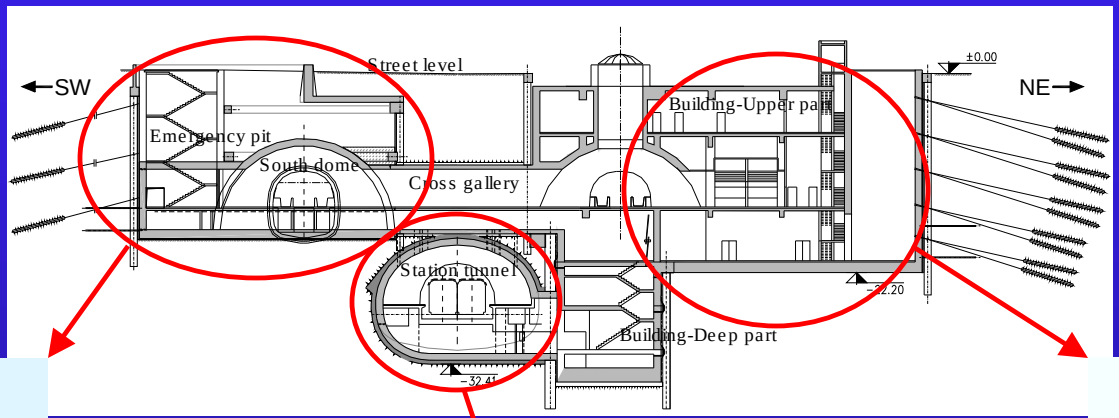


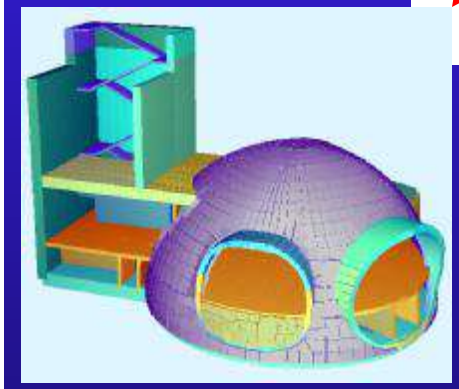
ü The whole complex lies under a significant Athens highway with heavy traffic

ü Several commercial buildings and manufacturing sites are inside the influence zone of the complex

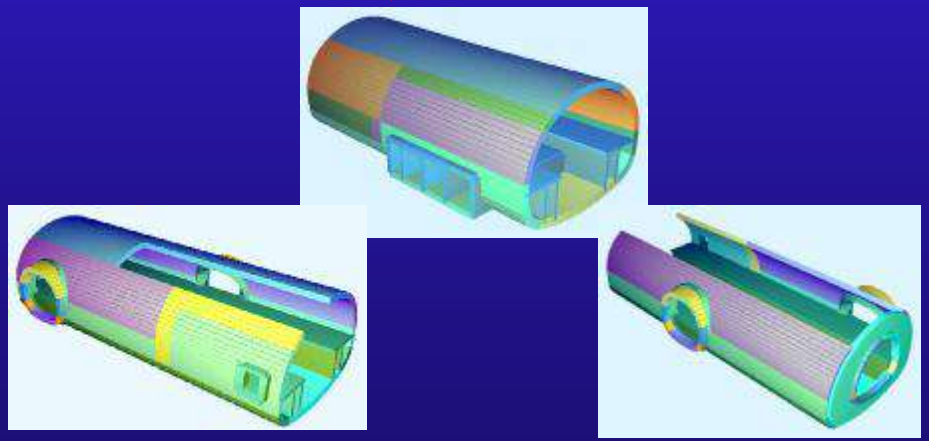
GENERAL DESCRIPTION

- Section A-A / Parts of Eleonas station Underground Complex



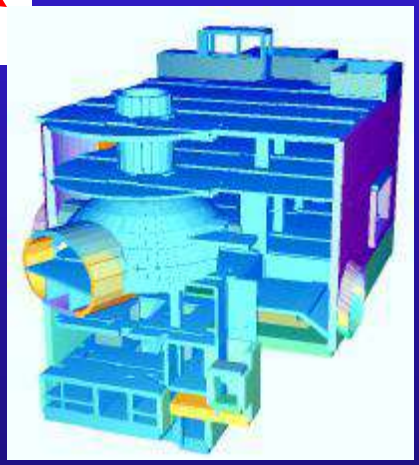


ü South Dome with Emergency Exit connected with the main Building via an underground cross gallery above station's tunnel



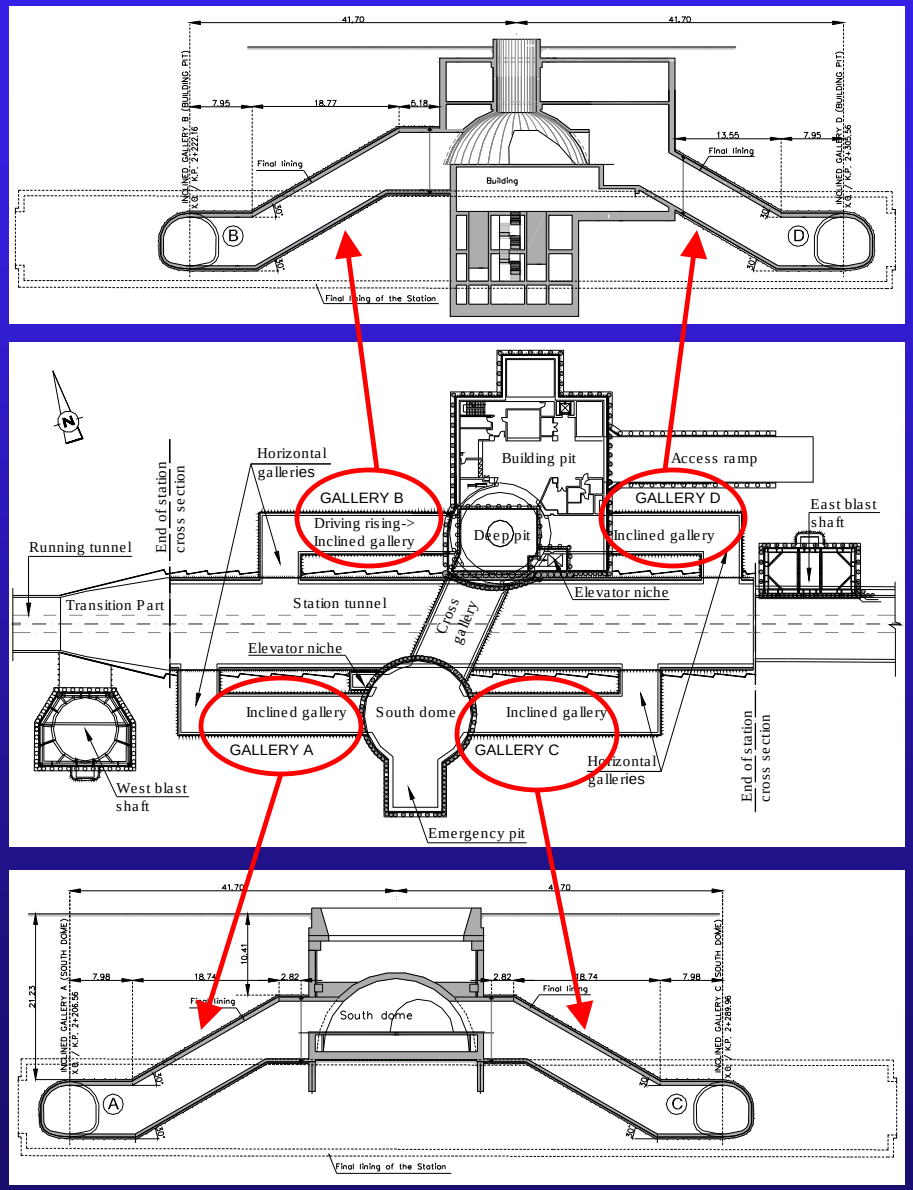
ü Underground Station Cavern 110m long

ü Overburden thickness approx. 18m



ü Main building with Deep Part, almost adjacent to the station tunnel

GENERAL DESCRIPTION



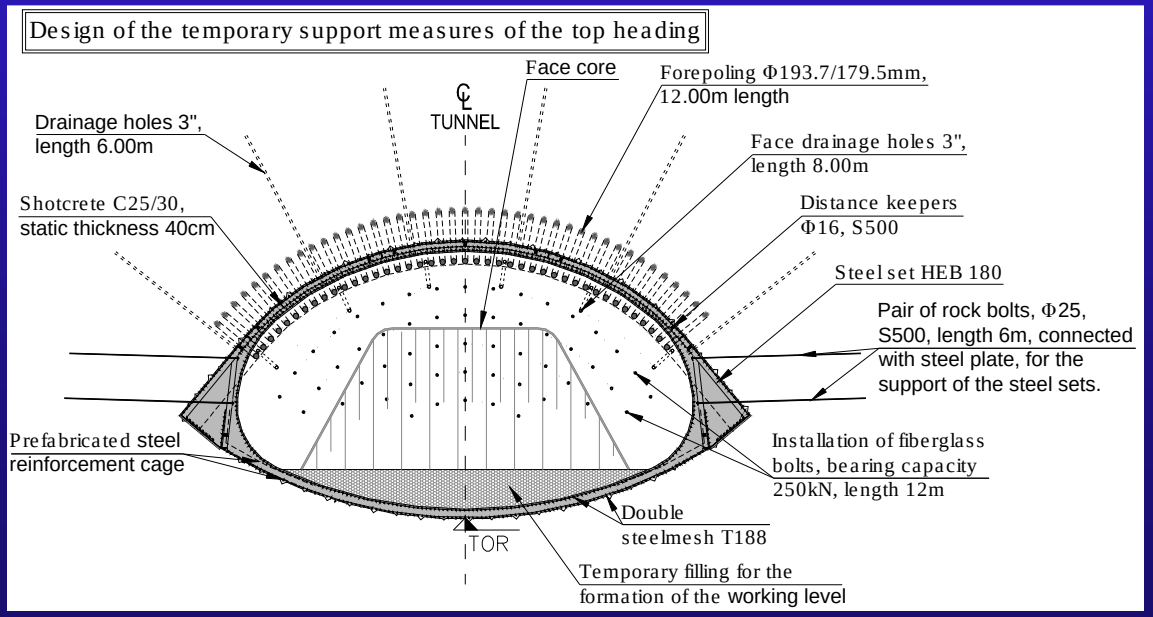
- Four inclined galleries provide access to the station tunnel
- Overburden thickness of the galleries varies from 22m for the deeper parts to approx. 11m

CONSTRUCTION SEQUENCE OF ELEONAS STATION UNDERGROUND COMPLEX

- Installation of the retaining system of Building Pit and South Dome
  - ü Reinforced Concrete piles
  - ü Prestressed Anchors
- Excavation of the station tunnel
  - ü NATM tunnelling
- Excavation of the First part of the galleries and installation of the final lining of the station tunnel
- Excavation of the Deep part of the Building Pit
  - ü Special application of a top-down method
- Concreting works of the building (up to a certain level) and the dome
- Construction of the remaining underground parts
  - ü Galleries
  - ü Cross gallery
- Concreting works of the remaining part of the building

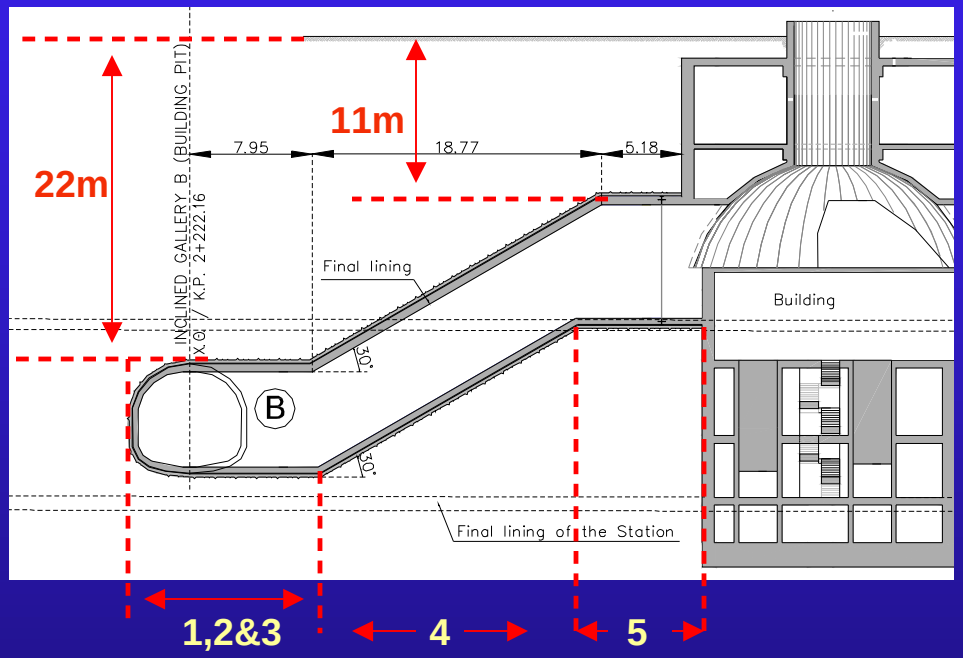
EXCAVATION AND TEMPORARY SUPPORT OF STATION TUNNEL

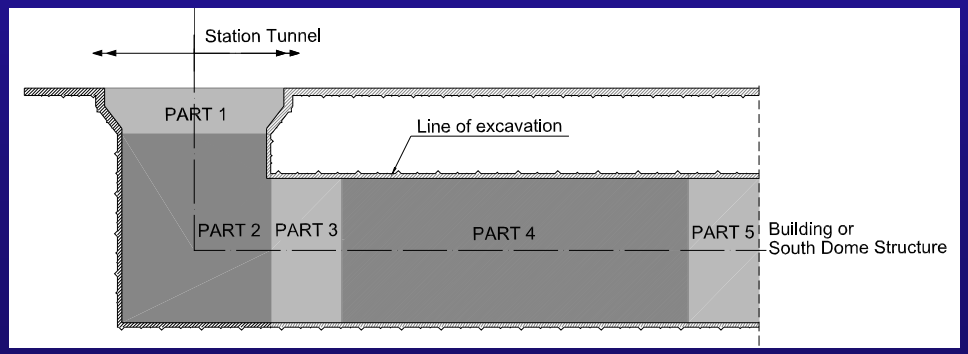
- Overburden thickness of the station tunnel
- Geological Formation at tunnels depth
  - ü Conglomerates and Marls
  - ü Small intercalations of sand and clay
- Application of NATM tunnelling in two discrete stages
  - ü Top heading with systematic use of grouted forepoling umbrellas
  - ü Bench



EXCAVATION AND TEMPORARY SUPPORT OF STATION TUNNEL

GEOMETRICAL DESCRIPTION OF GALLERIES

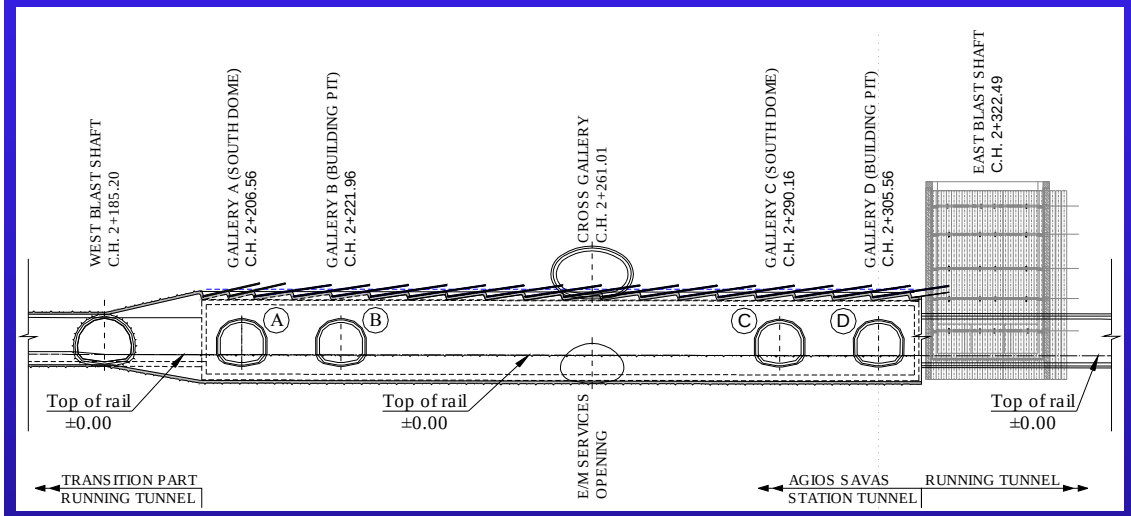




- Horizontal parts 1,2&3. Overburden 22m
- Inclined part 4. Overburden 22m to 11m
- Horizontal part 5. Overburden 11m
- Geological formations:
  - Deep parts 1,2&3
    - ü Conglomerates and Marls
    - ü Small intercalations of sand & Clay
- Shallow parts
  - üSand & Clay

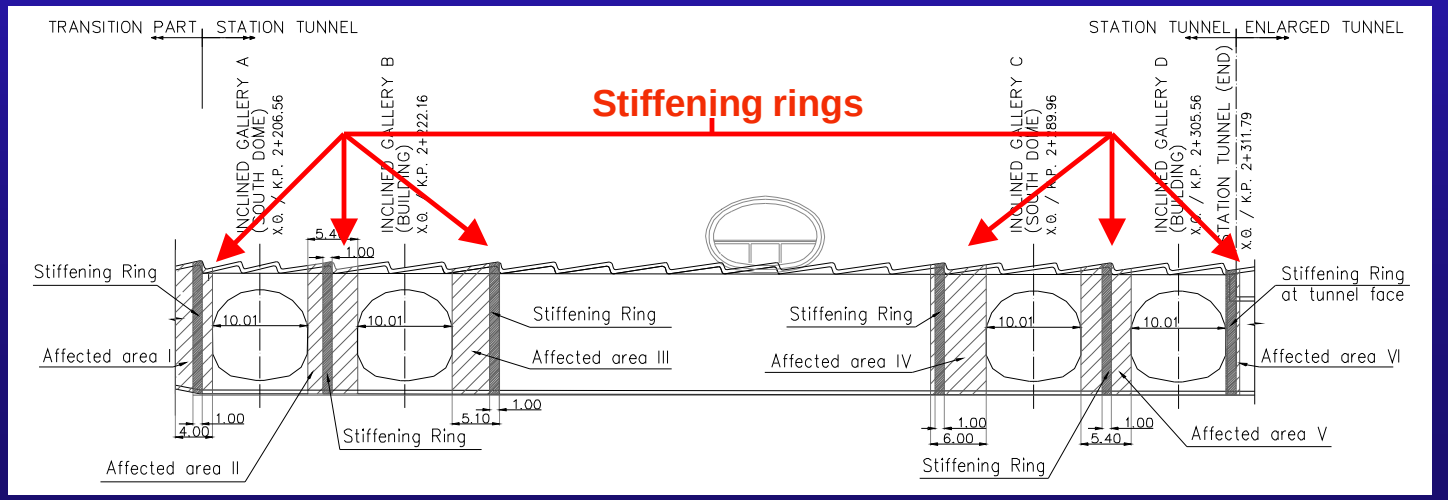
CONSTRUCTION OF THE LARGE OPENINGS IN STATION TUNNEL'S TEMPORARY SHELL

- **SECTION ALONG STATION'S TUNNEL AXIS**



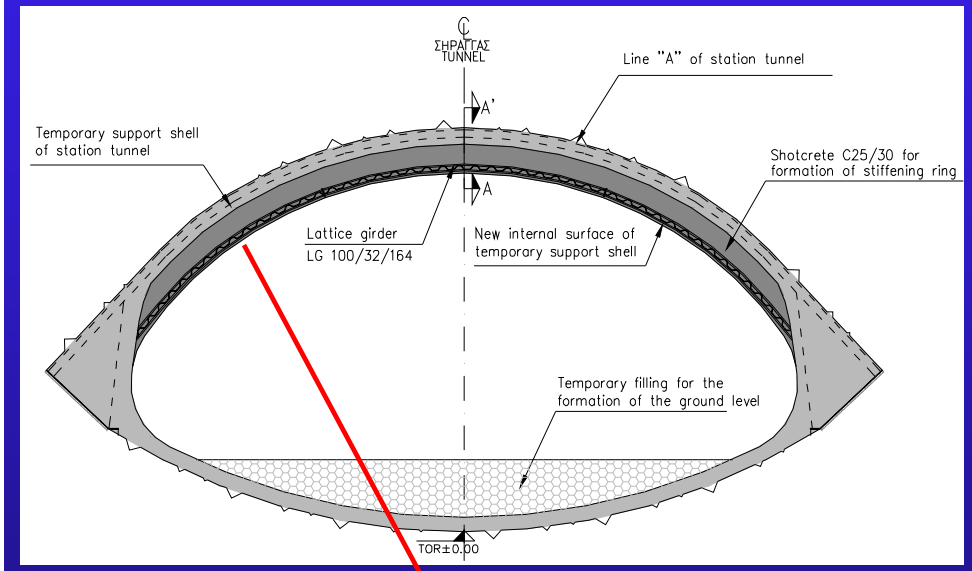
- **To start the excavation of the galleries four large openings, approx. 10m in width, constructed in the temporary shell of station's tunnel**

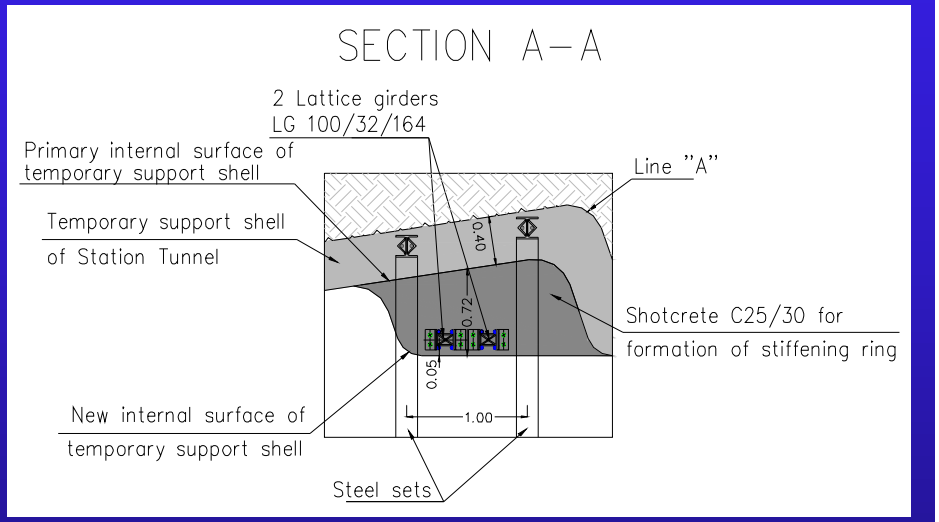
- **Stiffening rings in each side of the entrance to the galleries was constructed**



CONSTRUCTION OF THE LARGE OPENINGS IN STATION TUNNEL'S TEMPORARY SHELL

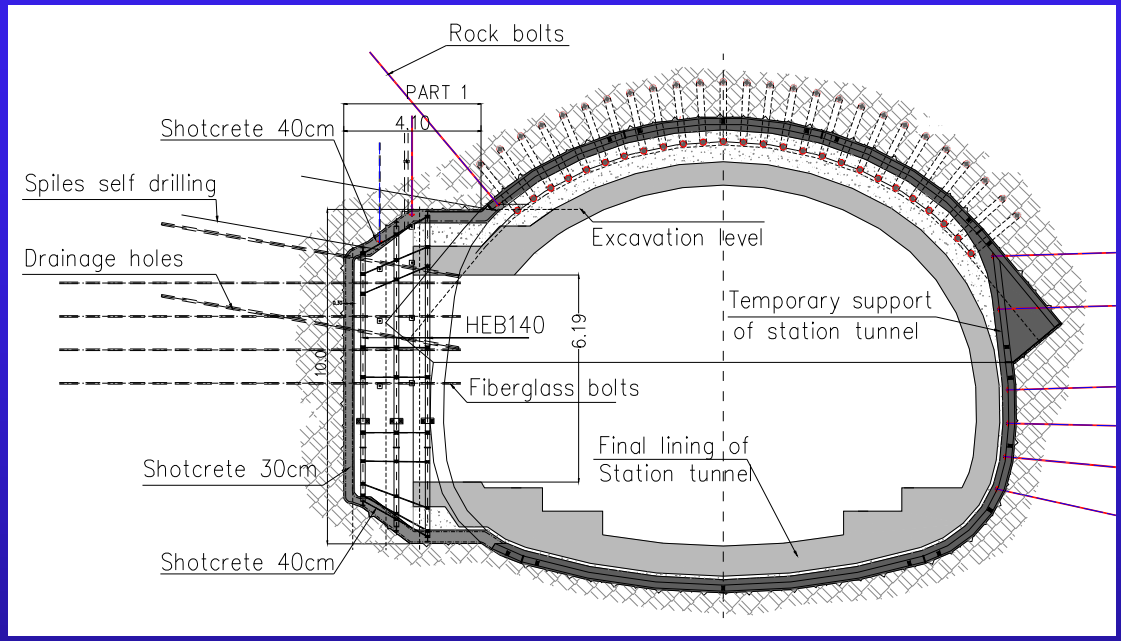
- The stiffening rings were installed at the end of construction phase A, in the maximum excavation enlargement due to forepoling





- The forepole umbrellas installed during the excavation of the Station tunnel provided a stiff system capable of bridging the 10m span of galleries entrances and to transfer the redistributed loads on the stiffening rings

EXCAVATION OF PART 1



• The excavation and temporary support of part 1 of the gallery was necessary in order to facilitate the installation of the final lining of the station tunnel up to a construction joint, which was foreseen at a 2m distance from the galleries entrances

Temporary Support Measures

• 40cm shotcrete C20/25 with wire mesh
• elephant feet
• self drilling spiles
• rockbolts fully grouted
• fiberglass bolts in the face
• drainage holes in the face

EXCAVATION OF PART 1

• Demolition of station tunnel's shotcret shell

• Installation of steel set HEB 140

• Protective measures on final excavation face of Part 1

• Installation of final row of self drilling spiles for future excavation of Part 2

INSTALLATION OF THE FINAL LINING OF THE STATION TUNNEL

In order to secure the already constructed underground station tunnel, the construction of the Final lining of the station tunnel was necessary in order to withstand all the additional loads due to:

- the construction of the deep part of the building
- the excavation and temporary support of parts 2 to 5 of the galleries
- the construction of the cross gallery above the crown of station tunnel

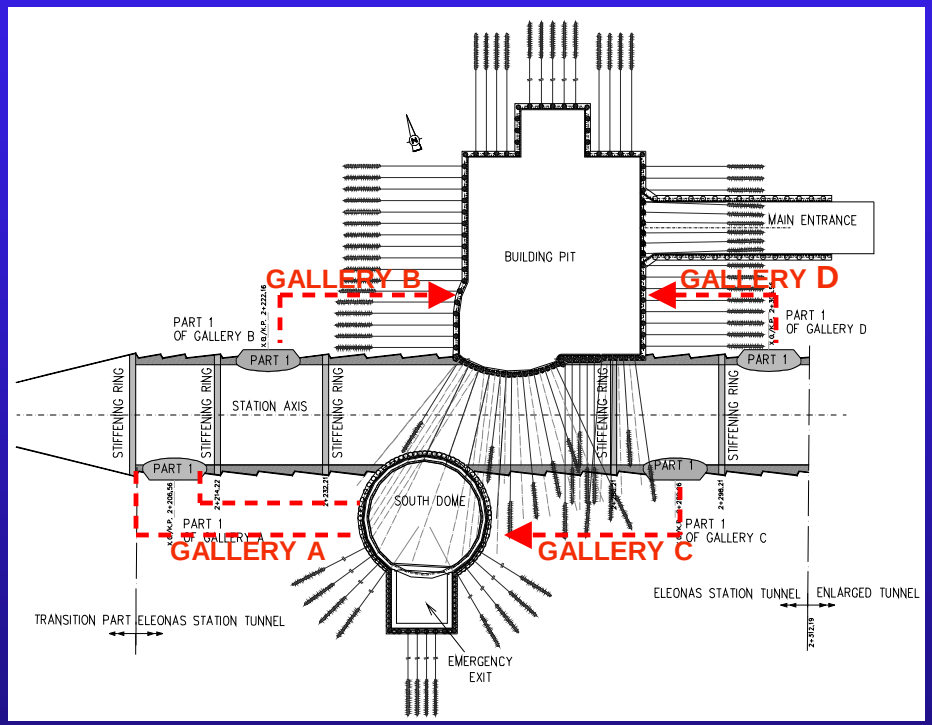
INSTALLATION OF THE FINAL LINING OF THE STATION TUNNEL

• Installation of steel reinforcement in the Final invert of the station tunnel

• Completed Final invert of the station tunnel

• Installation of waterproofing membrane in the station tunnel's crown

EXCAVATION AND TEMPORARY SUPPORT OF PARTS 2 TO 5 OF GALLERIES



COMPLETION OF STATION TUNNEL FINAL LINING

CONSTRUCTION OF GALLERY A UP TO THE SOUTH DOME PILES

PARTIAL CONCRETING OF BUILDING PERIMETER WALLS AND STIFFENING SLABS UP TO EL. –7m
UNLOCKING OF THE RELEVANT PRESTRESSED ANCHORS

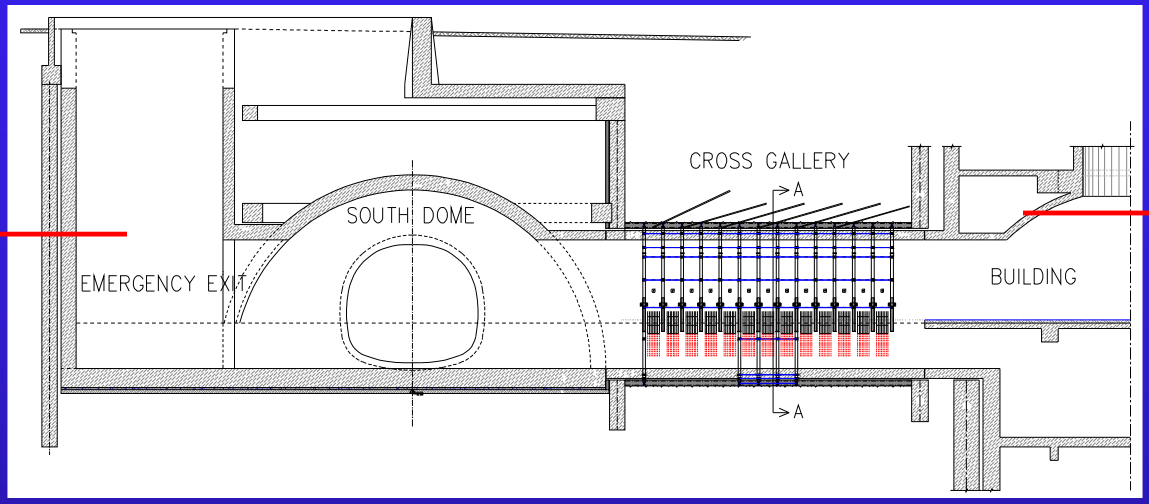
CONSTRUCTION OF GALLERY B

CONSTRUCTION OF GALLERY C

CONSTRUCTION OF GALLERY D

EXCAVATION AND TEMPORARY SUPPORT OF CROSS GALLERY

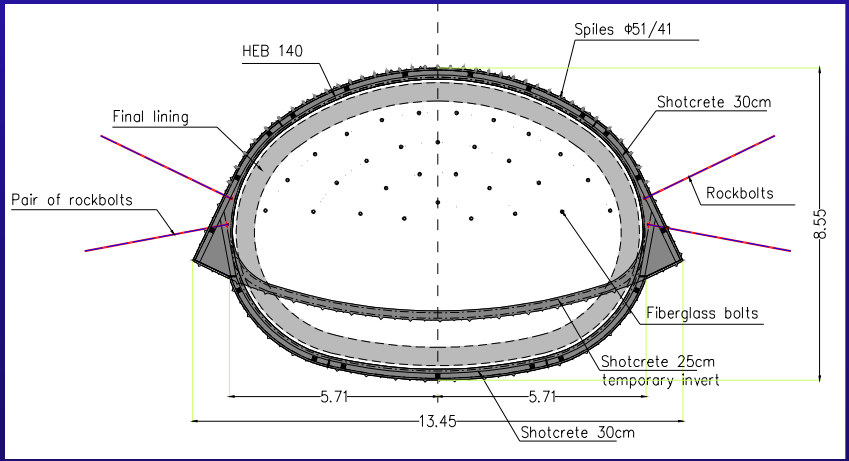
FINAL LINING OF THE SOUTH DOME



PARTIAL CONCRETING OF THE BUILDING

CUTTING THE PILES OF SOUTH DOME TO START THE EXCAVATION AND TEMPORARY SUPPORT OF GROSS GALLERY

- **Overburden thickness is approx. 10m**
- **Geological formations consist of sand and clay**



- **Top heading and Bench**
- **30cm shotcrete C2025 with wire mesh**
- **Elephant Feet**
- **Steel sets HEB 140**
- **Heavy spillway umbrella**
- **Fully grouted rockbolts**
- **Fiberglass bolts in tunnel's face**

CONCLUSIONS

- **Installation of the stiffening rings proved to be successful for the project. No additional surface settlements were measured**
- **The installation of the final lining of the Station tunnel was safe decision**
  - ü **Controllable surface settlements, when the excavation and temporary support of the cross gallery will start**
  - ü **Withstanding all the additional loads**
- **Extensive geotechnical monitoring program enabled the necessary data for the evaluation of the design – construction coupled system**