Title: Design considerations and special construction method for a shaft and main tunnel junction at Athens Metro – Geoponiki Shaft

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Summary: The paper describes the principal design concepts applied and the construction sequence adopted for Geoponiki Shaft, which operates as a ventilation and blast shaft for the main Athens metro tunnel. Due to its complexity, the special geometrical limitations and the access constraints from a construction point of view, a special method was adopted. Geoponiki Shaft complex consists of several large structures (Shaft, E/M tunnel, Cavern, Enlarged Cross Section) either adjacent or closely located, under a heavy traffic main avenue of Athens. Taking into consideration the above layout as well as the demand for keeping surface settlements below 25mm, it is concluded that unique difficulties are anticipated during the design stage and the sequential construction works.

GENERAL DESCRIPTION

The basic demand of the design was the development of a simple construction method, which could guarantee all the requirements regarding safety, surface settlement limits and controlled stress – strain development on the structures.

Geoponiki Shaft complex consists of the Shaft itself, an E/M (Electro-Mechanic) tunnel recess, an underground Cavern and an Enlarged Cross Section for the starting stretch of the main tunnel, which are located under a heavy traffic main avenue of Athens. Conglomerates, marls, gravels and sandy clays are the main geological formations anticipated during construction.

The retaining structure of the Shaft consists of reinforced concrete piles (100cm diameter), with a spacing of maximum 1,30m. At the top of the pile wall a concrete wall with a height of 1,5m is foreseen (1,5m between surface and top of the cap beam). The concrete wall is incorporated in the cap beam, which is applied on the top of all piles. The depth of the rectangular shaft pit is 22,00m, while its plan view dimensions are 17,20m x 9,60m. (Figs 1, 2)

For retaining the pile wall in the area of Geoponiki Shaft, two strut levels (reinforced concrete stiffening frames at the first and second stiffening level) were applied. The pile cap beam acts as the first stiffening level. The reinforced concrete frame of the second stiffening level is temporary and has to be removed before the construction of the final lining. The struts in the area of the Shaft are installed at levels +18,905 and +7.45m. The allowed excavation depth is max. 1,0m below the strut level.

After each excavation step in the area of the Shaft, the gap between the piles should be covered by shotcrete up to the front border of the piles. There were two exceptions for the application of shotcrete, in the area behind the second stiffening frame and in the area of the piles at the Cavern entrance directly above the second stiffening frame.

Two additional piles inside the Shaft's area were required for the support of the 2nd stiffening frame adjacent to the opening of the Cavern. These two piles should be constructed from the surface level as well and be removed during Shaft sinking step-by-step down to the elevation of +8.00m. At elevation of +7.45m (centre line) the stiffening frame was founded on these two piles. (Figs 5, 6)

The two piles have minimum reinforcement for installation purposes in the area where they had to be dimolished after the installation of the final lining within the Enlarged Cross Section and the Cavern and before the installation of the final lining of the Shaft.

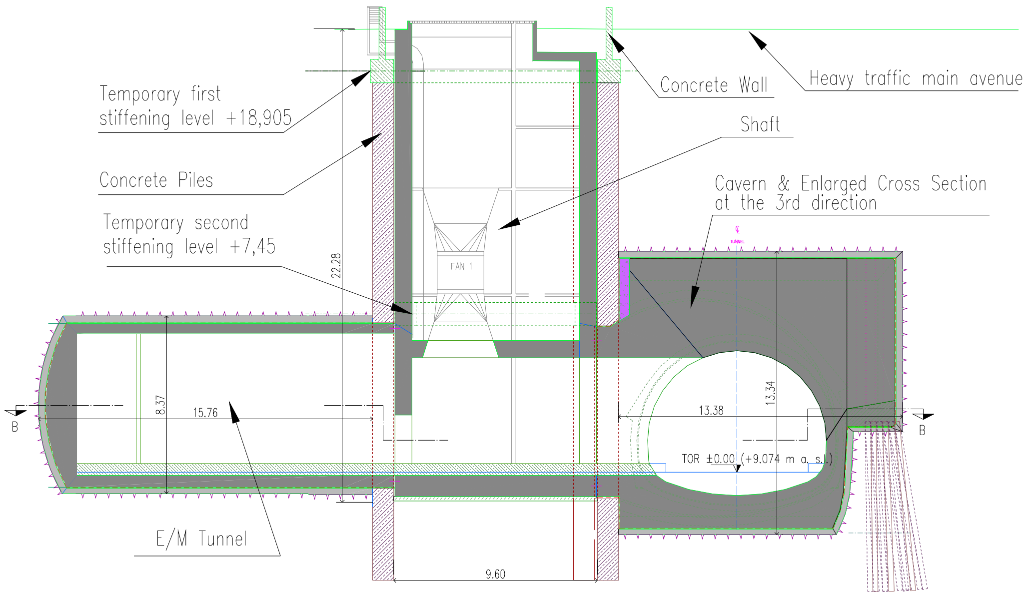

Figure 1: General section of Geoponiki Shaft complex (Section A-A).

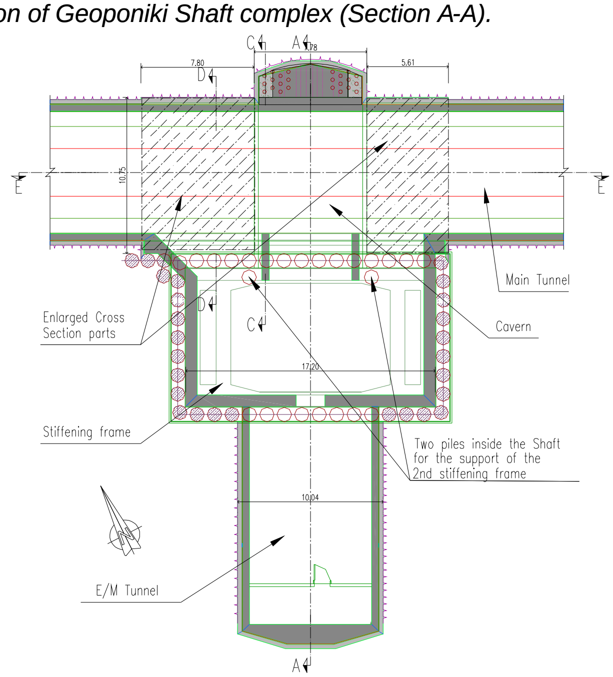

Figure 2: General plan view of Geoponiki Shaft complex (Section B-B).

CONSTRUCTION SEQUENCE

The construction sequence of Geoponiki Shaft complex according to the final design, is briefly presented below:

1. Installation of all the Shaft's piles including the 2 piles inside the Shaft's area.
2. Installation of the cap beam (first stiffening level) and the retaining concrete wall.
3. Excavation down to the second stiffening level and installation of spiles above the E/M tunnel in the area of the concrete frame. The spiles are required due to the excavation and temporary support of the E/M tunnel.

4. Construction of the 2nd concrete frame.
5. Excavation up to the bottom of the Shaft and installation of a 20cm reinforced concrete slab.
6. Backfilling up to top heading level of E/M tunnel and Cavern.
7. Excavation of the top heading of the E/M tunnel.
8. Excavation of the top heading of the Cavern with gradual enlargement due to forepolling. (Fig. 7)
9. Excavation towards the pile-wall with removal of the triangular shaped crown of the gradually enlarged area. (Fig. 3)
10. Installation of additional measures for the load transfer during the opening of the Cavern's side-wall [micro-piles, shotcrete layer at the Cavern's vault, shotcreted side-walls with anchored beams and load transfer disks (at the side of the Cavern shotcreted and at the side of the Shaft concreted) at the pile-wall]. (Figs 4, 8, 9, 10)
11. Excavation of the top heading of the Enlarged Cross Section of the main tunnel (step 10 was completely finished before starting the excavation works). Further excavation of the top heading of the running tunnel was required. (Fig. 14)
12. Excavation of backfilling within the Shaft.
13. Excavation of bench and invert of the E/M tunnel.
14. Excavation of bench and invert of the Cavern.
15. Excavation of bench and invert of the Enlarged Cross Section of the main tunnel.
16. Installation of the final lining within the Enlarged Cross Section of the main tunnel and within the Cavern.
17. Installation of final lining of the E/M tunnel.
18. Removal of the two piles inside the Shaft's area.
19. Installation of final lining at the bottom of the Shaft and additional temporary strut.
20. Removal of the 2nd stiffening frame.
21. Construction of the final lining of the Shaft in the area of the 2nd stiffening frame.
22. Removal of the temporary strut and completion of the final lining of the Shaft.
23. Removal of the piles in the area of the remaining side openings and completion of the final lining in this area.

During the excavation of the Shaft an extremely competent and well cemented conglomerate was met at the level of at the crown of the E/M tunnel. This made the excavation process extremely difficult and costly. Due to the above reason, it was proposed to stop the excavation of the Shaft at the E/M's top heading's floor level and to continue with the excavation of the E/M tunnel and the Cavern in order to speed up the construction process and to face the well cemented conglomerate afterwards with a bench process excavation of two free surfaces of attack. For this purpose, some minor modifications to the original design were made in order to accomplish immediate access to the Cavern and the Enlarged Cross Section of the main tunnel.

GEOLOGY

GROUND WATER

No water pressure has been taken into consideration, since systematic drainage holes for water pressure relief were executed. The drainage holes had to be drilled on a systematic pattern while their length and pattern was adapted on a daily base on site in accordance to local conditions.

GEOTECHNICAL PARAMETERS

The Geotechnical parameters of Geoponiki Shaft considered for the statical calculations are given below:

Ground Layer	Depth(m)*	γ(kN/m^3)	φ(^{o})	c(kPa)	E(MPa)
I	0-2	20	32	5	20
II	2-17	21	24	20	75
III	17-22	23	32	35	500
IV	>22	23	28	30	300

*0 level corresponds to ground surface.

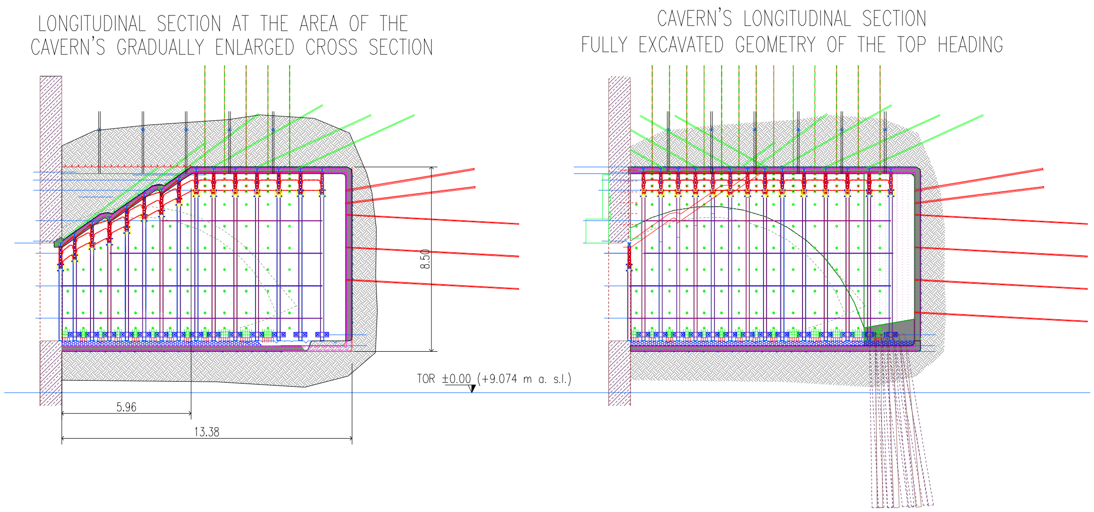

Figure 3: Longitudinal section of Cavern's top heading (Section C-C).

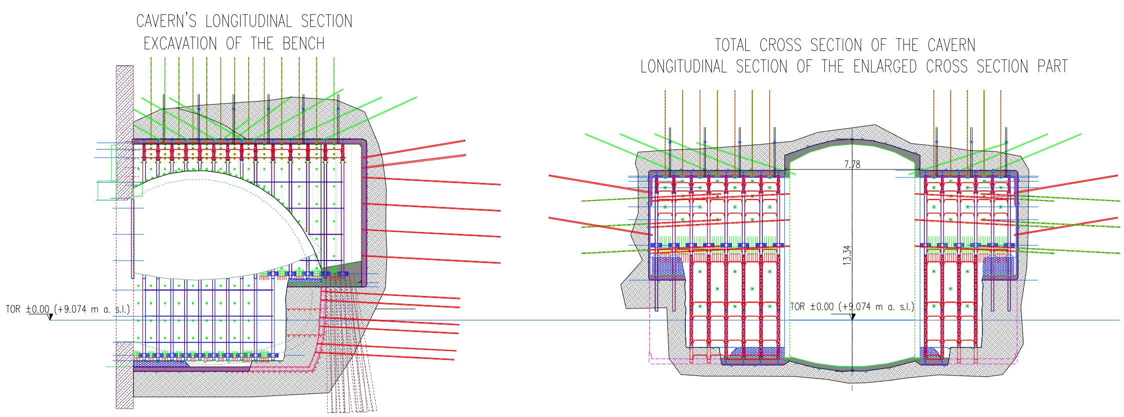

Figure 4: General sections of Cavern's full excavated section (Section C-C & Section E-E).

Figure 5: 2nd Stiffening frame and Support disk.

Figure 6: 2nd Stiffening frame. View of support piles.

Figure 7: Installations of spiles at Cavern's opening.

Figure 8: Cavern's gradually enlarged section.

Figure 9: Reverse excavation in Cavern.

Figure 10: Pile-wall in Cavern.

CONSTRUCTION & DESIGN DETAILS

1ST STIFFENING LEVEL

Due to the great span of the required opening (17,20m x 9,60m) and due to the stresses developed by considering the earthquake load case, it was necessary to design a concrete frame at the first stiffening level.

The cap beam was acting as a stiffening frame, furthermore there were two concrete struts connected with the cap beam. The wall was connected with the cap beam of the piles. (Fig. 1)

2ND STIFFENING LEVEL

As it was mentioned for the 1st stiffening frame, also the 2nd stiffening frame was influenced by the big span of the required opening within the Shaft. Furthermore, the 2nd stiffening frame was foreseen by the design as a support for the Enlarged Cross Section along the pile-wall. The excavation of the Enlarged Cross Section caused high loads on this concrete frame towards the horizontal direction (towards the Shaft). In addition, the frame acted also as a beam in vertical direction.

The frame was consisted of a concrete cross section 1.0m x 1.1m (with enlargements at the area of the struts) along the pile-wall and together with the two concrete struts, which were part of the frame (Figs 1, 2, 5, 6).

CAVERN'S TEMPORARY SUPPORT MEASURES

The Cavern itself consisted of a gradually enlarged cross section, which should be excavated, immediately after the opening under the pile-wall, for approximately 6m long. A part of the Cavern was characterized by fixed cross section geometry for every step of advance. The triangular shaped crown of the Cavern's gradually enlarged section was removed at a second phase with a back (reverse) excavation direction after the completion of the Cavern's excavation at its full length.

A part of the pile-wall was exposed after the completion of the Cavern's temporary support. The temporary support of the Cavern was consisted of 30cm shotcrete, steel sets HEB160 at the sidewalls and lattice girders LG140/26 at the crown, 24 spiles (Ø51/5mm fully grouted, 6m length, 35cm spacing), rock-bolts Ø25, S500, 4m length and 25cm shotcrete for the temporary and final invert (Figs 3, 4, 7, 8).

CAVERN'S SIDEWALLS

For the opening of the sidewall of the Cavern perpendicular to the main tunnel axis, it was necessary to carry the loads of the overburden, which were distributed along the sidewall as normal forces. Therefore, the sidewalls were constructed by multilayer shotcrete, thus creating a heavy arch which it was supported on a foundation beam with micro-piles in the ground on the one side and on a supporting disk system on the other side towards the Shaft. In addition, it incorporates 3 prestressed anchors inside the arch, to strengthen the weak crown of the arch. The shotcrete quality class was chosen to be C30/37.

The prestressed anchors installed in the shotcrete arch, were loaded by a tension load of 837kN. The anchors were tensioned after the hardening of the shotcrete. The calculated system consisted of an arch with a prestressed beam, which was connected from the one side to the Shaft sidewall and the stiffening frame and from the other side, to the arch's foundation. Thus, a prestressed beam was created at the top of the arch, capable enough to undertake safely the calculated loads of the Cavern and the first part of the Enlarged Cross Section. Inside the crown of the arch, 132cm² longitudinal steel reinforcement in the upper and lower line were required. The thickness of the shotcrete arch was 1m and was constructed with 7 subsequent layers of shotcrete. In each layer, steel mesh T196 was embedded according to the design calculated reinforcement (Figs 12, 13, 15, 16).

SUPPORT DISKS

Inside the Cavern, the two prestressed beams should be sufficiently supported in order to carry the vertical overburden load (appr. 9827kN, including a safety factor of 1,35).

At the part of the pile-wall which was delimited by the top of the Cavern opening and by the crown of the Cavern, a support disk was built from both sides. These disks incorporated specially reinforced horizontal bands with height h=0,70m which act as stiffening zones (consoles) for the load transferred by the prestressed beams.

Ten (10) anchors were installed between the piles in order to apply uniform pressure on the disk. In addition, five (5) extra anchors were placed in the area of the concrete stiffening frame, thus allowing the disk to move in accordance with the concrete stiffening frame and with a significantly higher rigidity. All anchors were loaded to 502kN.

By the construction of the two anchored concrete disks the vertical load could be transferred through the piles and on the second stiffening frame. In this way a transfer load mechanism to the first stiffening frame through the piles and the construction of the cap beam was also established.

High loads were expected to the immediate neighbouring piles next to the Cavern's opening and due to the fact that the consoles were not capable of transferring the load from the frame onto these piles, two additional piles in the Shaft's area were necessary, for supporting the part of the second stiffening frame connected with the support disks. The loads were placed on the second stiffening frame and were evenly distributed over 8,44m (the width of the disk corresponds to 7piles) (Figs 9, 10, 11, 17, 18).

FOUNDATION OF THE ARCH

The two Cavern's arches were founded on a micro-pile cap beam. On each side of the micro-pile cap beam, 12 micro-piles of 8,0m length and Ø250mm were installed. The length of the micro-piles was determined by the excavation depth of the bench. During the excavation of the bench, the micro-piles were founded adequately under the floor level of the bench; in order to perform a safe transfer of the developed loads (Figs 4, 12).

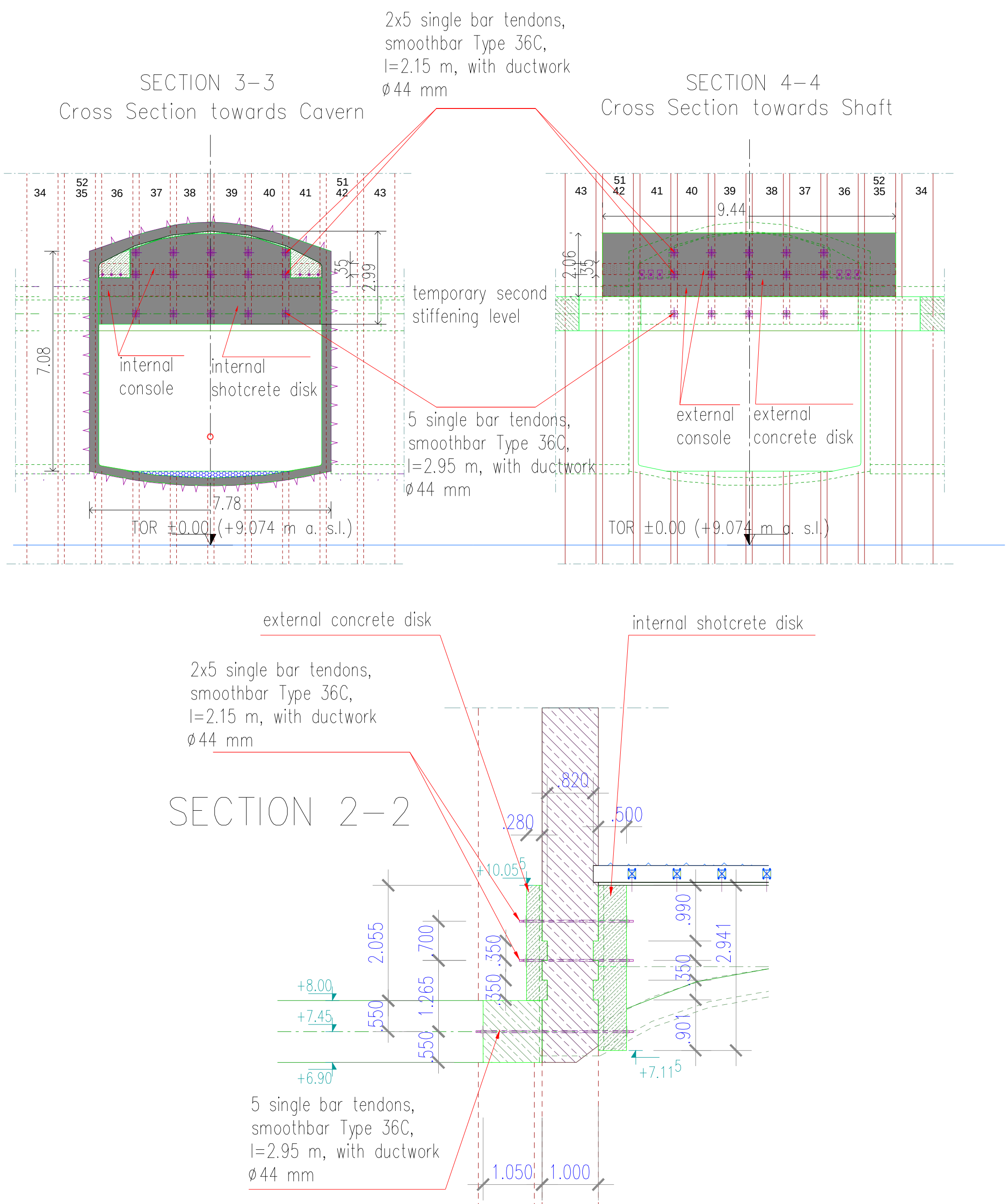

Figure 11: Cross sections and construction details of the support disks.

MAIN TUNNEL - ENLARGED CROSS SECTION

Geoponiki Shaft serves the need of a blast shaft for the main tunnel, so the side towards the main tunnel should be left open for the development of an adequate air flow during the metro train operation. Moreover, adequate space should be left for the construction of the final lining.

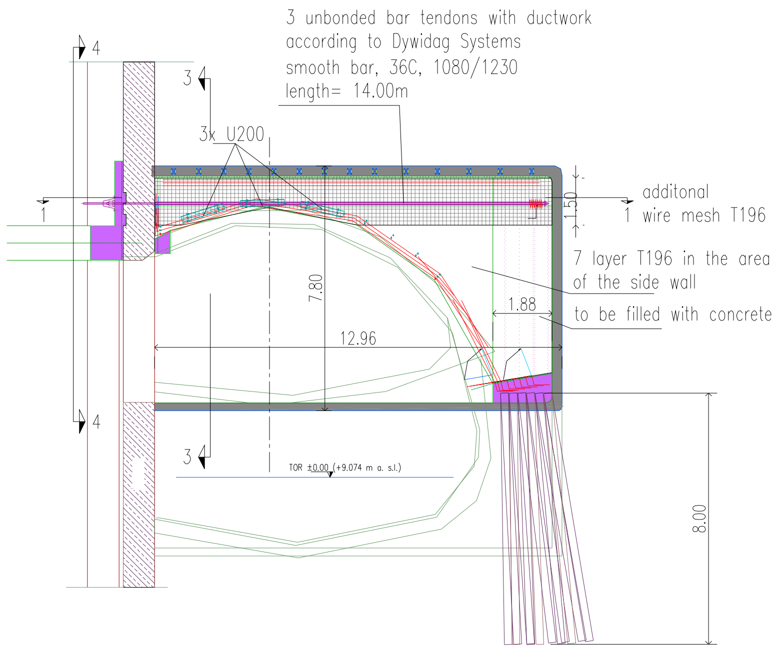

Figure 12: Details of reinforcement in the Cavern's sidewall arch (SECTION C-C).

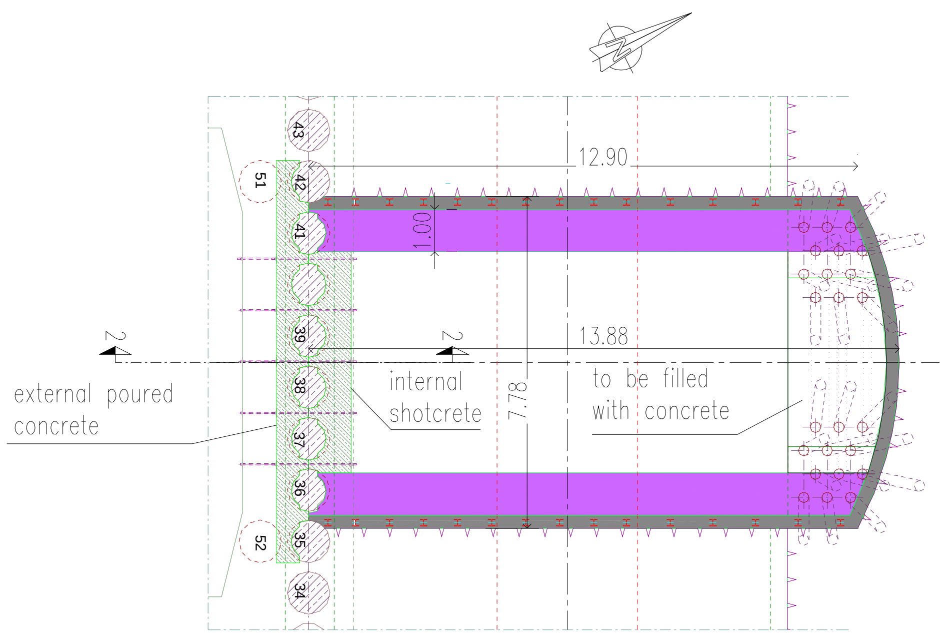

Figure 13: Plan view of the Cavern (SECTION 1-1).

For the above reasons, the part of the main tunnel next to the Shaft was designed by following specific geometry, known as the Enlarged Cross Section part. The shotcrete shell of the Enlarged Cross Section is directly connected on the piles of the Shaft and transfers the developed loads through the piles on the second stiffening frame (Figs 14, 19, 20).

The most crucial and delicate point of this section, from the design and construction point of view, was the efficiency and the quality of the shell's connection on the piles.

The temporary support of the Enlarged Cross Section consisted of:

- 40cm shotcrete shell
- Lattice Girder LG180/26
- 29 spiles Ø51/5mm, 6m length, 35cm spacing, fully grouted
- Drainage holes Ø76mm, 4,5m length
- Rock-bolts Ø25mm, S500, 5m length, fully grouted, in a staggered grid 2mx1m
- 30cm shotcreted temporary invert
- 35cm shotcreted final invert
- Two layers of T196 steel mesh
- 20 fiberglass anchors at the tunnel's face, 250kN, 8m length, installed every 4m of advance

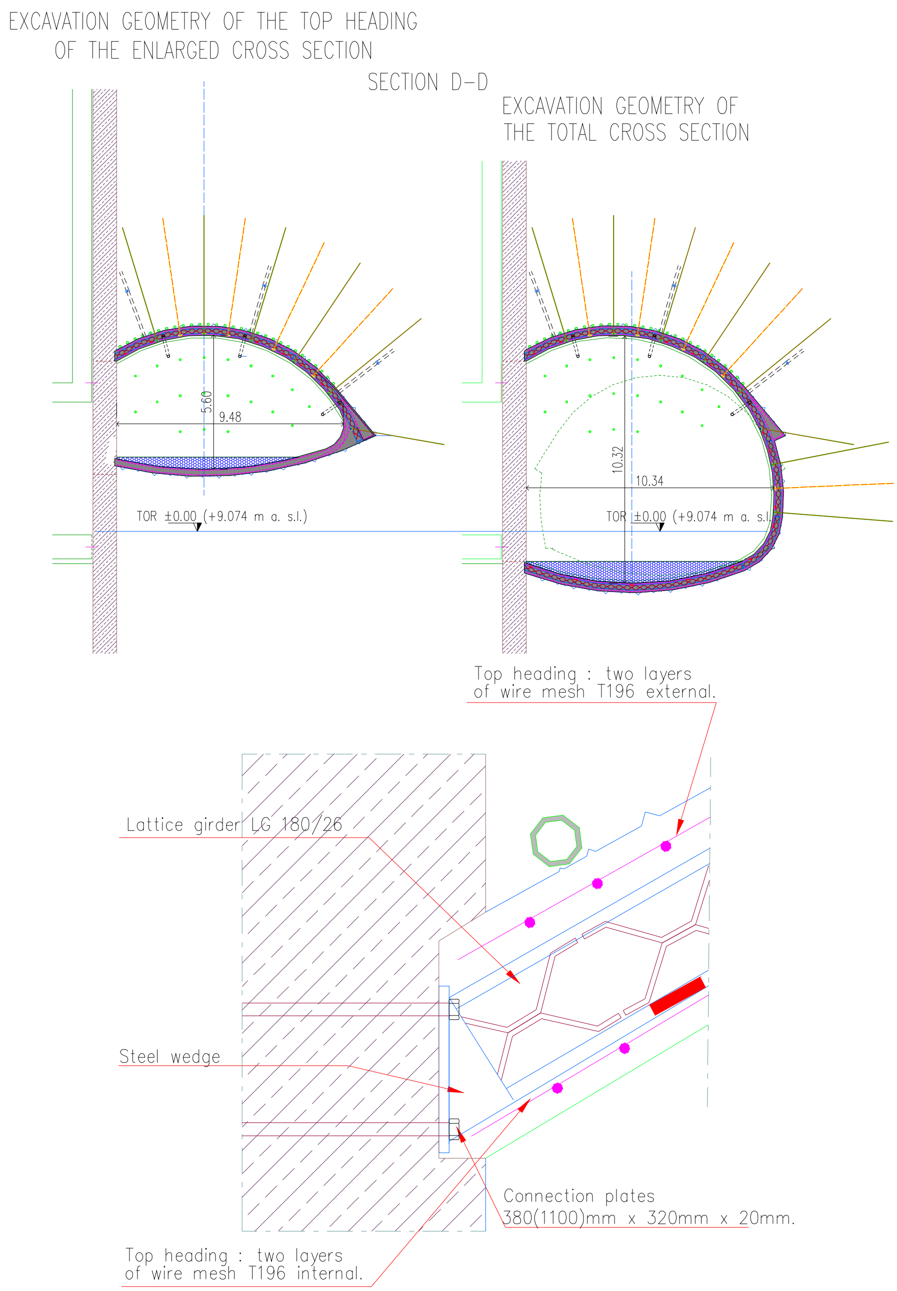

Figure 14: Cross sections of the Enlarged Cross section and details of the shell's connection on the piles.


Figure 15: Arch reinforcement towards support disk.


Figure 16: Arch & prestressed anchor's bond.


Figure 17: Tensioning of Anchors.


Figure 18: Support disk from Cavern's side.


Figure 19: Spiling at the Cavern's sidewall.

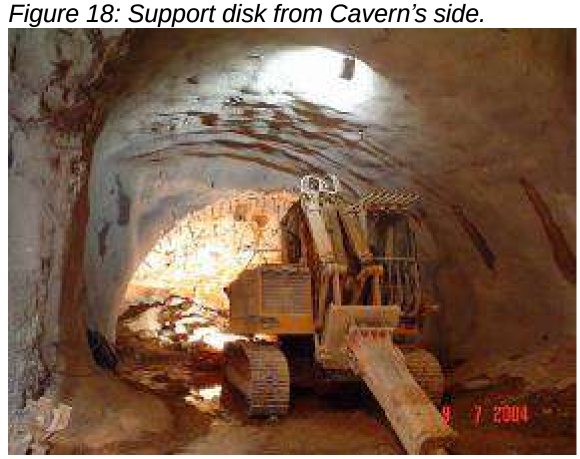
Figure 20: Enlarged Cross Section view.

SETTLEMENTS

For the evaluation of the expected settlements during the design stage, finite element multi staged analyses were performed. For each major underground opening (E/M tunnel, Shaft, Cavern, Enlarged Cross Section, Main Tunnel) a numerical 2 dimensional analysis was performed. Due to the contractual requirement for keeping the total surface settlements lower than 25mm, the share of each major opening to the development of settlements should be kept at the minimum possible value. Thus, the stress response of the region around Geoponiki Shaft complex is more or less elastic and therefore, by a conservative approach, the calculated settlements by 2-D analyses for each major ground opening could be superposed.

An exact three-dimensional analysis of the whole complex was not performed since it was time-consuming and very difficult to include all the parameters that affect the outcome of the analysis. Therefore, sufficient safety factors were implemented in the calculations in order to anticipate the expected conditions of the actual underground construction.

The maximum settlement measured around Geoponiki Shaft complex due to the underground excavation, was approx. 12mm. This value was an irrefutable verification of the design and the construction team's success. (Figs 21, 22)

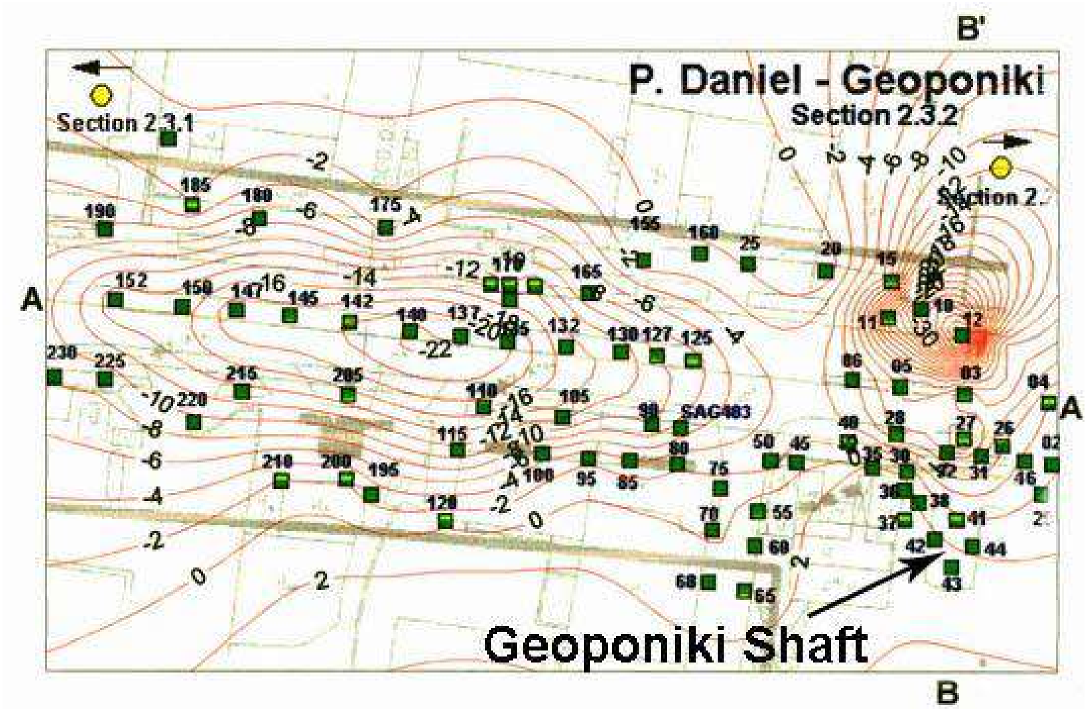

Figure 21: Settlements plan view on the main tunnel's axis near Geoponiki Shaft.

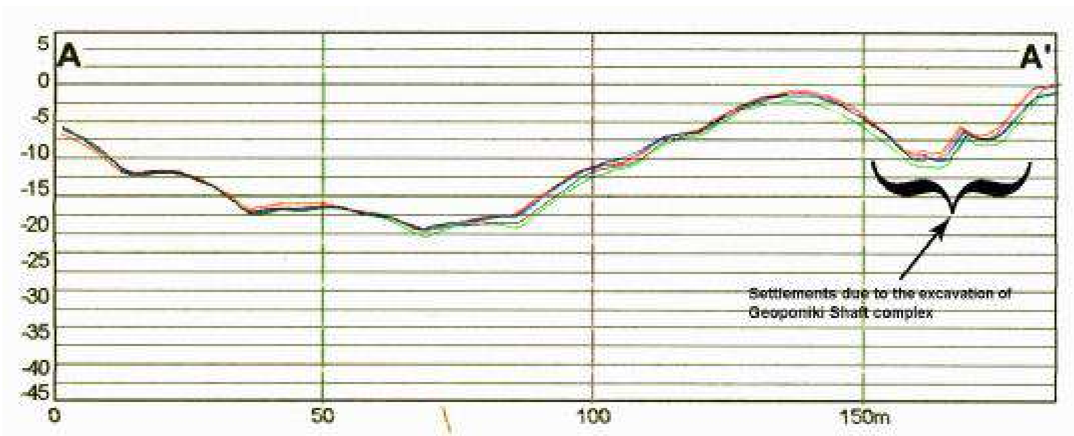

Figure 22: Settlements section A-A on the main tunnel's axis.

CONCLUSIONS

The initial contractual provision of the whole metro line under construction, had considered that Geoponiki Shaft could be excavated independently from the Main Tunnel. Due to several obstacles of the construction plan, it was required that Geoponiki Shaft had to be redesigned in order to serve also as an excavation and main production access shaft. However, the proximity of the Main Tunnel and the great dimensions of the blast shaft, next to a heavy traffic avenue, created special conditions and severe constrains for the construction as well as for the design.

Due to these special conditions, complicated systems had to be implemented during design in order to overcome several difficulties. However, although the whole approach seems complicated, it actually provides a smooth way of construction. The design took into consideration that the whole construction process should be implemented by underground machinery, materials and personnel. This key factor gave to the contractor the opportunity to meet the construction timetable of the Running tunnel without referring to alternative equipment and specialized personnel.

Important and innovative features of the design were the bridging effect approach of the Cavern's overburden loads through prestressed anchoring system and the arch construction. The aforementioned features made possible the construction of the Cavern in close contact with the Shaft and the Main Tunnel's excavation. These complicated and sophisticated features are extremely difficult to be constructed in restricted underground worksite spaces. However, the use of shotcrete instead of concrete and the simple reinforcement arrangements, as well as the extensive use of steel mesh (multilayered construction of the arch shell) made these features possible to be implemented with high construction quality and the minimum surface disturbance.

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 the 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

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(2) Omikron Kappa Consulting Ltd, Daily Reports from the Designer on Site, May-June-July 2004.