Special Design Methods for Construction of Tunnel Portals in Areas with Extremely Steep Morphology

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ABSTRACT

This paper describes the design methods and the construction techniques applied at two (2) tunnel sites in Greece, where the highway alignment runs almost parallel to very high and extremely steep mountainous cliffs and slopes in a seaside area. The project belongs to a three-lane national highway tunnelling system, approximately 50 km outside Athens. The rock mass consists of slightly to intensively cataclastic limestones, conglomerates and tectonic breccia. The tunnel portals are located almost nearby the existing national highway, connecting Athens to Peloponnese. Certain safety issues had to be applied with regard to the evidence of rockfalls and the structural stability considerations of the existing mountain slopes, due to tunneling under low side cover conditions at cross-sections up to 240 m^2 (approximate height 14 m and width 19 m).

Special design issues had to be applied due to the presence of an active seismic extended fault zone passing through the tunnels. Any effort of performing earthmoving works and open-cut excavations was impossible due to the steep morphology of the ground surface in combination with the existing environmental restrictions. Prototype and innovative design methods for special construction of reinforced concrete structures (RCS and RCSP) for forming adequate side cover feature for the tunnels were employed. Specific designs for filling the internal tunnel area with special box shaped polysterine material were adopted.

Extended numerical modelling and significant detailization of the construction sequence were developed in order to secure the tunnel advance, the close monitoring and control of all movements of the existing structures and the surrounding rock mass of the tunnels, as well as the deformation response of the concrete structures due to tunnelling.

1. INTRODUCTION

The highway "Athens – Corinth – Patra", which connects Athens to Peloponese is part of PATHE (Patra-Athens-Thessaloniki-Evzoni) National Highway Project that links Peloponese to Northern Greece. The owner of PATHE Highway Project is the Ministry of Environment – Planning & Public Works and the contractor is AKTOR S.A. In the section of the highway called "Kakia Skala" that is named after the area and is located approximately 50 km outside Athens, as presented in Figure 1, five highway tunnels AS1a, AS1d, AS2a, AS2d and AS3d are under construction. The "Athens – Corinth – Patra" highway project is an Olympic Games 2004 project.

Tunnel AS1 comprises a double-bore tunnel, whose portals are located almost aside to the existing national highway. The length of the right bore (AS1d) is 845 m, of the left bore (AS1a) it is 280 m and the area of the cross sections of the tunnel is up to 240 m^2 (approximate height 14 m and width 19 m).

Due to the existing steep morphology of the ground surface and the current environmental restrictions, the east portal (entrance) of the right bore of the tunnel AS1 and the west portal (exit) of the left bore of the same tunnel required special design methods and construction techniques. Different solutions were examined and the most efficient and economic one was chosen for each case.

Figure 1 Location of the tunnels of Kakia Skala along the "Athens – Corinth – Patra" highway.

2. GEOLOGY

The terrain in the vicinity of the tunnel AS1 is characterized by moderately to steeply inclined slopes and cliffs, as shown in Figure 2. Near the exit of the tunnel, the portal is located in a shallow gully, which is going up to a height of approximately 200 m. Loose or outcrop boulders are observed in the whole surrounding area of the tunnel. The inclination of the open cuts in the tunnel portals is 80-90^{o} relative to the horizontal. The rock mass consists of cataclastic limestones, conglomerates and tectonic breccia.

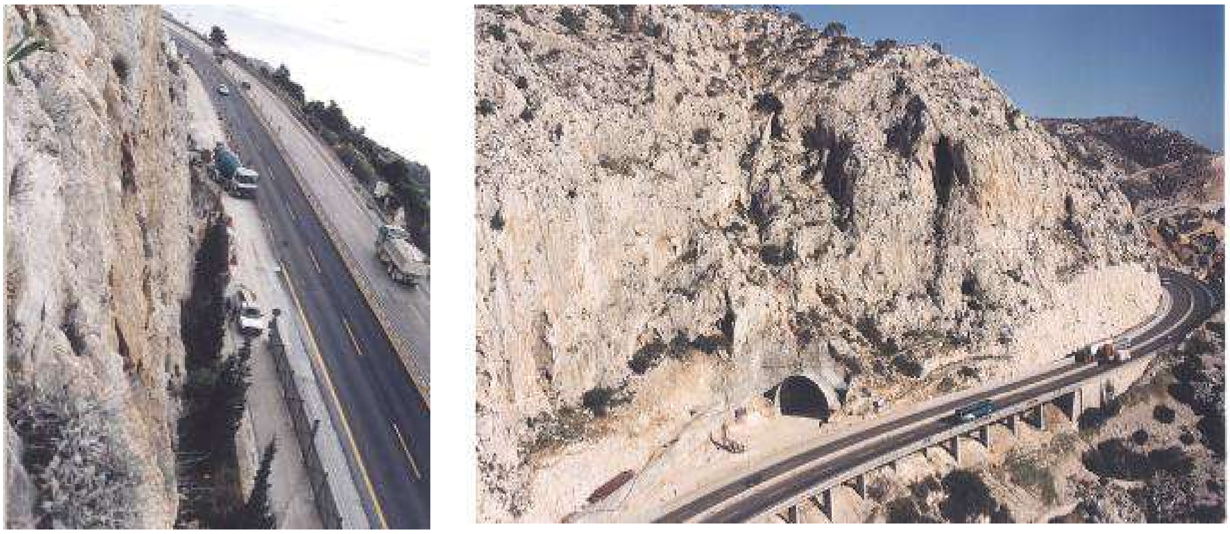

Figure 2 Extremely steep morphology in the area of the tunnels of Kakia Skala.

In particular, near the area of the tunnel portals, talus material and artificial deposits, as well as limestones moderately to highly tectonic are encountered. The geological formations are faulted and loosened. The tectonic structure of the area near the tunnel portals is characterized by the presence of possible fault zones of direction NE-SW. Zones of mylonitic material consisting of clayey sand are observed due to the intense tectonic distress of the limestones, especially in the close area of the entrance portal. The limestones in their majority are permeable formations and the talus material is moderately permeable. The greater area of the project is characterized by a zone of increased seismicity due to destructive earthquakes that have taken place in the past; the last one happened in 1981. The main fault zone in the area of Kakia Skala, which is about 15km long, is considered as active from a geotectonic point of view.

Due to the significance of ensuring slope stability in the area of the tunnel portals and considering the degree of uncertainty concerning the geological and geotechnical conditions of the area as well as the environmental restrictions, it was decided to limit the excavations for the construction of the tunnel portals through the application of special design methods, which involve the construction of reinforced concrete structures and the application of the required support measures.

3. PRESENTATION OF THE PROBLEM AND TECHNICAL SOLUTION

The location of the east portal of the right bore (AS1d) and the west portal of the left bore (AS1a) was determined based on the most recent topographical surveying of the area, the highway requirements, the environmental restrictions and the tunnel construction possibilities and limitations.

The difficulties in design and construction of the two portals arose from the following reasons:

- Proximity to the existing National Highway and need to maintain traffic circulation under the required safety measures.
- The tunnel axis intersects in an angle of 0^o-10^o and 35^o the ground surface contour lines in the east and west portal respectively. This results to requiring a significant length of construction before the tunnel enters the rockmass on its full section.
- The modulation of the portals takes place in disturbed areas due to former excavations with too high and steep open cuts, which present significant rockfalls and structural instability.
- Environmental restrictions are applied, which limit the possibilities of open cut excavations.
- Reduction of construction time is required, since the project has to be finished for the Olympic Games 2004 that will take place in Athens in August 2004.

Different alternative solutions concerning the construction of the tunnel portals AS1a and AS1d were examined, as described in detail below.

3.1 East portal of the right bore of tunnel AS1

The first solution involved the construction of a reinforced concrete structure filling the tunnel cross-section with concrete B15 in the critical parts and B10 in the rest of the cross-section, combined with a concrete pile wall. The reinforced concrete structure required the construction of a retaining toe wall made by concrete B25 in order to decrease the size of the structure and ensure maintenance of highway traffic and safety measures.

The second alternative solution referred to the construction of a pre-arch of significant length in order to perform the excavation and the application of the final lining. This solution was rejected mainly for construction reasons. In particular, the constant change of the cross-section and thus of the geometry of the pre-arches, as well as the inability of sufficient anchoring of the pre-arch in the rock mass led to rejection of this solution. Furthermore, this solution needed the construction of a permanent feature, which would create construction problems in the existing National Highway.

Therefore the first solution was applied, but with certain changes (Final Design of the East Entrance Tunnel Portal AS1d, PATHE, Kakia Skala, Greece). The concrete that would fill the internal tunnel area was replaced by a special polysterine material. The main advantages of using polysterine instead of concrete are cost reduction of underground excavation and higher advance rate.

More specifically, the chosen solution presented in Figure 3, involved:

- Anchored concrete pile wall for 70 m consisted of piles with diameter 1 m and axial distance 1.5 m. The free length of the piles is 20.55 m. The piles were anchored with permanent double corrosion protection anchors of working load of 630 kN and prestressed force of 350 kN, whose lengths varied between 12 and 20 m.
- Reinforced concrete (C16/20) structure of repletion and rehabilitation of the tunnel cross-section (RCSP) combined with a retaining concrete wall (C20/25) and application of polysterine material were implemented for the next 45 m. Beyond that point the application of polysterine was considered too difficult. The construction of the retaining wall is employed for reducing the width of the reinforced concrete structure. In this way, the required width of 15 m of the National Highway for traffic circulation and 4m for worksite use was achieved.
- RCSP made by concrete (C16/20) combined with a retaining wall of concrete C20/25 without application of polysterine material was implemented for the next 30 m.
- RCSP made by concrete (C16/20) combined with a cantilever beam in its toe for stability against sliding were implemented for the last 31.83 m of this section.

Furthermore, in the area of construction of the RCSP, the implementation of micropiles was required for additional anchoring of the reinforced concrete structure to the rock mass. Two rows of micropiles of 250 mm diameter and 6 m length at an axial distance of 1 m were installed at the top level of the RCSP with 20^o downward gradient.

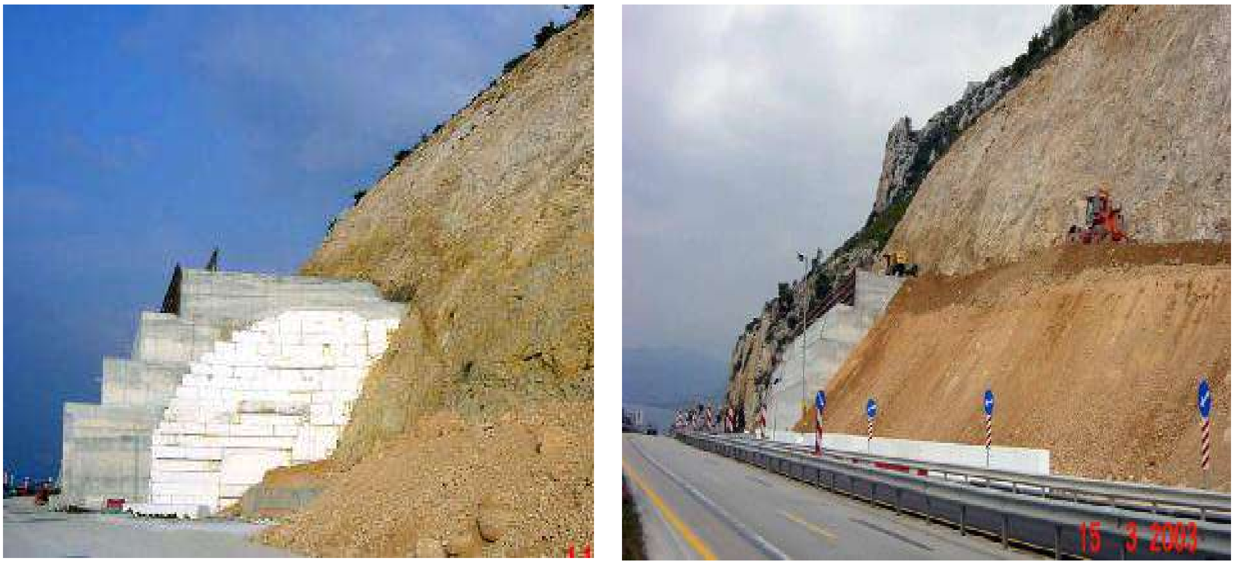

Figure 3 Reinforced concrete structure in east portal of right bore of AS1 with polysterine.

3.2 West portal of the left bore of tunnel AS1

The main difference between the two portals was that in the east portal the tunnel cross-section was about 30% inside the existing slope, while on the west portal the tunnel cross-section was about 70% inside the existing slope. The design and construction method applied for the modulation of the west portal (AS1a) is almost similar to the one implemented in the east portal (AS1d). The solution concerning the construction of a pre-arch was rejected for the same reasons as in the east portal. Therefore, it was decided to construct a reinforced concrete structure (RCS) made of C20/25 and S500, shown in Figure 4, for the quickest and safest entrance of the tunnel in underground excavation as well as for reduction of the disturbance and interference with the surrounding open cuts. Moreover, the concrete pile wall was designed to adjust to the permanent modulation of the portal and to sustain the disturbed boulders and the artificial deposits in order to minimize the interference with higher unstable slopes. At the toe of the RCS, a cantilever beam was designed and constructed in order to prevent sliding of the structure and ensure its stability (Final Design of the West Entrance Tunnel Portal AS1a, PATHE, Kakia Skala, Greece).

Figure 4 Reinforced concrete structure in west portal of left bore of AS1.

4. POLYSTERINE AGAINST CONCRETE

The expanded polysterine was assessed suitable to replace concrete, which was to be removed through the actual tunnel excavation, at the central part of the RCSP that was constructed in the east portal of the right bore of AS1. Due to the properties of polysterine, which are presented in Table 1, such as compressibility and strength, it was judged appropriate for the specific application.

Table 1. Properties of expanded polysterine.

DENSITY	kg/m^3	25
PRESSURE FOR 10% DEFORMATION	kPa	150-200
PRESSURE FOR <2% DEFORMATION	kPa	35-50
STRENGTH IN BENDING	kPa	220-470
STRENGTH IN SHEAR	kPa	150-200
STRENGTH IN TENSION	kPa	220-400
YOUNG'S MODULUS	MPa	5.6-9.2
POISSON RATIO	-	0.02

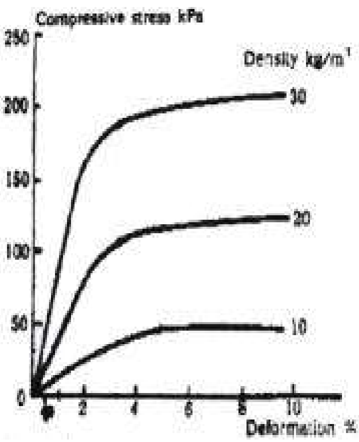

Figure 5 Stress-strain curves of polysterine for different densities.

Polysterine was placed in segments, joined with mortar in order to behave as a uniform material. The pressure of compression that the structure of polysterine undertook depended on the height of concreting above the tunnel crown, which was about 1.5 m. Thus, the pressure developed was estimated to be about 40 kPa, so based on the diagram of Figure 5, 2% of deformation was expected for each segment of polysterine and 5% total deformation.

5. MODELING METHODOLOGY - RESULTS

In order to design and dimension the RCSP and RCS, as well as the retaining measures required for the construction of the east and west portal of the right and left bores respectively, several analyses were carried out.

Possible failure mechanisms that could develop on the open cuts were examined. The analyses were performed by simulating the geometry of the open earth cuts, the geotechnical and hydrological conditions, as well as the stages of excavation and the implementation of prestressed anchors. The stability of the open cuts consisting of soil, against circular failure mechanism was investigated through the use of the software program LARIX-3S by CUBUS, which uses Krey and Janbu methods and determines the lowest safety factor against stability of the retaining system. The analyses were carried out in drained conditions with and without earthquake loading and in undrained conditions. The allowable factors of safety were 1.4 for structural loading, 1.3 for undrained conditions and 1.0 for earthquake loading. The stability of the open cuts comprising rock against plane failure mechanism was examined through the use of the software program ROCPLANE by ROCSCIENCE INC, which examines all possible wedges and respective failures. The free and embedded length of the piles, the forces acting on the anchors as well as the axial and shear forces and the moments, which were used for determining the required reinforcement of the piles and the pile cap, resulted from employing the software program LARIX-3G by CUBUS. One of the sections examined is shown in Figure 6. The geotechnical parameters of talus material that was used for the simulation process are unit weight γ=24 kN/m^3, cohesion c=60 kPa and angle of friction φ=35^o.

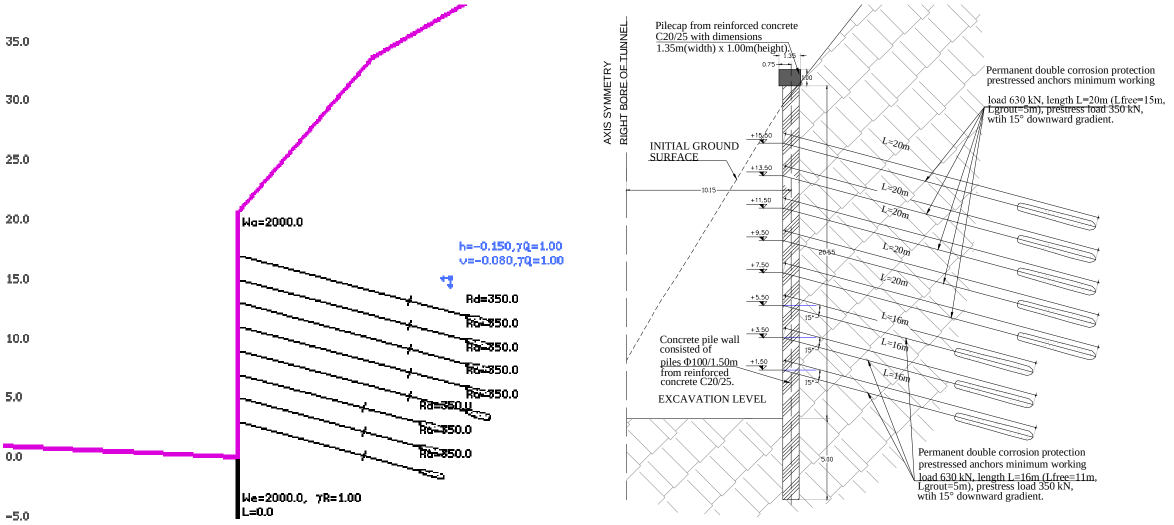

Figure 6 Section of stability analysis of the north side open cuts of the east portal against circular failure mechanism through the use of the software program LARIX-3S and the actual arrangement of anchors applied.

The final solution for dimensioning the retaining measures derived from constant trials and analyses of the geometry, the length of the piles, the number of prestressed anchors and the modulation of the open cuts, as presented in the flow chart in Figure 7.

The simulation of the RCSP and RCS, the stages of construction and all the combinations of loadings was carried out through the use of the software program NEXT/S by COMPUTEC SOFTWARE, which employs the finite element method. Also the cantilever beam was dimensioned against sliding, and the bearing capacity of the ground was examined in both cases. The implementation of micropiles was also simulated in the analyses. The interaction of ground with the reinforced concrete structures was simulated by springs, which were calculated based on the relation S=k*F, where F is the influence area and k the respective modulus of subgrade reaction for soil reaction. The reinforcement required for the concrete structures and the cantilever beam were calculated based on the results of the respective analyses, as presented in Figure 8.

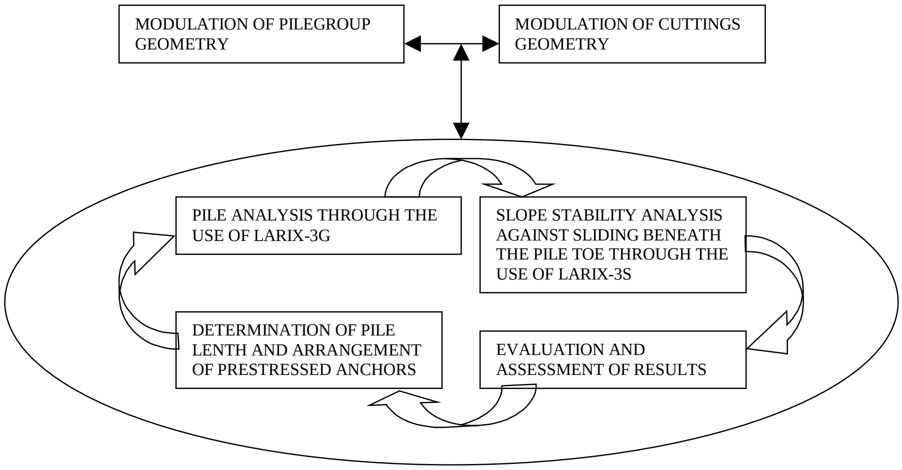

Figure 7. Flow chart of the design sequence carried out for dimensioning of the retaining system.

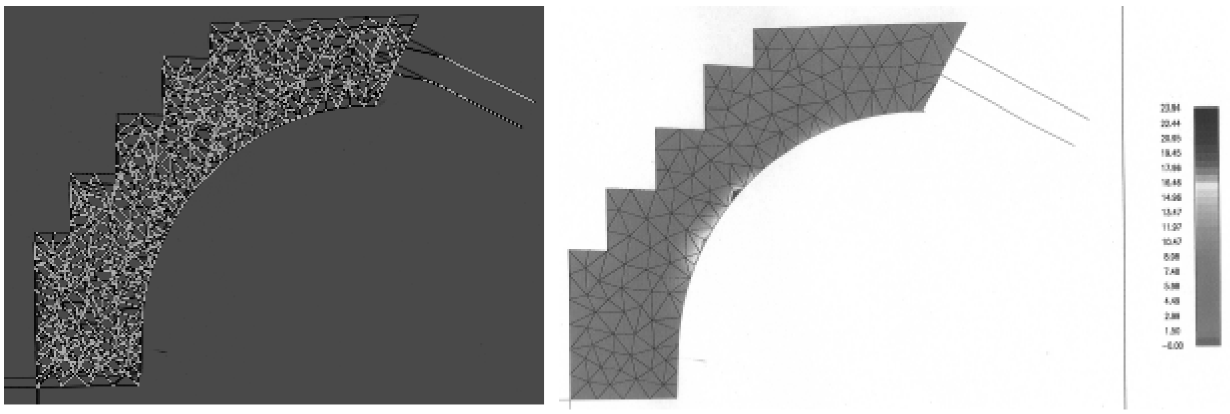

Figure 8 Deformed mesh from the simulation of the RSCP with the implementation of micropiles and reinforcement (in cm^2) required from the results produced.

6. SUPPORT AND DRAINAGE MEASURES OF THE TUNNEL PORTALS

Considering the conditions of construction, the numerical analyses results concerning the required measures for stability of the retaining system, the estimation of the on-site behavior of the geological formations, the importance of the location, the design methods and construction techniques applied in similar projects and the reduction of construction cost, the following measures were implemented to achieve sufficient support and drainage of the portals.

Concerning the east (entrance) portal of the tunnel AS1, the appropriate support measures applied, as presented in Figure 9, included steel fiber shotcrete of 10 cm thickness, fiberglass bolts fully grouted with 10^o downward gradient, of 12 m length, working load 250 kN, in a staggered grid of 1.5 x 1.5 m. Collection and arrangement of pluvial water during and after the construction of the portals is achieved through drainage trenches constructed above the pile cap with dimensions 0.5 x 0.5 m and 1:1 gradient of the side slopes and a permanent drainage trench constructed on the top of the RCSP with dimensions 1.5 x 1.25 m. In the permanent trench a wire net is retained with steel posts IPE100, as shown in Figure 9, in order to protect the trench from possible rockfalls.

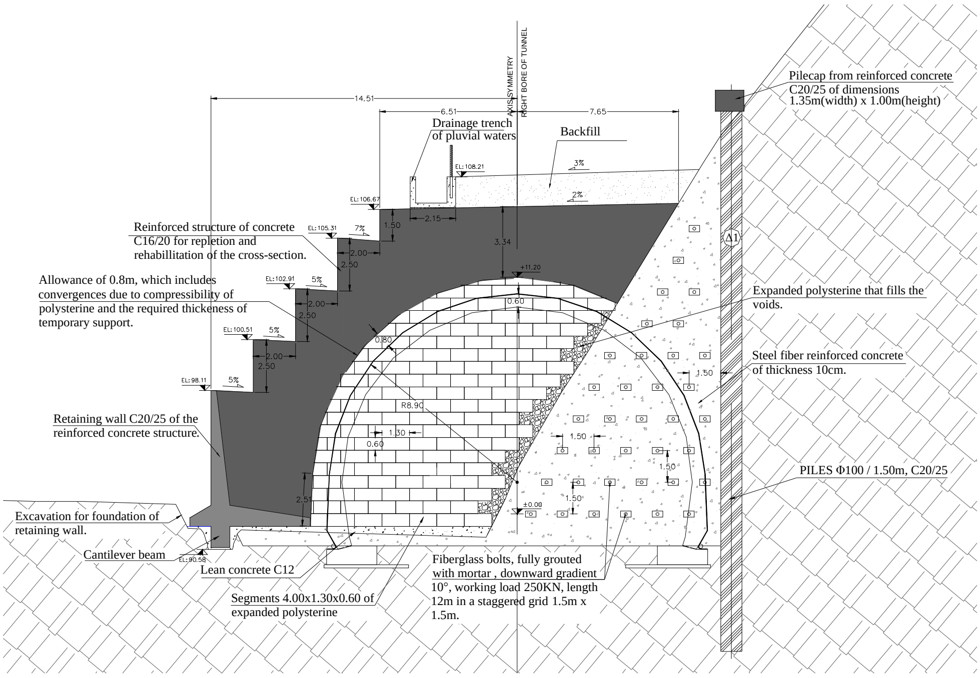

Figure 9 RCSP in the east portal and the required support measures.

Regarding the west (exit) portal of the tunnel AS1, the appropriate support measures, shown in Figure 10, were applied on the lateral open cuts of the portals that were formed in gradient 3:2 and 2:1 and on the portal face and included:

- Permanent rock anchors fully grouted, placed normally to the cutting surface, with 10^{o} upward gradient in rock and 10^{o} downwards gradient in soil, of 6 m length, diameter 25 mm and steel grade S500, working load 200 kN, in a staggered grid 2 x 2 m.
- Steel fiber shotcrete of 5 cm thickness for the lateral open cuts and 10 cm for the portal face.
- Drainage holes of 3’’ diameter, with 10^{o} upward gradient, 8m length, in 2 m axial distance, within which a semi-perforated PVC pipe of 2’’ diameter covered with geotextile is installed.
- In every case that indication of water is noted on the surface of the steel fiber shotcrete, relief holes of 2’’ diameter with 10^{o} upward gradient, 0.5 m length, in an appropriate arrangement and density, within which a semi-perforated PVC pipe of 2’’ diameter is placed.

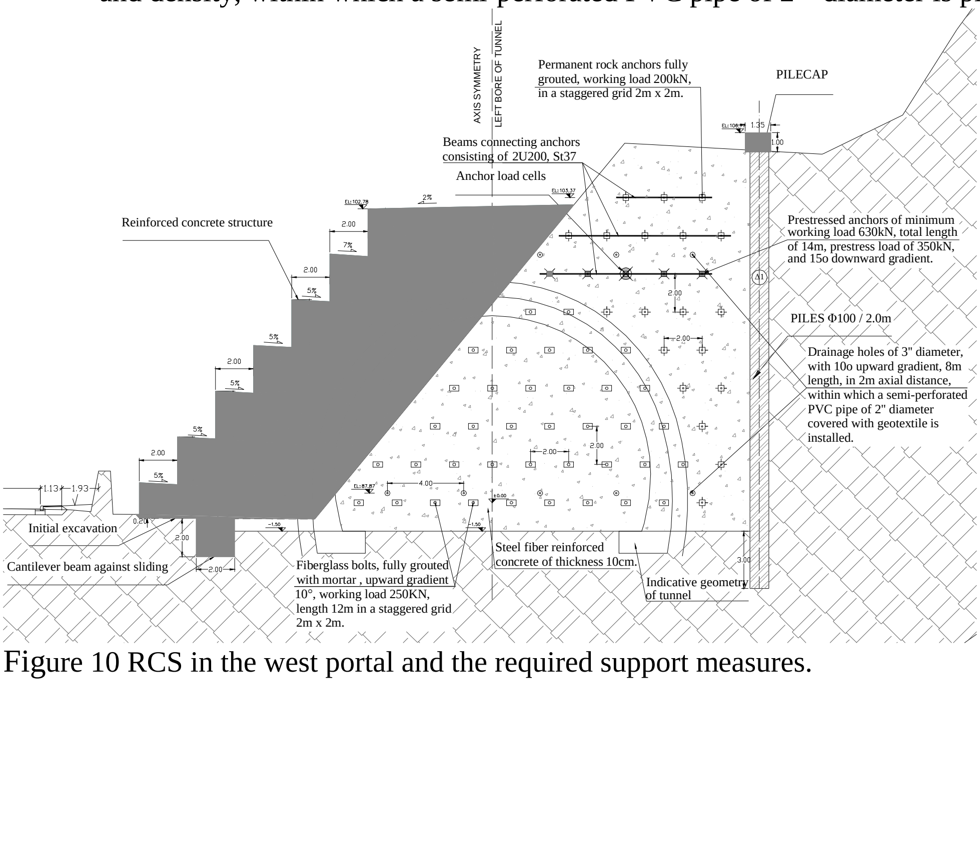

Figure 10 RCS in the west portal and the required support measures.

Furthermore, on the portal face prestressed anchors of minimum working load 630 kN, total length of 14 m (free length 9 m and grouted length 5 m), prestress load of 350 kN and 15^o downward gradient as well as beams, which connect the prestressed anchors and are consisted of two steel profiles U200, St37, were implemented. Also fiberglass bolts fully grouted with 10^o upward gradient, of 12 m length, working load 250 kN, in a staggered grid of 2 x 2 m were installed on the portal face.

7. GEOTECHNICAL MONITORING

An extensive program of geotechnical measurements was undertaken during and after the construction of the two tunnel portals in order to assess the behavior of the open cuts, the function of the retaining system, the support measures and the reinforced concrete structures. Hence, special instruments were installed in specific locations and the frequency of obtaining measurements and the trigger criteria were defined.

Three-dimensional optical targets of topographical recording of micro-displacements on the ground surface and anchor load cells on the prestressed anchors were implemented and measurements were obtained every two days. Also, check and impression of development and enlargement of cracks as well as assessment of the water flow capability of the drainage holes was carried out every week.
The warning levels were determined to be:

- Microdisplacements of the surface: rate < 5 mm/day, total displacement < 40 mm
- Microdisplacements of the piles: rate < 2 mm/day, total displacement < 20 mm
- Microdisplacements of the RCSP and RCS: rate < 2 mm/day, total displacement < 20 mm

The actual measured values were kept in all cases below the above limits.

8. CONCLUSIONS

Original design methods and special construction techniques were implemented for the construction of two tunnel portals and proved to be safe, cost and time effective. Due to safety, environmental, morphological and space restrictions as well as the existence of an active seismic fault zone passing through the tunnels, two (2) reinforced concrete structures for 30% (RCSP) and 70% (RCS) of the tunnel section inside the existing slope were designed and constructed. In one case a significant amount of concrete was replaced by a composite construction of polysterine boxes, which resulted in higher rate of excavation progress and lower cost. In order to ensure stability of the reinforced concrete structures, a retaining system slightly different for each portal was employed, which consisted mainly out of concrete pile walls, micropiles, pre-stressed anchors, fiberglass bolts and cantilever beams. Selection and design of the support measures was based upon the numerical analyses results, according to which, the chosen measures were sufficient to stabilize the tunnel portals and the surrounding open cuts. The static adequacy of the selected support measures was checked under seismic loading. A critical point and requirement for the effectiveness of the above measures was the proper implementation according to the design. As a consequence, the tunnel portals were successfully constructed and the tunnel AS1 was effectively excavated.

9. REFERENCES

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