Chapter 47

EVINOS-MORNOS TUNNEL - GREECE

CONSTRUCTION OF A 30 KM LONG HYDRAULIC TUNNEL IN LESS THAN THREE YEARS UNDER THE MOST ADVERSE GEOLOGICAL CONDITIONS

by Remo Grandori, Manfred Jaeger, Fabrizio Antonini, Luis Vigl

Dr. Ing. Remo Grandori Managing Director SELI SPA, Rome, Italy
Dipl. Ing. Manfred Jaeger Managing Director JAEGER mbH, Schruns, Austria
Dr. Ing. Fabrizio Antonini Project Manager SELI SPA, Rome, Italy
Dr. Ing. Luis Vigl Project Manager Vorarlberger Illwerke AG, Schruns, Austria

ABSTRACT

The EVINOS-MORNOS tunnel project with its 30 km of length is one of the longest hydraulic tunnel in the world realised with TBM method.
The adverse geological conditions, the high cover and the short construction schedule were a great challenge for the successful construction of this tunnel.
The paper will describe:

- the criteria adopted for the tunnel design, the selection of the construction methods and equipment,
- the productions of the 4 TBMs adopted and the comparison of the behaviour of the different type of TBMs in the various rock conditions, including special conditions,
- the characteristics of the adopted in situ and precast linings,
- a comparison between the foreseen and actual construction schedules,
- the contractual implications of realising a tunnel in such a severe and complex conditions.

GENERAL DESCRIPTION OF THE PROJECT

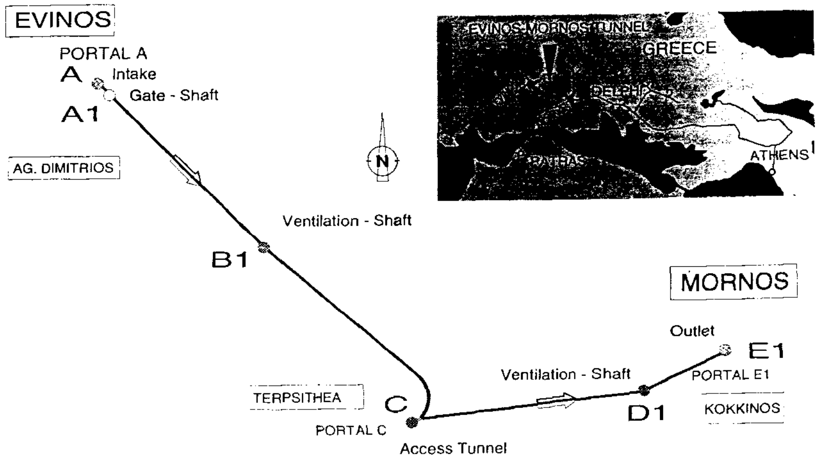
REASONS AND URGENCY OF THE PROJECT

Athens - the capital of Greece - accomodates almost half of the greek inhabitants. The water consumption is expected to grow up to 1.7 million cu.m./day till the year 2030.
The "Evinos-Mornos Project" was studied first in the year 1970 and foresees the diversion of a yearly by runoff of 200-230 cu.m./a from the 350 sq.km. large catchment area of the Evinos river to the Mornos basin and thereby to the city of Athens. The major structures of the project are a 120 m high earthfill dam with a dam volume of 12 million cu.m., a total barrage capacity of 120 million cu.m. and the 30 km long Evinos-Mornos tunnel with an internal diameter of 3.50 m. The major purpose of the project is to provide supply of water for Athens till the year 2030.

LOCATION AND GENERAL SCHEME

The Mornos basin is located 150 km northwest of Athens. 30 km west the Evinos river runs down to the sea side west of Nafpaktos (at the Gulf of Korinthos).
The tunnel was divided into four headings: the first heading starting at the intake at Agios Dimitrios (portal A), two headings starting from Therpsitea (portal C) and the fourth heading starting from the outlet at Kokkinos (portal E1) at the Mornos basin (Fig. 1).

FIG. 1 General plan view of the project and of the whole aqueduct scheme



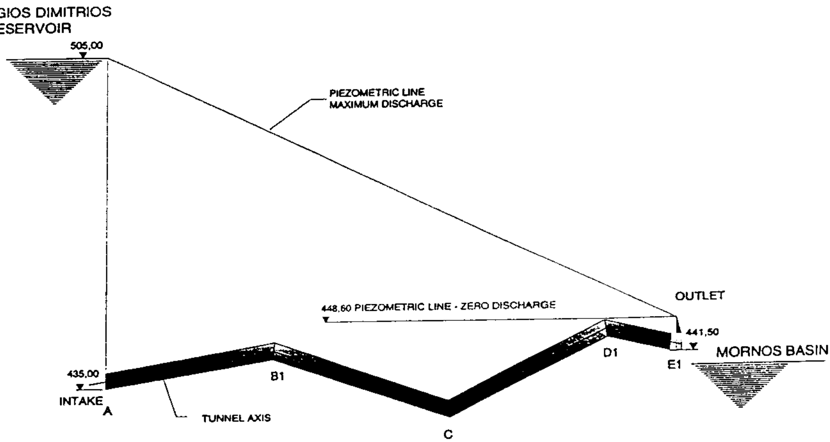
Between the intake (A), the intermediate access (C) and the outlet (E1) due to upward excavation two high points with ventilation shafts (B1 and D1) are located.
Beside the tunnel diversion system contains the following operational structures:

- intake tower at portal A (30 m high, dia. 4.0 m),
- gate shaft near the portal A (70 m high, dia. 5.0 m)
- ventilation shafts at B1 and D1 (240 and 250 m high, dia. 0.25 m),
- intermediate access at C with steel door and depletion facilities,
- outlet structure at E1.

HYDRAULIC FUNCTIONING AND DIMENSIONING

At the upstream end of the tunnel (intake Portal A) the Agios Dimitrios dam is located which has the purpose to work as a retention reservoir from the wet-season runoff-peak, but also as a reservoir for water storage. The water diversion is controlled from the gates (A1) near the intake and a free outflow right above the highwater level at the Mornos basin is provided. Thereby the maximum internal water pressure in the tunnel is about 7 bar at the intake and zero at the outlet. The design discharge capacity of the system is 26 cu.m./sec which is related to the inflow scenery at the Agios Dimitrios reservoir (Fig. 2). The discharge capacity is determined by tunnel roughness and only marginally by local head losses. The tunnel is lined with a very smooth cast in situ lining for 12,5 km with a roughness factor of 85, according to Manning-Strickler. For 17,0 km it is lined with a segmental lining with a systematically roughness resulting in a Manning-Strickler factor of approximately 70. With the internal tunnel diameter of 3,50 m the design discharge can be well achieved.

FIG. 2 Hydraulic profile of the project



Tendering system and Contract conditions

The project was internationally tendered by the Greek Ministry of Public works at the end of 1991. The contract was awarded to the Greek-Italian-Austrian Joint Venture, called GR.IT.AU. Evinos Joint Venture. The award was based on a "Design and Build" type contract and thereby the contractor is responsible for the design, the construction and for maintaining and operation of the structure for a guarantee period lasting for three years.

Geological Conditions

Geological longitudinal section

Hereinbelow is the geological longitudinal section of the Evinos-Mornos Tunnel drafted according to the actual excavation records (Fig. 3, 4, 5).

From the Intake station 1500 m the geological section shows fine grained and later chaotic flysch. At the station 1500 m the flysch is overthrusted by limestone. The following upper-cretaceous limestone formation intersected by cherts in the core of the anticline reaches to station 3700 m. From station 3700 m the station 4950 follows an alteration of chaotic and fine grained flysch which again is overthrusted by limestone.

The limestone of Triassic and Upper Cretaceous age, intersected by a zone of cherts, reaches to station 9200. A transition zone from limestone to flysch is followed by an alteration of chaotic and fine grained flysch formations to station 29392, zone where is located the outlet portal at the Mornos river.

TABLE 1. Geological sections

Station	Formations	max. overburden
0 - 1500 m	flysch	300 m
3.700 m	limestone (cherts)	700 m
4.950 m	flysch	1.300 m
9.200 m	limestone (cherts)	1.100 m
	alternating fine grained and chaotic flysch	1.100 m

Properties of geological formation

Along the tunnel axis of the Evinos-Mornos Tunnel the following geological formations were found:

FIGURE 3

EVINOS ACQUEDUCT PROJECT
TUNNEL GEOLOGICAL PROFILE

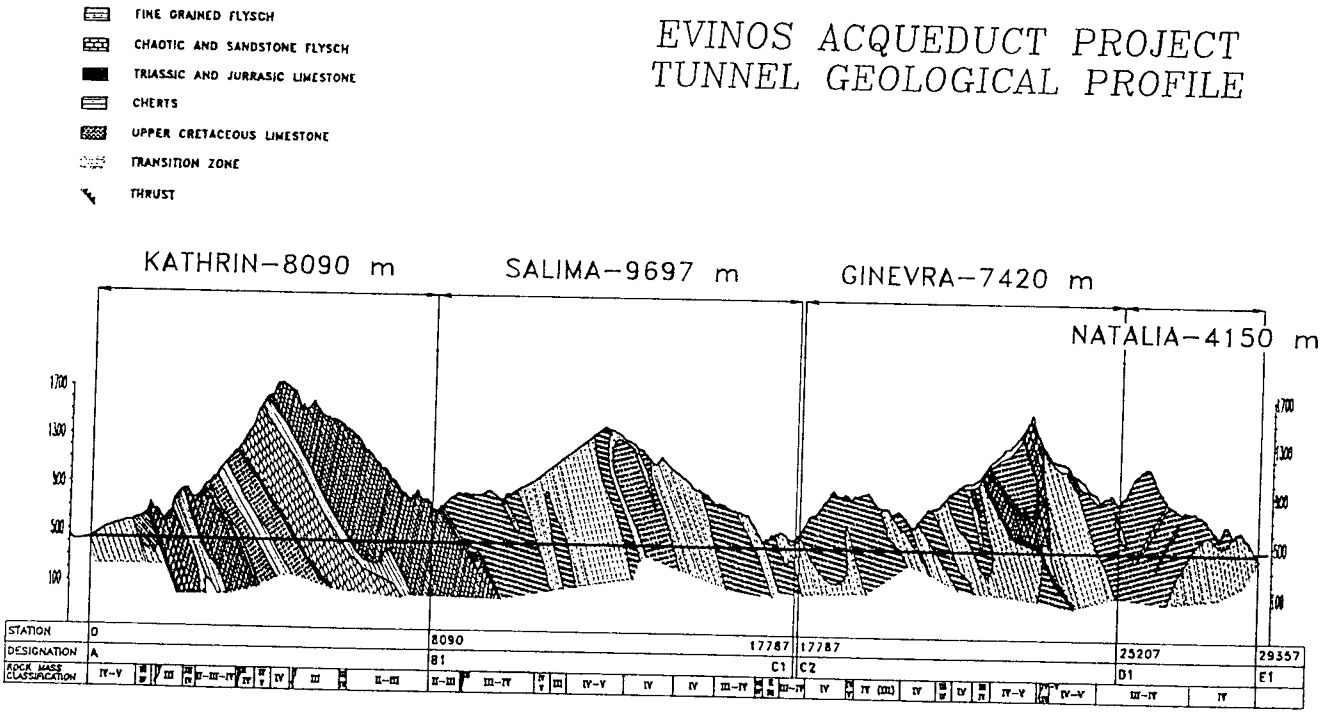
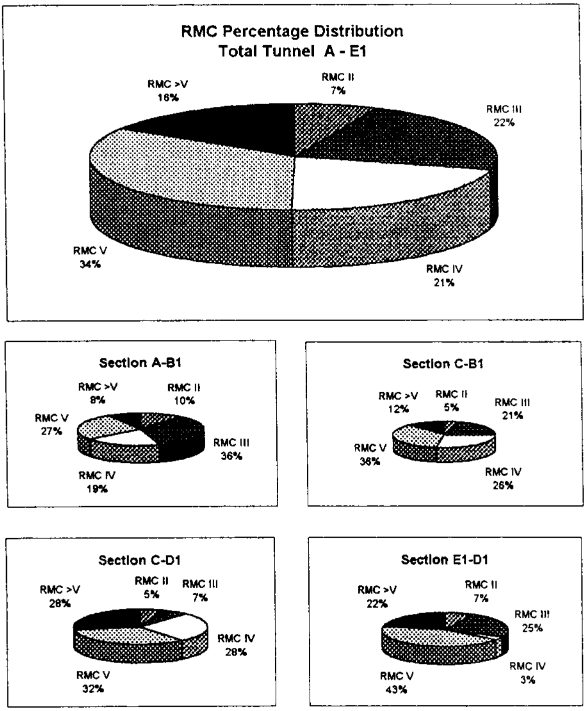


FIG. 4 Percentage distribution of rock classes

Actual Rock Mass Classification

Section	Advance	RMC II	RMC III	RMC IV	RMC V	RMC >V
A-B1	8090	849	2823	1560	2194	664
C-B1	9697	449	2083	2546	3430	1189
C-D1 *)	6925	355	443	1869	2212	1866
E1-D1	4185	298	1055	128	1781	923
Sum	28897	1951	6404	6103	9617	4642

*) TBM still under production, dates updated till end of december 1994



Fine grained flysch

It represents a typical sequence of bedded claystone with inter-calations of thin bedded sand and siltstones. This formation was folded and fractured by tectonic stresses.

Chaotic and sandstone flysch

It stands for irregular or "chaotic" sedimentation of sandstones alter-nating with clay and siltstones; it was folded, fractured and partly tectonized.

Triassic and Jurassic Limestone

It appears as medium to thin bedded lime-stone with mm thin clay layers and chert nodules. It was solid, folded and jointed. Rock mechanical con-ditions for excavation as well as the bearing behaviour was good.

Cherts

They are thin bedded Radiolarities with inter-calations of thin bedded claystone. The percen-tage of claystone varies from 10 to 50%. The claystones are of "changeable" and very little strenght. The Radiolarities are solid rocks with very high compressive strenght. They are very abrasive. In sections of high clay content the Radiolarities were highly tectonically fractured. In the cherts formation, squeezing phenomena were often encountered. In sections with less clay content, the Radiolarities worked as a firm skeleton of the rock mass and the geomechanical properties were much better.

Upper Cretacious Limestone

It is a thin bedded limestone with clayey firms and chert nodules. It was folded and little jointed. The other pro-perties were very similar to that of Triassic and Jurassic Limestone.

Transition zones

They are not fault zones. It is the tran-sition in normal sedi-mentation from lime-stone to flysch. They appear as interbeddings of limestone, sand-stone, siltstone and argillaceous slates. The argillaceous strata were of very "changeable strenght".

FIG. 5 **Rock classes V and over V with more than 600 m of cover**

TUNNEL A-B (TBM Kathrin)		
RMC V	1620 m	between ch.3570-6900
RMC >V	350 m	between ch.3570-6900
TUNNEL C-B (TBM Salima)		
RMC V	527 m	between ch.3630-5370
RMC >V	582 m	between ch.3630-5370
TUNNEL C-D1 (TBM Ginevra)		
RMC V	606 m	between ch.4630-6600
RMC >V	760 m	between ch.4630-6600

Thrust zones

The thrust zones are the result of overthrust of limestone over flysch or, as it was encoun-tered in three locations along the ED1 tunnel section, of flysch over flysch. These last were not anticipated by the geological investiga-tions mainly because it is very difficult to establish and map from outside the front of a flysch over flysch thrust. In these zones the rock mass were loosing its mechanical properties and behaved as a collapsing soil, with significant squeezing phenomena (upto 14 cm reduction in diameter at 1 m from the face and in one hour time) and immediate collapses of the tunnel face, or even ahead of the tunnel face. These thrust zones together with some cherts formations, were the most difficult formations to be excavated and supported, specially under the bigger covers.

Methane inflow

Methane inflow was encountered more or less along 80% of the flysch formation lenght.

Mainly in section C-D1 the amount of inflow was very high; in this section the excavation methodology and the ventilation system were changed in order to reduce the stoppage due to gas excess inflow. At Portal A, chainage 5500 m an unforeseen high gas inflow was encountered in thin clay layers intercalating in limestone layers.

GENERAL DESIGN CRITERIA FOR THE EVINOS-MORNOS TUNNEL APPLICATION

The general design criteria for the Evinos-Mornos Tunnel can be summarized as follows:

Discharge capacity - First of all the internal tunnel diameter was determined by the design discharge capacity like described above. The internal diameter leads to the excavation diameter depending on the lining system.

Excavation method and lining system - The Client had foreseen two different excavations, respectively lining systems depending on geological indication.

For the flysch formations a double shield TBM excavation combined with a precast segment lining was indicated. For formations with expected better geological properties, limestone f.i., open type TBM excavation with NATM preliminary support and final cast in situ lining was instead indicated. In view to tunnel design both systems act slightly different and depending of the achievable concrete quality and the stiffness of the support they require a different lining thickness and different convergences.

Determined by the necessary convergences and the capability of the lining an excavation diameter of 4,04 respectively 4,12 m was necessary for double shield TBM excavation with segmental lining. An excavation diameter of 4,20 m was necessary for open type TBM excavation combined with NATM preliminary support and final cast in situ lining.

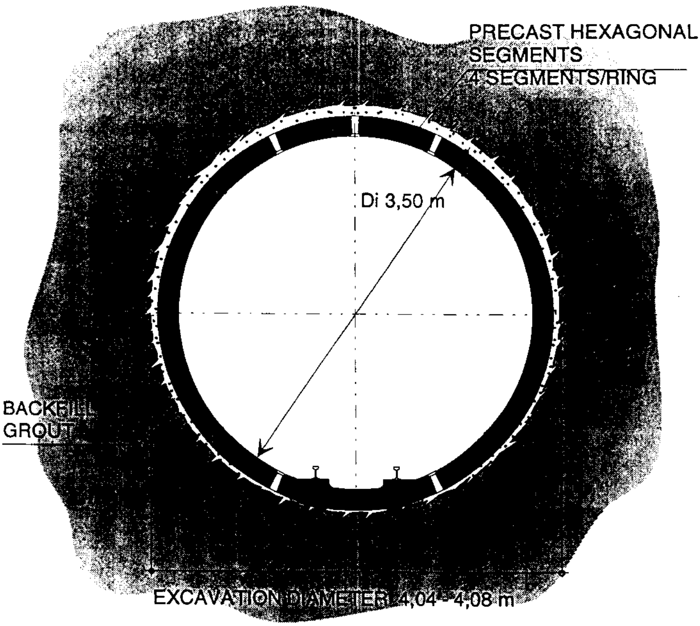
Watertightness - According to the tender at the Evinos-Mornos tunnel maximal water losses of 4 l/sec.km are permitted. This means that the tunnel has to be watertight in technical sense. Watertightness by far is provided by a highly impermeable rockmass and a high external groundwater table for the major lenght of the tunnel. Thereby the lining itself has not to be watertight, but the system containing of lining, surrounding rock and groundwater table has to provide watertightness. To achieve this is necessary to undertake grouting.

Structural safety - Depending on rock mechanical parameters for the different geological formations, standing for the capability of the rock mass, and on the overburden, standing for the external stress level, the necessary bearing capability for the different lining systems was determined using by the Mohr-Coulomb failure criterion for strenght, and an elasto-plastic model for stress calculation. Characteristic lines were used to determine the deformation to be expected. Beside the external rock load the necessary grouting pressure was taken into account for the determination of the lining thickness.

SEGMENTAL FINAL LINING FOR HYDRAULIC TUNNEL IN ROCK (figure 6)

As mentioned above one of the aspects for the lining of a hydraulic tunnel is the aspect of the friction losses. A segmental lining causes a systematically roughness which results in a relative low roughness factor (k_{stri} = /0 f.i.). This can be easily evaluated by chosing a larger diameter which reduces the friction losses overproportionally. At the Evinos tunnel this effect was compensated by the very low roughness of the cast in situ lined portions.

FIG. 6 Typical cross section - Precast segment lining



The next aspect of a hydraulic tunnel is the aspect of water-tightness which must not be seen independent from the surrounding rock and the ground water table. At the Evinos tunnel watertightness was improved by means of grouting. To provide grouting, the joints between the segments had to be sealed. This was made for partially with sealing strips. At the radial joints, where the total capability of the lining has to be provided, grooves for sealing strips were avoided and the joints were sealed by a special mortar.

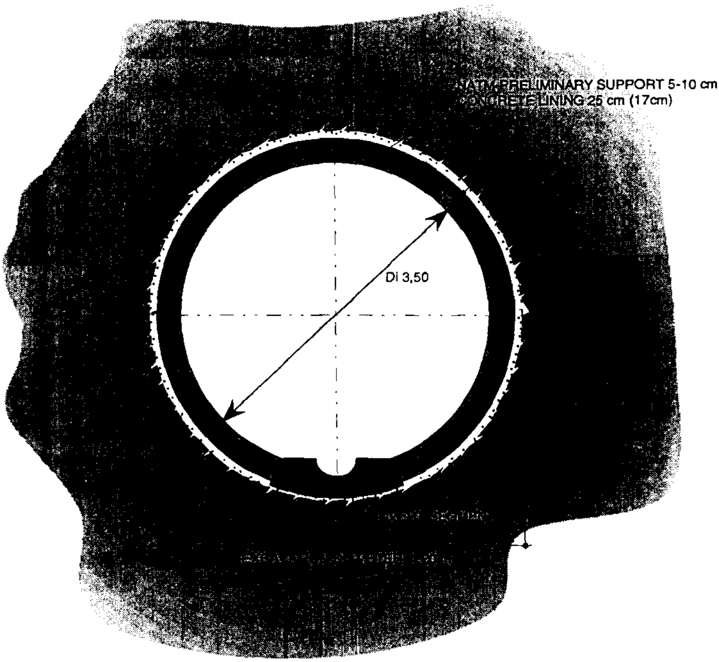
In situ lining for hydraulic tunnels in rock

The in situ lining system is quite different to the segmental lining. Due to the fact that in situ concrete is applied a long time after excavation, tunnel safety till this time has to be provided by the preliminary support.

At the one hand the tunnel has time enough to stabilize till the final lining is applied and the safety of the system is raised considerably, at the other hand one may arise the question if so much additional safety is needed and economical in view to the excavation diameter and construction time.

The criteria for the thickness of the final lining are structural safety, minimal thickness for construction and grouting pressure. At the Evinos tunnel the dominating criterion for the thickness of the cast in situ lning was the minimal thickness for construction (typical section see figure 7).

<u>FIG. 7</u> Typical cross section - In situ lining



The designed thickness was 25 cm resulting in a minimum remaining thickness of approximately 17 cm after taking convergences into account. This criterion allows that the concrete quality must be too high (B 25) resulting in low hydratation heat, low content of fissures and good properties in view to watertightness.

As mentioned above the lining is very smooth resulting in a roughness coefficient of:

$$k_{stri} = 85 \text{ f.i.}$$

ROCK MASS CLASSIFICATION SYSTEM AND ROCK CLASSES DISTRIBUTION

The Client selected the Bieniawski R.M.R. rock mass classification for the whole of the tunnel. In the sections excavated by open type TBM the R.M.R. classes, to witches the contractor associated NATM support class, were also used as payment classes.

In the geological forecast of the client all the tunnel should have been excavated in rock R.M.R. classes from II to IV, with thrust zones and fault zones in rock class V. Figure 4 shows the encountered distribution of rock classes all along the tunnel. About 34% of the tunnel was excavated in class V.

In addition, about 16 % of the tunnel was excavated in a ground mass (indicated as class Over 5) that could not be described by the Bieniawski classification system since the rockmass structure was so deteriorated that the actual RMR parameters could not be measured. In these particular thrusted, folded or faulted zones practically the ground was behaving as a soil like mass, with immediate collapse of the face and/or immediate high squeezing phenomena. Of these 16% of tunnel, almost 10% required the application of special methods of execution witches negatively affected the productivities and the construction costs.

As regard the utilisation of the RMR system in the Evinos tunnel project and in general in TBM tunnel projects, we note the following:

- RMR system worked fine in the Evinos tunnel over 85% of its lenght, this percentage constitutes a very good result taking into account the extremely bad geological conditions of this tunnel, where more than 70% interested ground masses of very low mechanical properties.
- In the rest of this tunnel, since the ground was reduced to a soil like mass, RMR system could not be applied as no other rock classification system could have been applied.
- Other applications of RMR system made by the authors in TBM excavated tunnel in ground masses of better quality (the tunnels were always in rock) resulted in a 100% success as regard the possibility of describe all rock conditions by RMR values and classes.
- It is normally not sufficient to base the payments of a tunnel contract only on the RMR classes, without introducing other parameters as: rock type, water inflow, overburden and other parameters eventually characteristics of the litotypes of the various tunnels (as for example the weathering speed, the swelling behaviour, the abrasivity or other).

As a conclusion regard this matter it can be stated that:

- RMR classification system is a very powerfull and useful tool for the design and the construction of rock tunnels.
- The above does not mean that RMR system, as any other rock classification system, could be used alone as a single parameter to design, construct and compensate a tunnel.
- As any other Rock Mass Classification System RMR classification system could not be applied when soil type ground masses are encountered.

CONSTRUCTION METHODS

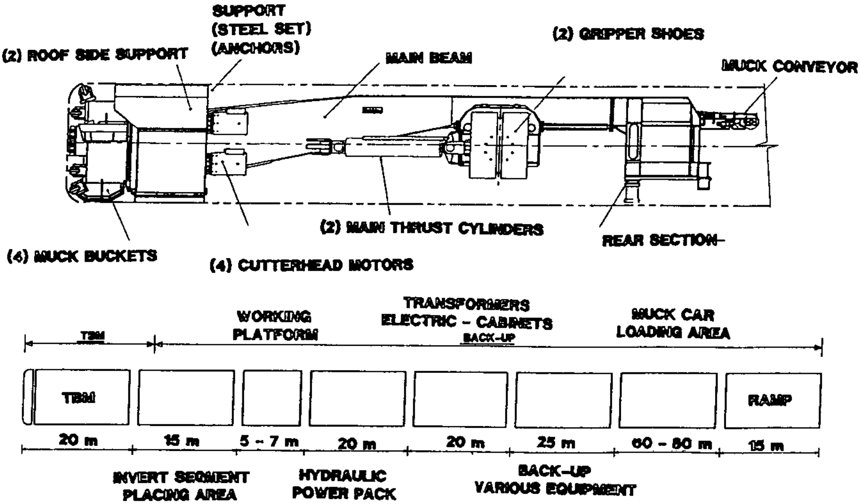
Selection of the construction methods according to tunnel design and construction schedule

The main construction methods adopted for excavating the tunnel and reasons behind these chooses have been described in the previous chapter. The following main remarks are underlined by the authors:

Excavation and support system with the Open Type TBMs (Fig. 8): The two Robbins open type TBM were very similar in design and specification, as well the two Rowa back-up.

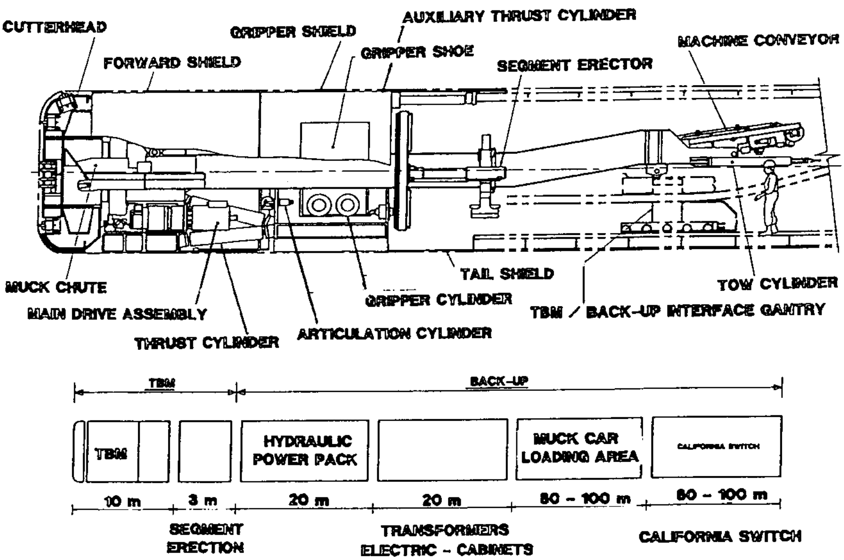
The installations of the rock supports was foreseen in two different sections of the tunnel. Steel set and wire mesh immediately behind the roof shield of the TBM, i.e. at about three meters from the tunnels face. Shotcrete from a special platform at distance of 20-30 mts from the tunnel face.

FIG. 8 Open TBM and backup scheme



Excavation and lining system with the Double Shield TBMs (Fig. 9)
The two almost identical Robbins Double Shield TBM and back-up were overhauled and modified to suit the project requirements by a collaboration BORETEC-SELI.

FIG. 9 Double shield TBM and backup scheme



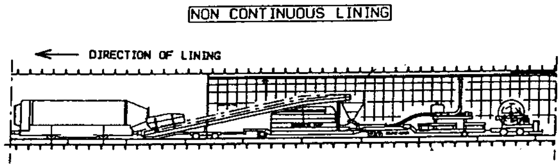
In particular:

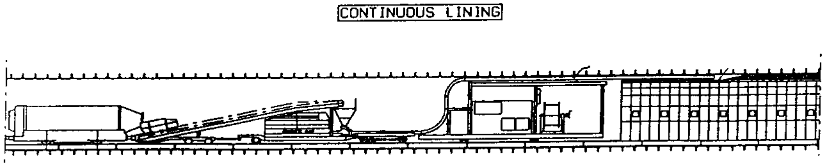
- the cutterhead was of new manufacture with 17 inches backloading cutters, smooth design to work in unstable rocks, overboring system (up to 8 cm increase in excavation diameter);
- the Gripper and Tail shield were specially designed and manufactured to allow the installation of honeycomb type precast lining at distance of about 9 mts from tunnel face.

In situ lining (Fig. 10)

Two different methods were applied in the two sections of the tunnel lined in situ.

FIG.10 In situ lining - Continuous and non continuous





Continuous Lining System (in A-B1 section) - By using a 90 mts long telescopic shutters system (in 10*9mts sections), 30 cu.m./hr capacity concrete pump and a concrete transport train of 3*7 cu.m. capacity nachmixers, 24 hours "continuous" lining operations could be performed. This system was selected for the A-B1 section because of the longer length to be lined in very limited time. The term continuous means that the concreting and shutters moving operation are done continuously and contemporary all along the 24 hours. In this system the limit of production is given by one of the following parameters whichever occur first: concrete transport capacity, shutters moving maximum speed, minimum curing time.

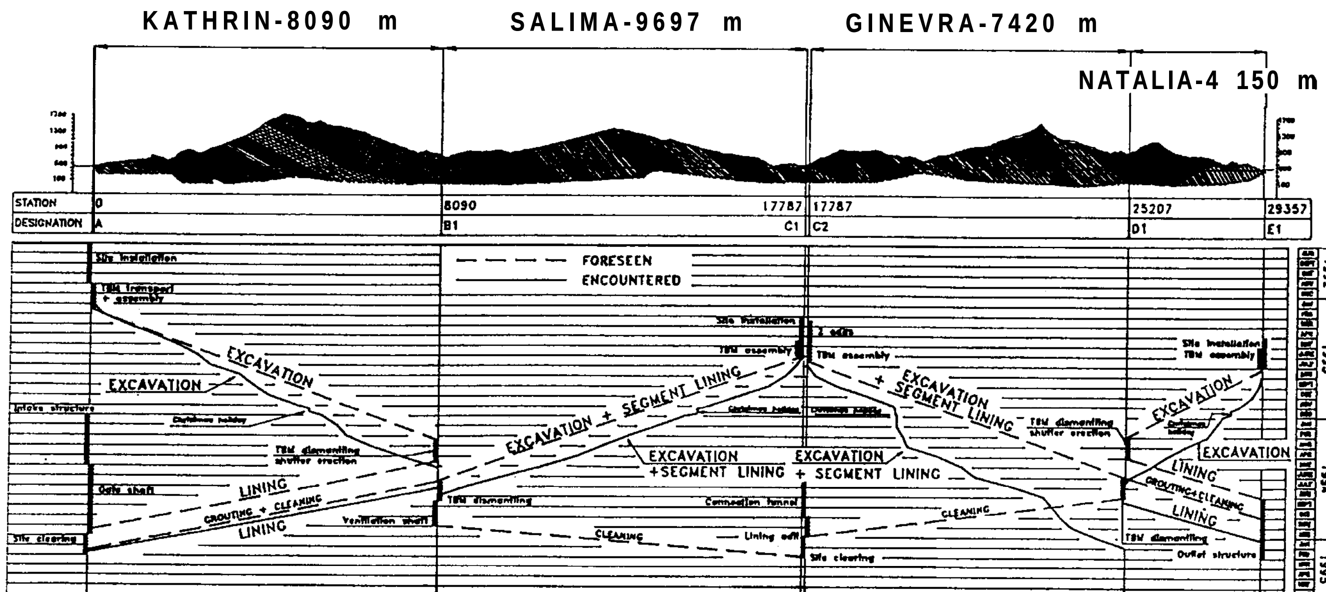
Non Continuous Lining system (in D1-E1 section) - By using a 63 mts non telescopic shutters system (n.7*9m sections), a 50 cu.m./hr capacity concrete pump and a concrete transport train of 3*9 cu.m. capacity nachmixers, "non continuous" lining operations were performed. This system was selected for the D1-E1 section because the smaller length was allowing enough time for the slightly reduced productions characteristic of this method.

Non continuous means that the lining operation and the shutter moving operation are not performed contemporary but in sequence. With this system the production limit is given by the total shutter length. This length could not be increased over a certain limit (60 to 70 mts typically in the 4 m diameter range) because otherwise the complete lining cycle (Lining+Curing+Shutter movimentation) could not be completed in the 24 hours.

FIGURE 11

EVINOS ACQUEDUCT PROJECT
ACCELERATED CONSTRUCTION SCHEDULE

FINE GRAINED FLYSCH
CHAOTIC AND SANDSTONE FLYSCH
TRIASSIC AND JURRASIC LIMESTONE
CHERTS
UPPER CRETACEOUS LIMESTONE
TRANSITION ZONE
THRUST



Precast lining

The four hexagonal precast segments, 20 cm thick and 1,25 mts long, were erected under the tail shield. Longitudinal joints were of the knockee type; transversal joints were flat.

Apart from the short installation time, one important advantage of using the hexagonal type segments is the absence of fastening bolts, with the well known consequent advantages of better hydraulic roughness coefficient, resistance and durability.

A special study was performed by Illwerke of Austria, the tunnel designer, in order to select the more appropriate sealing system for the segment joints, taking into consideration: the operating conditions of the tunnel, the geological formations, the overburden and the level of the external groundwater table.

In the case of the Evinos-Mornos Tunnel, being the rock formations impermeable and the level of the groundwater normally higher than the tunnel internal pressure, the main functions of the segment joint sealing system are:

- allow the execution of the contact grouting operations (1-3 bars) and of the consolidation groutings (20 bars) without leakages,
- assure the complete filling of the joints itself with the grouting mix.

The today available seals (rubber, hydrophilic, others) with difficulties could keep the grouting pressure of 20 bars and in addition, not letting circulate the grouting mixture along the joints, they do not allow the perfect filling of the joints.

On the base of the test results and studies, it was therefore decided to seal the joints with special mortar (SIKA REP, DARAGROUT, EMACO). These mortar, when subject to the high grouting pressure, work as a filter, the water pass through the mortar carrying out the fines of the grouting mix. These fines little by little fill the voids in the joints and self implement the tightness.

CONSTRUCTION SCHEDULE (Figure 11)

Description of the foreseen accelerated construction schedule

One of the most important technical aspect of the project has been the extremely short construction schedule. When the Contract was awarded very few people in the tunneling industry was believing that a 30 km tunnel in such a difficult ground conditions could be bored by TBM and could be completed in 42 months as foreseen in the Contract.

When, following an acceleration agreement with the client, the construction time was reduced to 33,5 months despite the fact that the completion of the access roads to Portal C and Portal E1 (from which three of the four TBM had to bore) was delayed by 10-11 months, only the contractor and the Greek state was believing in the possibility to complete the tunnel in time. The time available for each TBM to complete (excavate+lining+grouting) its section from the moment that the relative access road was available were:

Section A-B1 (8,1 km) = 30,0 months
Section C-B1 (9,7 km) = 22,5 months
Section C-D1 (7,4 km) = 22,5 months
Section E1-D1 (4,2 km) = 21,5 months

The acceleration construction schedule was not based on increased foreseen TBM productions (although additional investments were required in order to potenziate the TBM) that could have been of difficult achievement under such difficult ground conditions.

The main actions in order to achieve the shorter construction time were:

- The utilisation of a fourth TBM proceeding from portal E1
- The execution of the grouting operations contemporary with the excavation+precast lining in the double shield excavated sections
- The execution of grouting operations contemporary with lining activities in the in situ lined section
- The utilisation of a continuous lining system in the tunnel section A-B1
- The work organisation on 7 days per week production

Realised construction schedule

The actual realised schedule confirmed the good reserve of the acceleration construction schedule since, despite the fact that three of the four TBMs delayed the completion of excavations from 4 to 5 months due to the extremely adverse geological conditions encountered, it was steel possible to complete the tunnel on schedule.

PRODUCTIONS AND MAIN CONSTRUCTION PROBLEMS

TBMs productions analysis

The following table resume the productions records of the four TBMs utilised in the project:

TABLE 2. Productions records

TBM names		Kathrin	Salima	Ginevra	Natalia
TBM types		Open Type	Double Shield	Double Shield	Open Type
Tunnel Section		A-B1	C-B1	C-D1	E1-D1
Length of tunnel (m)		8090	9697	7421	4185
Total Exc. days (d)		382	360	442	273
Daily advance (m)	Best	57	60	50	42,4
Daily advance (m)	Aver.	21,2	26,9	16,8	15,3
Weekly advance (m)	Best	327	298	248	185
Monthly advance (m)	Best	743	1018	849	666

The best cumulative monthly advance of the 4 TBMs have been 2684 m.

Although significative, the above numbers can not give a clear picture of the performances of the four TBMS since they do not specify the geological conditions under witches the productions have been realised from the different TBMs.

In order to evaluate the performances of each TBM in the different ground conditions is preferable to refer to Figure 12, where are shown the average productions obtained by the four TBMS in the different R.M.R. rock classes as well in the high collapsing and squeezing soil like situations.

From the figure it can be evidenced that:

- All the four TBMs performed well in the full range of rock classes (Classes II to V since class I has not be found)
- All the four TBMs performed, but with highly reduced productions, also in the very difficult soil like conditions when immediate collapsing of the face and high squeezing were experienced. Of course, in order to advance in such extreme conditions special construction methods have been adopted as described in the following chapters of this paper.

In addition to the above general remarks it is important to make a comparison of the different behaviours between the two open type TBMs (named Natalia and Kathrin) and the two Double Shield TBMs (named Salima and Ginevra) in the different rock conditions.

In this regards it can be noted that:

- Passing from Rock Classes from II to V the average productions of the open type TBMs decreased substantially (the production in rock class V are less than half than in rock class II) while the productions of the two Double Shield TBMs remained almost constant.
- The average productions of the Open Type TBMs in rock class II are higher than the ones of the Double Shield TBMs; these is explained by the fact that, since the Double Shield TBMs were erecting a precast final lining, the productions in the better rock classes were limited by these operations.

Figure 13 shows the progressive advance of each TBM without evidencing the different ground conditions each TBM encountered.

FIG. 12 **Average TBM advances for rock class**

	RMC II	RMC III	RMC IV	RMC V	RMC Col	RMC Squ
TBM Kathrin	36,4	30,0	24,4	16,9	12,2	7,2
TBM Natalia	35,3	25,4	22,7	16,3	8,4	4,2
TBM Salima	27,2	31,1	28,6	27,3	19,0	18,1
TBM Ginevra	23,7	29,5	26,0	25,7	15,0	11,7

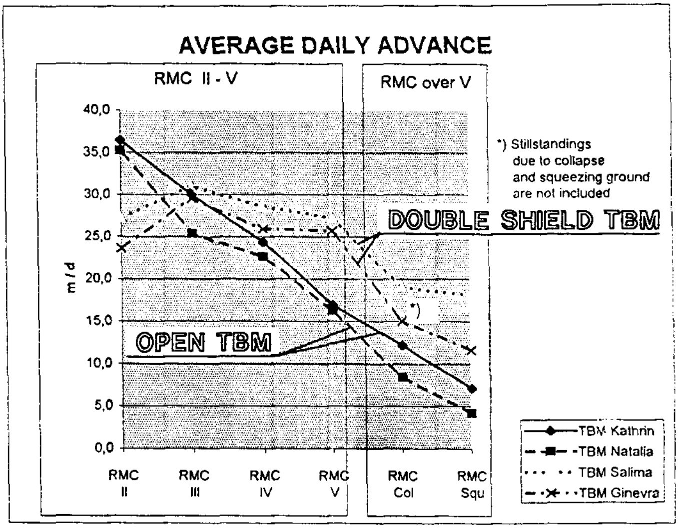
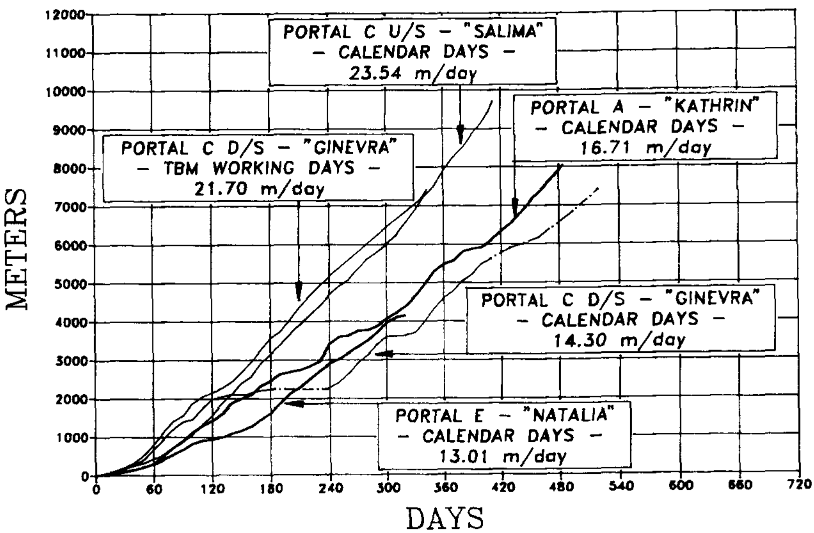


FIG. 13 **Progressive TBM advances**



DESCRIPTION OF THE MAJOR GEOLOGICAL DIFFICULTIES

Most of the Evinos-Mornos tunnel have been bored under difficult ground conditions.
As already mentioned above, about 16% of the tunnel was driven through very adverse ground, with soil like characteristics that could not be classified by RMR system. Of this 16% about 7% was still handled with the foreseen methods for rock class V, while the remaining 9% was creating huge problems to the advance of the TBMs and required special operations to be overcome by the machines.
In particular, the main difficulties were encountered in the flysch formations in the flysch over flysch overthrust zones and probable under high residual tectonical stresses. Similar problems were encountered in some particular cherts formations.

ADVANCE METHODS IN SPECIAL GROUND CONDITIONS

Ginevra TBM face collapse at chainage 2240

After the first 2000 mts excavated at very fast rate the Ginevra Double Shield TBM entered in a very disturbed flisch zone were the structure of the rock formations was completely destroyed into a kind of non cemented mass formed by big sandstone blocks swimming in non cohesive clay materials. In the same time high concentration of gas were measured.
At chainage 2240 a big collapse of material in front of the cutterhead stop the cutterhead rotation and create a cavern of more than 10 mts high over the TBM. The operations required to restart the TBM excavations are represented in Figure 14a-14b and the total stand by time was about 50 days after witches the normal production was resumed.

FIG. 14a Double Shield TBM advancing scheme in special conditions at ch.2241

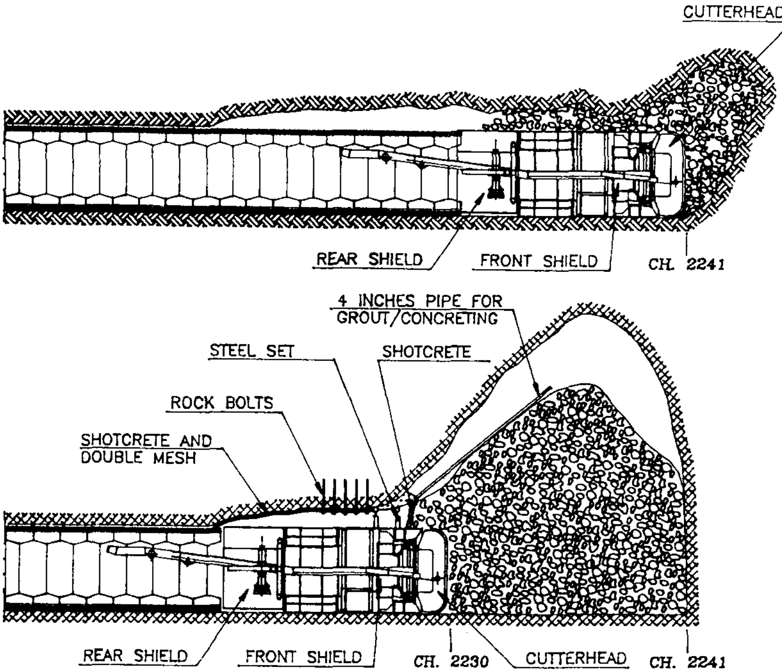
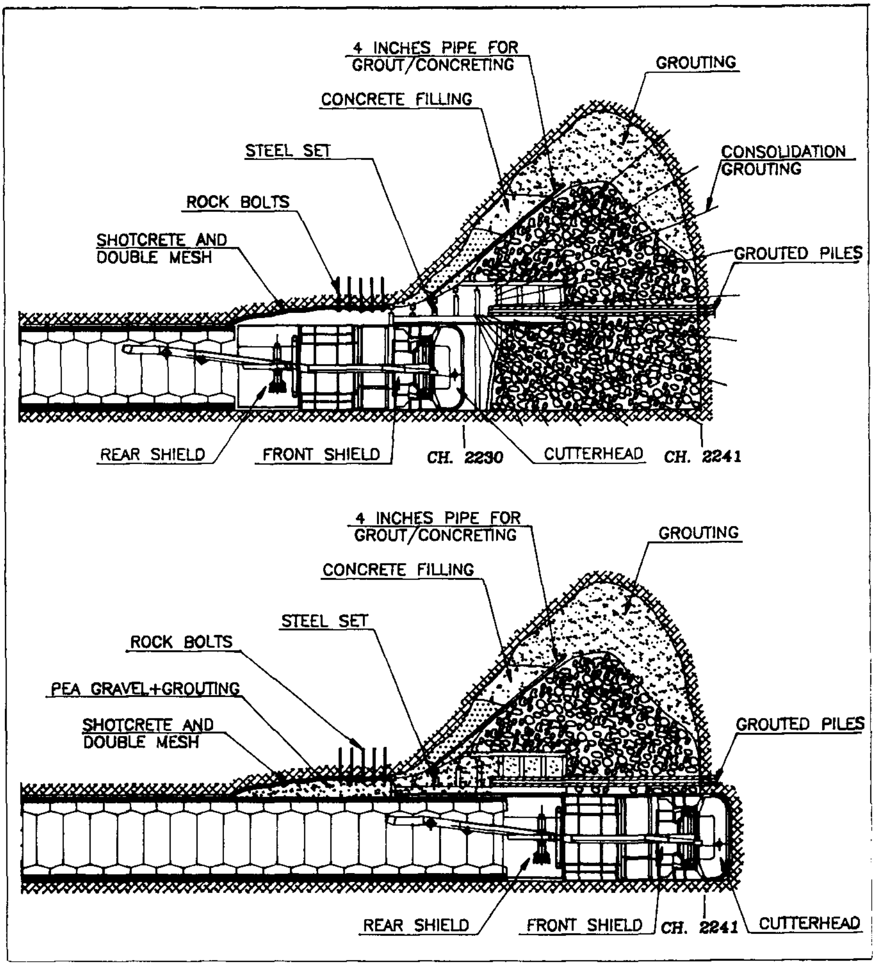


FIG. 14b Double Shield TBM advancing scheme in special conditions at ch.2241



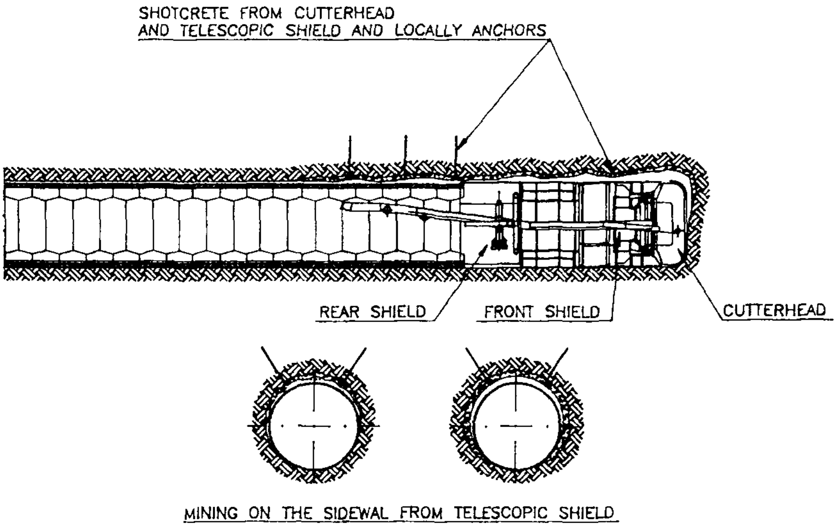
Ginevra TBM continuous collapsing and squeezing ground between ch. 5505 and ch.6173

This have been the most difficult part to be excavated in all the tunnel length for the combination of:

- Immediate collapsing of the tunnel face
- High squeezing (more than 15 cm in diameter reduction at one meter from the face in almost zero time)
- High presence of gas
- Length of the highly disturbed zone (more than 650 mts)

As represented in Figure 15 the methods adopted to advance under these conditions have been the stabilisation of the tunnel face and crown with shotcrete executed from the TBM cutterhead door every 30-60 cm of TBM advance and the enlargement by handmining and

FIG. 15 **Double Shield TBM advancing scheme in squeezing and caving ground**



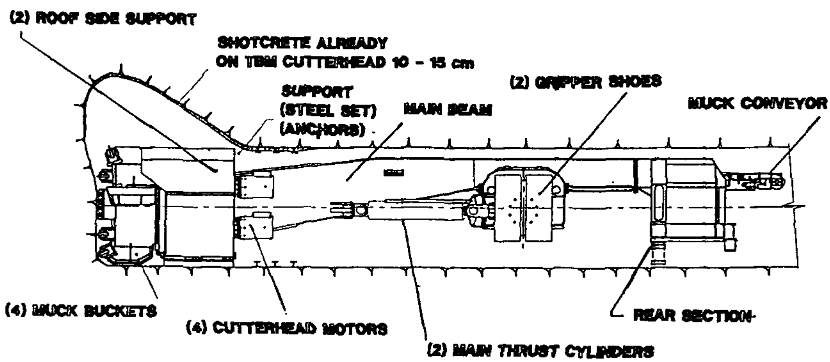
the stabilisation of the tunnel walls executed from the telescopic shield area.

The execution of these special and hard activities for three consecutive months, under the continuos presence of gas that obliged to stop the tunnel activities several time per day, was such a severe stress for the personnel and staff that we still wonder how they managed to resist for such a long time.

OPEN TYPE TBM ADVANCE IN CAVING ROUND

In several occasions the two Open Type TBMs faced extremely unstable ground conditions sometime associated with high and rapid squeezing of the tunnel walls. Figure 16 represents the special method adopted to excavate and support the ground in these zones.

FIG. 16 ***Open TBM advancing scheme in caving ground***



Practically, in addition to the normal foreseen (for rock class V) heavy steel sets + wire mesh supports erected after the TBM roof shield, in these ground it was necessary:

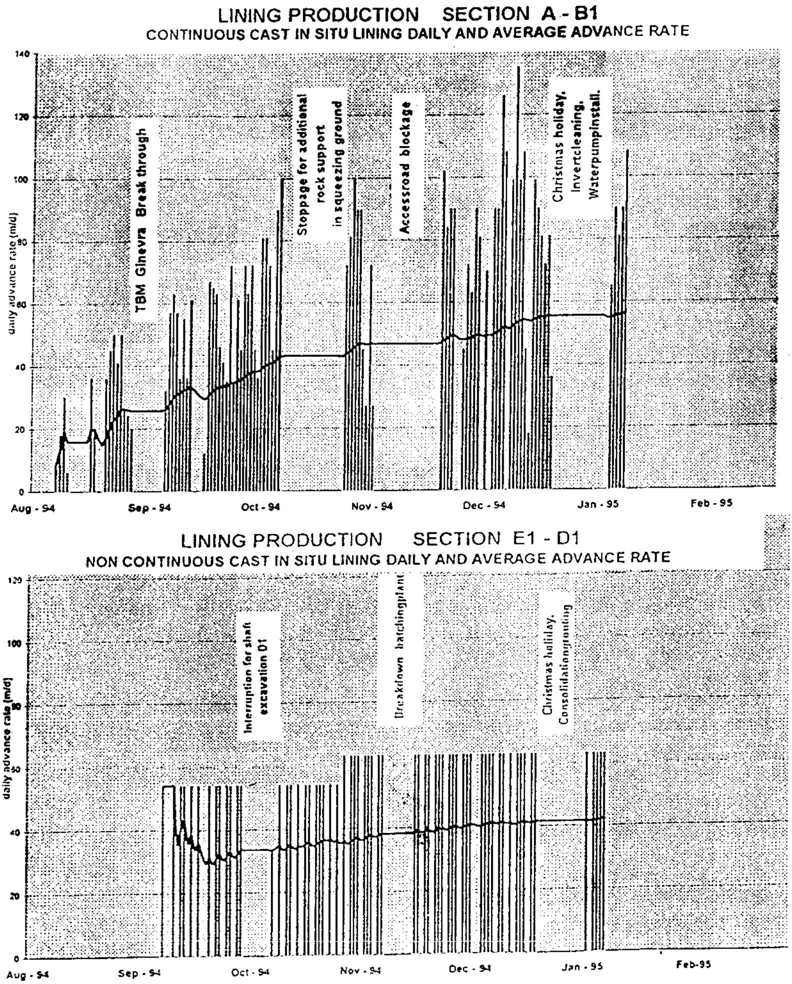
- to execute shotcrete immediately behind or even ahead of the TBM cutterhead instead of from the apposite back-up platform;
- to fill with shotcrete all the voids that were producing over and ahead of the cutterhead.

In some occasion was also necessary to cut down the already erected but deformed steel set, reexcavate the tunnel perimeter by handmining and, finally, reinstall the supports.

IN SITU LININGS PRODUCTION

The production of the lining operations executed with the two different systems described in a previous chapter in this paper, are represented in figure 17.

FIG. 17 Lining productions



With both systems the productions reached very high. The continuos lining system with the telescopic shutters reached better average and peak productions (up to 50% higher). The top lining performances with this system were:

- Best day = 140 mts
- Best month = 2120 mts

POSSIBLE FUTURE IMPROVEMENTS IN THE EXCAVATION AND LINING TECHNIQUES

The Open type TBM

These type of TBM, with the Robbins single gripper system design, prove to be still a reliable solution in a wide range of rock conditions. In the case of the Evinos-Mornos tunnel the reduced diameters facilitated the fast erection of the steel supports and of the shotcrete; therefore the reduction in productivity in bad rock classes were important but not dramatic.

These type of TBM probably could not be subject in the future to big improvements in the general design.

Their main advantages are the simplicity and the possibility to install supports very near behind the cutterhead.

Their main disadvantages are: the difficulties in finding the gripper reaction in weak rock, the difficult mechanisation of the support installation activities and the safety of the same operations. The disadavanges increase their importance and negative effect on productions with the bigger diameters.

The Double Shield TBM

The actual design and characteristics of the Double Shield TBM allow this type of machine to reach top performances in all the range of rock classes.

The design improvement shall be concentrated in the future in the Double Shield functioning in special ground conditions and namely:

Running fronts with blocks

In these extreme situations it is very important, in order to avoid big overexcavations, that future design of D.S.TBM will always include:

- A smooth cutterhead design offering the minimum friction to the cutterhead rotation
- Cutterhaed bucket design avoiding the entering of muck by gravity and the bucket openings shall be adjustable.
- Cutterhead structure protruding a minimum from the front shield
- Adjustable cutterhead revolution with high torque at low speed and high starting torque
- Possibility to realise a drilling + grouting pattern ahead of the face

In addition the cutterhead design shall provide bolted doors to have easy access to the tunnel face when is needed to stop the overexcavations and face instabilities by application of shotcrete and/or polyurethane foams to the tunnel face.

High and rapid squeezing grounds

In most of the tunnels high squeezing phenomena did not occur immediately behind the tunnel face but only after the TBM have passed and the supports or precast linings have been installed. In these cases the effect of squeezing it is only to be considered in relation with the typical cross sections design.

In special geological situations, due to the type of rock formation togheter with the tectonic actions and/or the overburden, immediate squeezing behaviour the tunnel can occur and the TBM shall be designed to cope with these ground.

In this cases the danger of having the rear shield of the TBM trapped by the squeezing ground shall be avoided by: overboring systems, high auxiliary shield thrust, reduced rear shield diameter or collapsible rear shield design.

the experience of the EVINOS tunnel is very encouraging in this sense since very high squeezing ground were overcome without major stoppages while on the contrary the collapsing of the tunnel face create bigger problems.

The Precast Lining systems

In the past 20 years the application of precast segmental linings have been concentrated

mainly in tunnel in soft ground and urban area (specially for railway and metro lines), the development of segmental lining design have followed the needs of these type of tunnels.
In the last five years also in hydraulic tunnel in rock the precast segmental lining solution have been adopted in several cases.
In the future more and more it will be necessary to modify and improve the actual segmental lining technique according to the specific needs of this category of underground works.
The In Situ Lining Systems
With the today systems it is possible to achieve extremely high lining performances.
For the above, although the frequency of application of the precast segmental lining as final lining of hydraulic tunnels will increase in the near future, it will remain in several case convenient from the economical or technical point of view, to realise in situ linings of tunnels.

CONTRACTUAL PROBLEMS

Risks involved in such a difficult and long tunnel project
The policy of the Client all around the world is to limit as much as possible the increases of costs during the construction in respect of the initial contract price.
In the case of the Evinos Mornos tunnel, with the utilisation of TBM types capable of cope with a wide range of ground conditions, it was possible to limit the risks of lower productions and relative extracosts only to extremely adverse geological events, like the extremely poor soil like ground conditions that obliged the contractor to adopt special and different from foreseen construction methods.
Adequacy of the pricing system
In the Evinos Mornos tunnel the pricing of the excavation with the open type TBM was related to the R.M.R. rock classes and the corresponding support classes, while the double shield TBM excavation was compensated with a single price valid for the whole range of R.M.R. classes.
This system worked fine except for the sections were the ground could not be described by the R.M.R. systems, that was only a minor portion of the tunnel length.
Shearing of Risks
As stated before the today tunnelling technique allow an experience contractor to reduce the risks to very special and adverse ground conditions.
On the other way it is no logic to consider that the contractor shall bear that risks, specially if the contract has been awarded in competition, since the normal influence on costs and construction schedule of a special condition event or series of events could be of a very big magnitude.
In this regards it has to be remembered that the Owner has the property of works and will take the benefit (social and/or economical) from the operation of them; for this simple reason it is the Owner that should bear the risk of extracosts due to unforeseen adverse ground conditions.
In relation to unforeseen adverse ground conditions the duty of the Contractors is to take all the necessary provision to minimise the extracosts and extratime needed to overcome the special conditions.

CONCLUSIONS

The completion on schedule of such a difficult and long tunnel as the EVINOS-MORNOS tunnel constitute a great technological and human success, being the merit of its completion due partially to the technology adopted and partially (but better mainly) to the hard work and capacity of the personnel who worked in the tunnel.