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A DEEP TUNNEL IN HIGHLY TECTONIZED MARL

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SUMMARY

Reference is made to the geological and geotechnical investigations and studies carried out for design and during construction of a 3 km section of Gran Sasso deep tunnels in arenaceous marl and in laminated marl. Geological history of concerned complex formation, including relevant tectonic events, is presented, in the context of a regional picture of origin and evolution of miocenic series in central Italy.
The difficulty to define geotechnical characteristics of rocks is emphasized, due to the influence, on mechanical properties of the whole, both of more or less soft marly matrix and of joints or latent discontinuity surfaces. The behaviour of formation at tunnels excavation, observed from field measurement data, and its relation with results of investigations and analyses, are pointed out. Some remarks on relaxation and collapse phenomena, involving marl and especially laminated marl widely around the cavity, suggest a possible line to interprete actual deformations amount, and to approach the problem of statics of the tunnels.

INTRODUCTION

The Gran Sasso tunnels, in Italy, are a section of the Rome-Adriatic motorway, which provides the shortest route across the highest of central Apennine mountains (Fig.1). Two-way tunnels cross Monte Gran Sasso for a lenght of about 10.0 kilometers; a small service tunnel, 2 km long, also forms part of the system, in proximity to north entrance. Centre to centre distance varies, according to nature of rock and to overburden, from a minimum of 46 m to a maximum of 88 m. Internal free section is 54 m^2. Assergi south entrance is at el. 958 m above sea level, San Nicola north one is at el. 889 m (Fig.2). Profile summit is about halfway between the entrances and gradient is 0.2 per cent at south side and 1.1-2.0 per cent at north side. Max overburden on the tunnels is 1500 m, corresponding to Monte Aquila top, el. 2500 m. Peculiar geological conditions make southern section of the tunnels quite different from northern one (Bruni F.1976).
The southern block is formed by sedimentary rock, essentially limestone, while the northern block consists of partially overturned soft rocks, such as arenaceous marl.
Max overburden on soft rocks reaches a value of 1000 m, at a distance of 3100 m from the north entrance.

The northern section of the works presented many design and construction problems, due to both complexity of the formation and the exceptional overburden. Wide studies and investigations were carried out there, before and during excavation; the tunnel is now completed, until the contact soft rock-limestone.

Fig. 1 Location of Gran Sasso Tunnel

Studies and systematic field measurements allowed for an interesting collection of data on behaviour of these formations, which are subject of this paper.

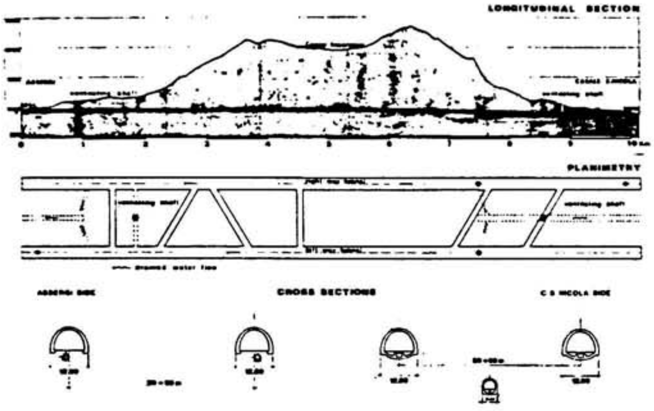


Fig. 2 Geometrical characteristics

1. GEOLOGY

1.1 General lines of Gran Sasso massif

Gran Sasso mountainous group consists of marine sedimentary rocks of "Abruzzese facies", which represent transition terms between the "Abruzzese facies" of central Apennines, mainly formed by algalic or coralliferous limestone, deposited in shallow waters, and "Umbro-Marchigiana facies", formed by deep sea calcareous-argillaceous sediments.
In that "transition facies", from Jurassic to Tertiary, calcareous sediments, partly detrital in massive banks, partly pelagic in more or less thin banks, accumulated.

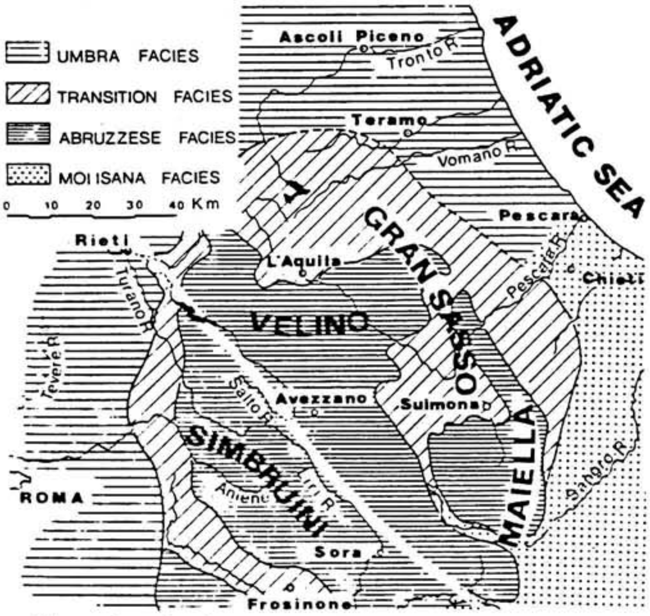


Fig. 3 Facies map

Starting from middle Pliocene, important tectonic phenomena divided up whole calcareous plateau of the central-southern Apennines in some blocks extended in NW-SE direction: Gran Sasso group constitutes northern extremity of them (Fig.3).
According to gravity tectonics common to all the central-southern Apennines, compressive and overthrust faults are present in every block along eastern edge, while tensile faults prevail in south-west zone of each of them.
Geological surveys and results of three vertical drillings made along tunnel axis, particularly showed that the calcareous dolomitic massif of Gran Sasso overslipped along an important slightly inclined fault, above an overturned calcareous-marly series.
That fault separates two blocks :

1) southern block, formed by a thick and practically continuous series, from Miocene to Lias, of dolomites and limestones.
   Two important NW-SE normal faults, Fontari and Valle Fredda faults, have a southern dip and are mylonitized, with large displacement.
   They progressively make the whole mentioned series lower at south, while its most raised share, at the field of the overthrusting, culminates at Monte Aquila, el. 2.500 m.

2) northern block, that received overthrusting stress, shows an anticlinal-synclinal recumbent structure, of which only overturned side remains. At its interior shingles of calcareous-dolomitic Lias series and cretaceous and tertiary limestone are still recognizable in reverse sequence, while the most important outcrops consist of notable masses of marl with arenaceous intercalations. Calcareous terms are greatly reduced in thickness by numerous faults sub-parallel to main overthrusting one, with consequent formation of the shingles, sometimes higly tectonized and penetrated with each other. On the contrary, the more plastic marly terms form layers of tectonized and folded deposit opposite to the front of the more rigid limestone. Downwards the overturned side, marl and marly limestone reassume normal stratigraphic bedding.
   Basical results for the knowledge of that structure were obtained by "Vaduccio" vertical borehole, which practically passed through all the northern block, reaching a depth of 1004 m.
   Geological reconstruction of the massif and its structural map are represented in Fig.4.

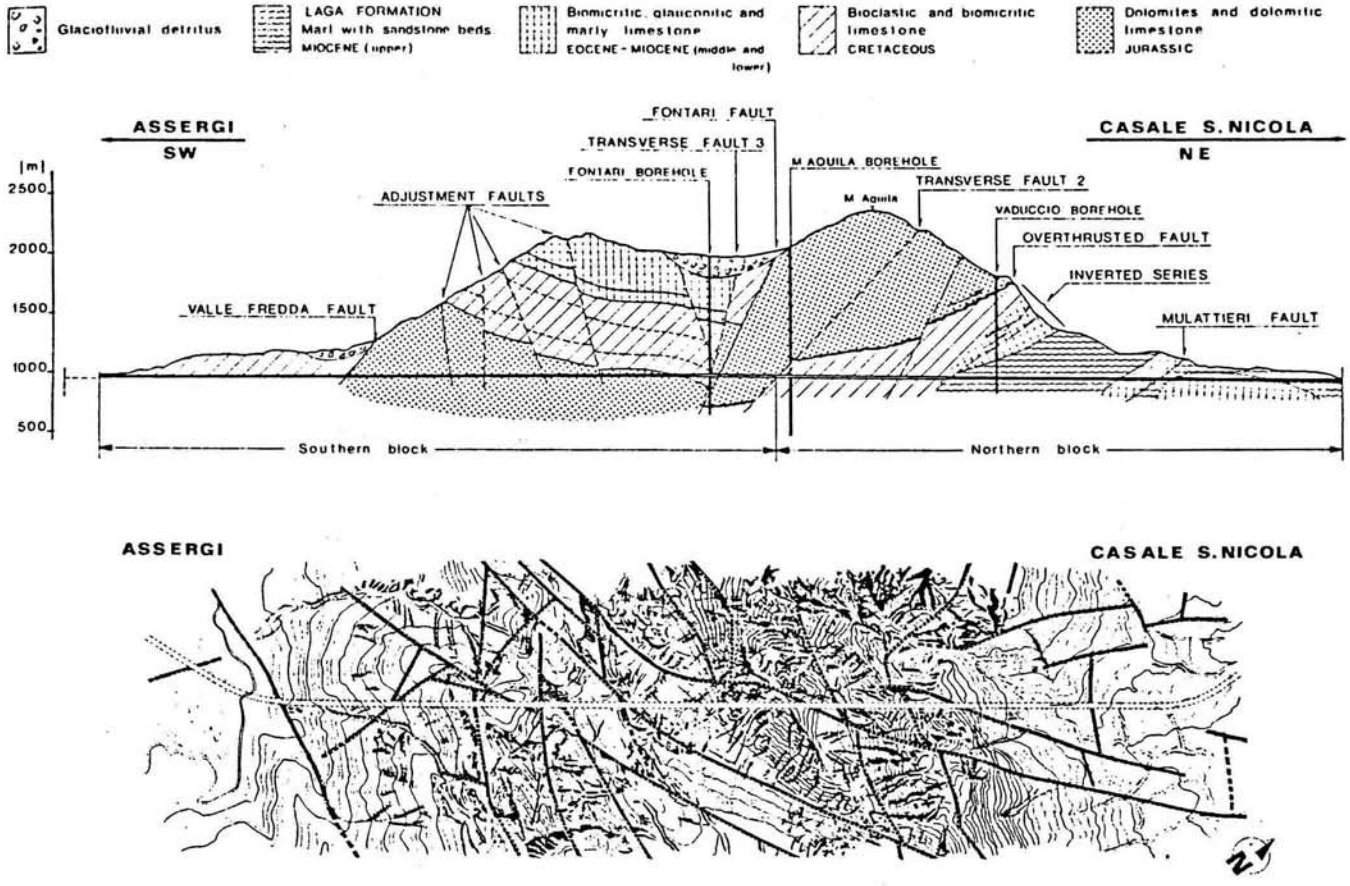


Fig. 4 Geological plan and profile

1.2 Regional sedimentology

"Laga formation" , or Flysch of Laga, of Miocenic l.s. age, included between foothills and hills overlooking Adriatic Sea, from Umbria to Molise, is composed of some large accumulations of more or less thick argillaceous-silty sediments, intercalated to arenaceous and micaceous banks with calcareous cement. Microfauna in series of this formation is particularly abundant in calcareous lithotypes. Usually a typical decrease of number and species of microfossils is connected with an important salinity variation of waters, due to developing of closed sedimentary basins.

That salinity crisis characterized, in whole Mediterranean area, Messinian stage of Upper Miocene, to which the Abruzzo molassic formation is concordantly referred (Fig.5).

"Laga" formation particularly develops in zone included between Teramo, Sibillini Mountains and Capannelle Pass. There, a trough was located with flysch sedimentation, called "Flysch Piceno" (Ten Haaf-1958),of Tortonian age and which reaches a thickness of 1.200 m. Near said Pass, the formation evidently shows characteristic imposing sandstone banks; on the contrary, in zone adjacent to the tunnels, near village of Casale S.Nicola, softer marly and marly-clayey lithofacies prevail, while irregularly intercalated arenaceous banks from a few cm to one or two metres thick represent only a small percentage of mass.

Fig.5 Central Apennine structural map

Sandstone layers are generally characterized by a graded sedimentation and, in lower part of their stratum, by presence of groove casts and of small rounded fragments of marl, which is typical sign of turbidities (Fig.6)

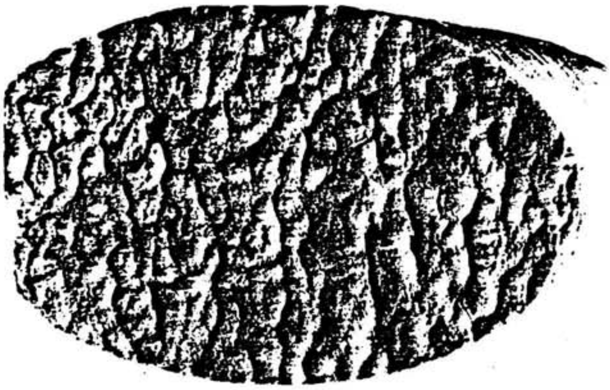


Fig.6 Groove casts on core sample

In more fine layers irregular synsedimentary of convolute bedding type (Fig.7) undulations and foldings can often be remarked.

Fig.7 Convolute bedding on core sample

In absence of other paleontological and stratigraphical references, observation of those sedimentary structures was of fundamental importance for determination of disposition of layers, particularly in pointing out zone of passage from normal to overturned bedding.

1.3 Miocene formations

Excavation of the Gran Sasso tunnel on Casale S.Nicola side, completely passed through Miocene formations, penetrating up into Eocene and Cretaceous limestone of overturned series. The Miocene formations consist of :

A - marl and silty marl with arenaceous intercalations of upper Miocene;

B - beige or grey limestone, with intercalated layers of marly limestone of middle Miocene.

At a short distance from entrance also glaciofluvial deposits were passed through along about 300 m.

A - Marl

In the tunnel, normally bedded marly-arenaceous formation consists of marl and silty marl. Marl doesn't contain important microfossils: it is frequently sterile or contains scarce plantonic forms and, sometimes, frequent bentonic forms, that can be referred to Messinian age. Environment is marine, typical of a closed basin with restricted circulation. Arenaceous intercalations are scarce, 54 m on 1.200 m of core samples, and generally thin , on an average 1-2 m.

B - Marly limestone

Under the formation of marl, and then in normal stratigraphical series, limestone and marly limestone were found during the tunnels excavation.
From distribution of principal microfauna species, two zones are distinguishable in the formation: upper, which can be attibuted to upper middle Tortonian, lower, which can be attributed to lower Tortonian-upper Helvetian.

1.4 Tectonics

Overthrust movement of Gran Sasso and other secondary displacements determined a vast reaction in marly formation of Adriatic side, intensely modifying its primary attitude.
In whole excavated stretch, it was possible to identify three zones with different lying and tectonization conditions (Fig.8) :

- first (Zone A), from entrance up to ch.1450, is formed by a rather flat anticlinal of marly limestone of Tortonian-Helvetian, surmounted by marl with arenaceous intercalations, which was mainly found in compact banks, except in a narrow belt along all contact with calcareous anticlinal;

- second (Zone B), from ch.1450 to about ch. 2300, consists of a tectonic shingle, extruded along a slightly inclined fault (Mulattieri fault). It is formed by very fractured marly limestone, with large calcitic recementings of Tortonian-Helvetian, and it is surmounted by regularly stratified marl. That too is in very thick banks, in normal series, with a regular attitude and a dip variable between 30° and 40°;

- third (Zone C), from ch. 2320 to ch.3060 consists of marl with arenaceous intercalations in an overturned attitude. Up to ch.2600 marl is in compact banks with a dip of about 40°, while, further that chainage, marl appears to be more tectonized and laminated, in chaotic lying and with frequent folds. In that last stretch stratification isn't any more evident, and, where it is definable, it presents a dip of about 15-20°.

On the whole, northern side of Gran Sasso is constituted by a recumbent break-thrust structure

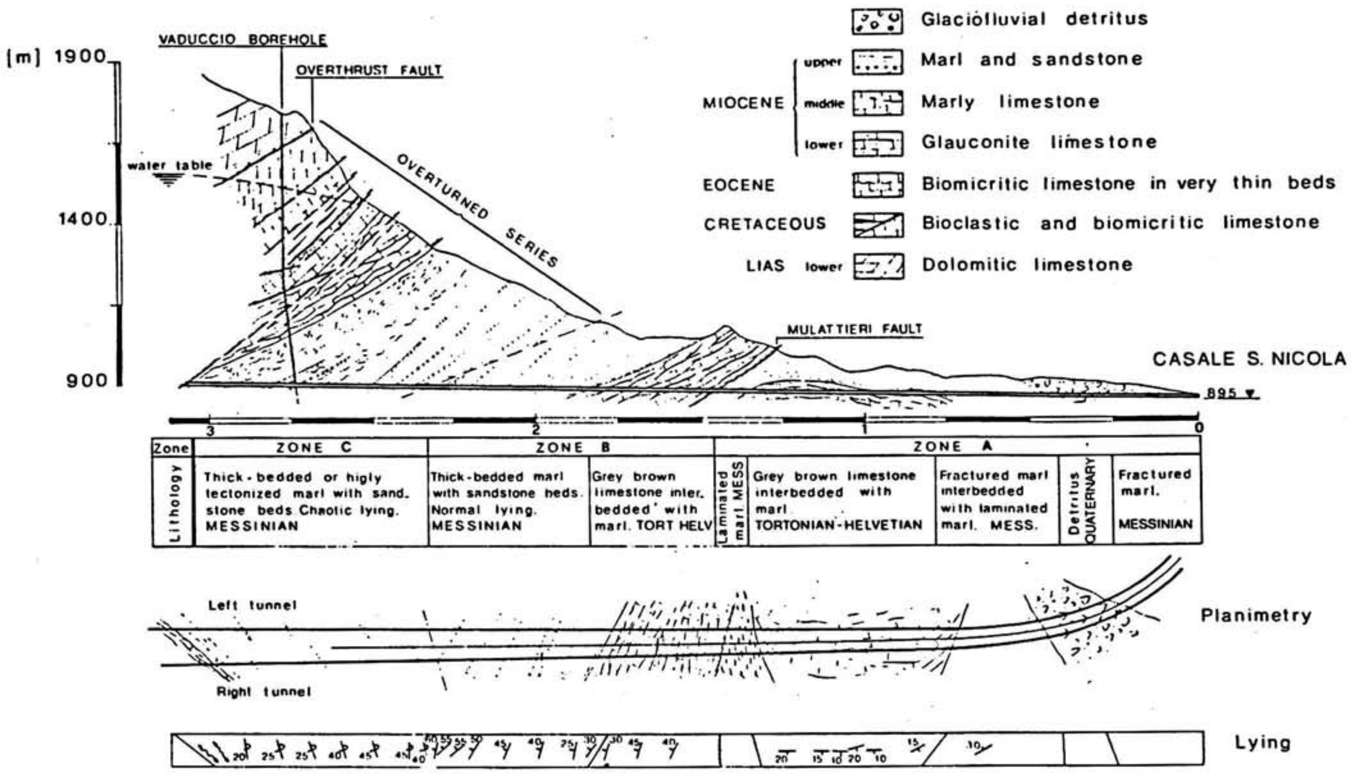


Fig.8 North block geology

with its overturned flank (Zone C) successively partly slipped on normal one (Zone B).
Such a geostructural evolution determined some zones with intense rock tectonization, which in particular was remarked :

1) in marl separating zones A and B, included between the calcareous anticlinal and the tectonic shingle. Here marl appears completely divided up into minute polished shingles for a thickness of about a hundred metres, having lost every trace of its original stratification;

2) at limit between zone B and C in presupposed "hinge" zone. Here layers have a variable and chaotic attitude for a stretch of 20-30 m. In fact layers of zone C are overturned and moderately inclined (40°), while those of zone B result much more inclined (75°) near the fault zone, where an overthrusting phenomenon of zone C over zone B is present;

3) near zone of contact with marly limestone of Tortonian at ch.3060, where besides accentuation of number and size of folds, an evident change of attitude can be observed, because of folds axis placed in an E-W direction, parallel to that of contact with the overthrusted calcareous block.

2. COMPLEX FORMATION

2.1 Lithology

Definition of lithological types constituting "marly formation" was based, apart from visual aspect of rock, on mineralogical, morphometrical and texture analysis of representative samples. Assumed classification is that of limits of carbonate/argillaceous minerals ratio proposed by Pettijohn (1957), for definition of various terms of lithologic limestone-argillite series, and of granulometric classes of Wentwort (1922) for clastic rocks, extended to carbonatic rocks by Leighton and Pendexter (1962) Those determinations made it possible to locate three main "lithological families".

a) Marly limestone
b) Marl
c) Sandstone

Actually, whole range of intermediate marly lithotypes is present in the rocky mass.

a) Marly limestone

This lithotype includes terms with a $CaCO_3$ content variable from 70% to 90%.
In a thin section the rock can be defined as an organic detritic limestone, with a fine or

medium grain (bioclastic limestone), scarce coarse elements and traces of pyrites and bituminous coatings, sometimes passing to grey compact calcareous marl.

b) Marl

This rock is homogeneous and compact, on the whole blackish-grey coloured and generally it shows an oriented texture. Its detritic component is mineralogically constituted of: quartz, feldspars, micas, iron oxides.
Carbonate cement, of a prevalently calcitic nature with subordinated dolomite, can be compared to a "micrite" of type I (Ø = 4+1 microns) and II (4+30 microns). At textural level a frequent isotientation of phyllosilicates and of opaque mineral veins was noted. A very particular facies of marl is represented by laminated marl. That denomination concerns lithotypes originally referable to marl and/or to stratified siltite which, by effect of high tectonic stresses, were reduced to small interlocked centimetrical chips in which every trace of original sedimentary structure disappeared. Moreover, in laminated marl a considerable percentage of open reticule minerals, such as montmorillonite and illite, was found. However frequency of that phenomenon isn't so big to influence rock behaviour and, consequently, technical effects in the tunnel.
Altogether, quantitative mineralogical association in marl and in laminated marl was found to be :

MINERALS	MARL	LAMINATED MARL
quartz	20 %	15÷20 %
feldspars	5÷10 %	5 %
micas	5÷10 %	20÷25 %
montmorillonite	5 %	10÷15 %
kaolinite	5 %	20÷30 %
Fe oxides	5 %	—
illite	5 %	—
calcite — dolomite	30÷45 %	20÷25 %

Table I Mineralogical analyses

c) Sandstone

Sandstone is a compact light-grey coloured lithotype, with a texture oriented with parallelism of opaque mineral veins, phyllosilicates and lithitic grains. Its detritic fraction (about 70%) generally consists of sandy grains of about 1/4+1/8 mm; on the contrary, in certain layers of lithitic elements of over 1 mm in diameter. Also in this lithotype grains are composed of quartz, feldspars, micas and iron oxides of various dimensions. Calcareous cement (micrite), of a calcitic-dolomitic nature, has a grain size included between 4-30 microns, which can be referred to a micrite of type II.
Frequently the arenaceous facies shows a graded sedimentation in lower portion of blocks with typical basic imprints; on the contrary, at summit, they gradually change into silt and marl.

2.2 Structural profiles

Rocks in the tunnels, can be schematically reduced to six elementary geostructural categories (Fig.9) :

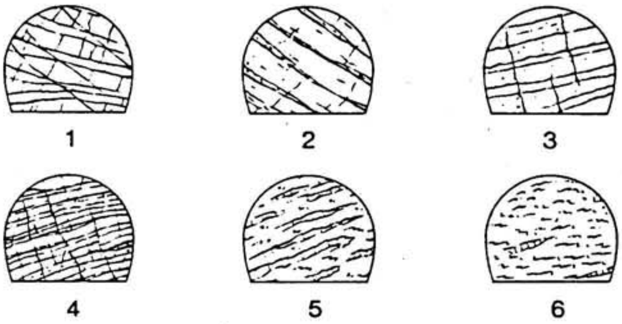


Fig.9 Structural profiles

1 marly limestone, in regular up to 2-3 m thick banks with rare interstratified pluridecimetrical levels of laminated marl.
In this lithofacies stratification joints present quite polished and perfectly smooth surfaces. Some diaclases, often with calcitic recementation, have evident striations, with a frequency of about 2-3 metres, and intersect calcareous banks normally to their bedding, isolating blocks of considerable size (> 1 m^3);

2 marl, with 2-3 m thick banks and structural discontinuities, practically analogous to those of previous category. Bedding joints, however, show not only polished surfaces but also important laminated strips;

3 sandstone, in large banks (from 1 to 4 metres) with intercalations of pluridecimetrical layers of marl or of extremely laminated marl;

4 marl in thin banks (< 1 m), interstratified with argillaceous marl and sporadic argillaceous levels, with translucent bedding joints and passing to laminated marl.
Wide translucent slip surfaces, with concave form, pass through the banks, mainly in a N-NE strike and, with the bedding joints, normally isolate blocks of a few dm^3 in volume;

5 marl in thin irregular layers, englobed in an abundant matrix of laminated marl. Very numerous discontinuities of rigid elements, generally some decimetre-distant, isolate a

series of more or less interlocked small blocks, with less than 1 dm^3 volume, practically immersed in a mass consisting of minute shingles of laminated marl;

6 laminated marl, which constitutes extreme stage of disgregation of marl. This lithofacies consists of very minute shingles, up to 10 mm thick, sometimes in a plastic state, flattened and tightened, with polished and greasy surfaces. Rocky mass is here formed by curls, folds and small residual chips of silty marl.

2.3 Joints classification

Joints classification was considered significant only for 1÷4 categories.
Two main classes of structural discontinuities were recognized on the basis of their origin, frequency and size :

- discontinuities of matrix
- discontinuities of whole rocky mass

First class origin is connected to diagenetic phenomena of sediment, that of the second one to sedimentation and tectonic thrusts.
Scheme of the various discontinuities is illustrated in figure 10.

For matrix :

a. Microfractures with calcitic recementation, and isorientated texture.

b. Local smooth surface fractures.

c. Fractures with millimetrical strips of laminated material.

For rock mass:

d. Large fractures with pluricentimetrical lenticular strips or with smooth surfaces

e. Bedding joints.

f. Faults with important tectonized stretches.

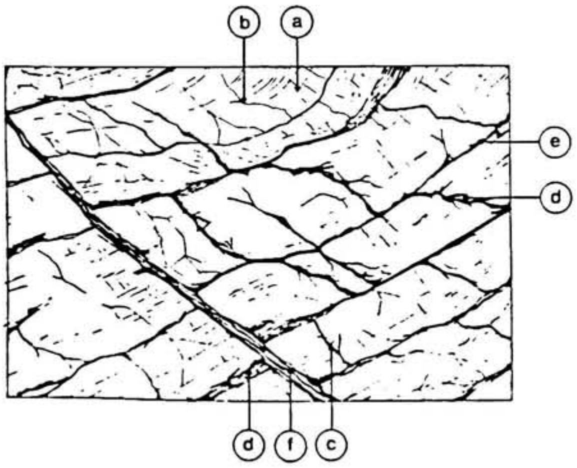


Fig.10 Discontinuities classification

The main strike of fractures in the rigid banks (N-S) is practically orthogonal to that of the bedding (E-W). In layers of argillaceous marl a marked subparallel to bedding joints schistosity is present.
Development and uniformity of distribution of discontinuities of b-d types gives to the mass character of a typical structure in interlocked blocks; average dimension of blocks was estimated between 0.5 and 1 m^3.
Main structural discontinuities of the matrix, type a, and of the mass, type e, determine a general anisotropy of the rock. Moreover, frequent and repeated alternations of sandstone-marl-laminated marl layers, give to the whole mass an heterogeneous character.
Those two peculiar properties, anisotropy and heterogeneity, justify classification of this formation among those of "complex" structure.

3. GEOTECHNICAL INVESTIGATIONS

Geotechnical characteristics of each lithotype of the formation were defined by traditional laboratory tests, while parameters for evaluation of mass behaviour were obtained both by laboratory tests on large blocks and in situ investigations.

3.1 Sampling techniques

For laboratory tests sampling techniques were adopted which allowed to draw :

a. undisturbed samples of matrix of each lithotype;

b. samples of large dimensions, which could include discontinuities of the rocky mass in a significant number.

Actually no difficulty was encountered, except for laminated marl, to core samples of matrix till a 100 mm diameter. On the contrary, drawing of big heterogeneous samples was more difficult, and neither obtainable with large diameter core drills. However, in many cases it was possible to remove cubical blocks with sides of about 1/2 metre, which were later modelled in laboratory.
Drawing of blocks was made in little openings excavated at sides of the tunnels.
On the bottom a step was left with an height and depth of about 1,50 m. Successive vertical cuts, immediately filled with a quickly setting cement, isolated a block, which after a few hours was undermined at its base with a similar procedure.
For laminated marl drawing and finishing of big blocks resulted generally possible, too.

3.2 Laboratory tests

Some results of laboratory tests on lithotypes are summarized in Tab. II.
Porosity was found to be directly proportional to variation of $CaCO_3$; in laminated lithotypes

its values from block tests appeared rather high, sometimes more near to those of loose materials than of rocks.

LITHOTYPES	marly limestone	sandstone	marl	laminated marl
W %	1.7	0.7	2.8	9.4
γ_d t/m³	2.63	2.5	2.5÷2.6	2.2÷2.3
γ_s t/m³	2.85	2.80	2.75÷2.80	2.71
n %	–	–	9.1÷7.1	18.8÷15.1
C_aCO_3 %	75	–	35÷65	25÷40
σ_c MN/m²	65÷80	70÷100	25÷50	–
σ_t MN/m²	5.6	8÷10	2.4	–
E_s MN/m²	–	19000	10000	–

Table II Geotechnical characteristics of lithotipes

For each lithotype uniaxial compressive strength of small samples oriented parallel to bedding was about 10% lower than that of normal ones. Only a few samples of marl showed higher scattering, about 25%, due to isorientation of lamellar femic minerals. Hystograms (Fig.11) of compressive and tensile strength of rock material ,for principal lithofacies showed an essential influence of percentage of $CaCO_3$ and of grain size of detrital fraction, while only in a less degree texture of rock was determinant.

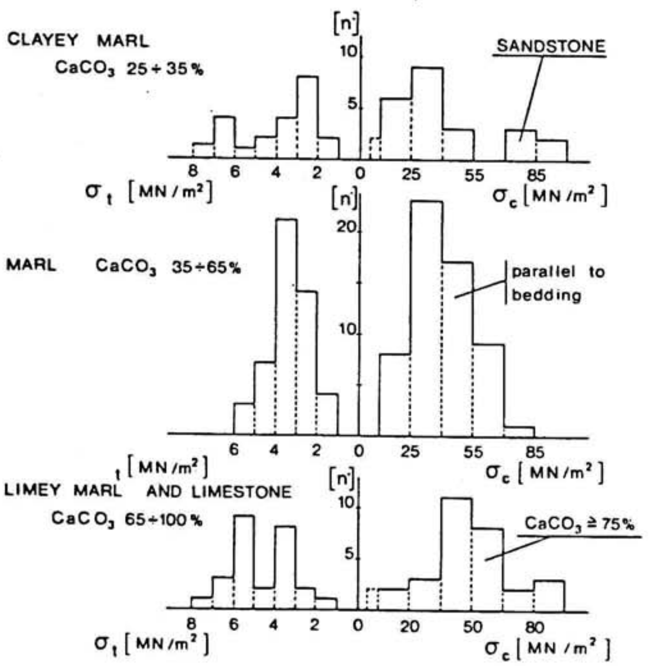


Fig.11 $\sigma_c - \sigma_t$ values for different $CaCO_3$ %

Otherwise, for large size samples (l =50 cm)of rock mass, presence of the b-c-d-e discontinuities caused a radical reduction of mechanical properties, so that blocks uniaxial strength was found to be 10 times lower than that of matrix for marl. That element was absolutely indicative of behaviour of unlined wall of the excavated tunnel.

Relevant differences were also registered between results of deformation tests on small samples of rock material and on large blocks of rock mass. In fact, values of modulus E for heterogeneous complex blocks were only 10% in respect to those carried out on small matrix samples (Fig.13), so well predicting the magnitude of deformation to be foreseen in full scale opening..

Triaxial tests were performed only on marly matrix samples; intrinsic curve and curves of direct shear tests along joints in large blocks (Baldovin G.,1970) of hard and of laminated marl are shown in Fig.12

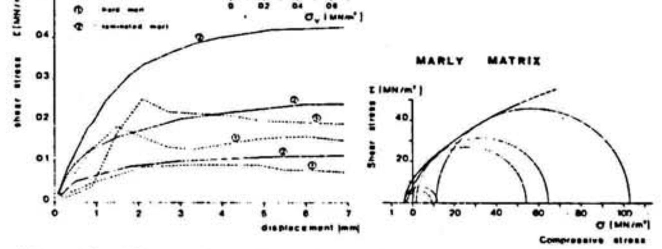


Fig.12 Direct and triaxial shear tests

Those direct shear tests were the only possible and adequate for this type of complex formation.

3.3 In situ tests

Deformability characteristics of the rock mass and tensional state around the cavity were defi

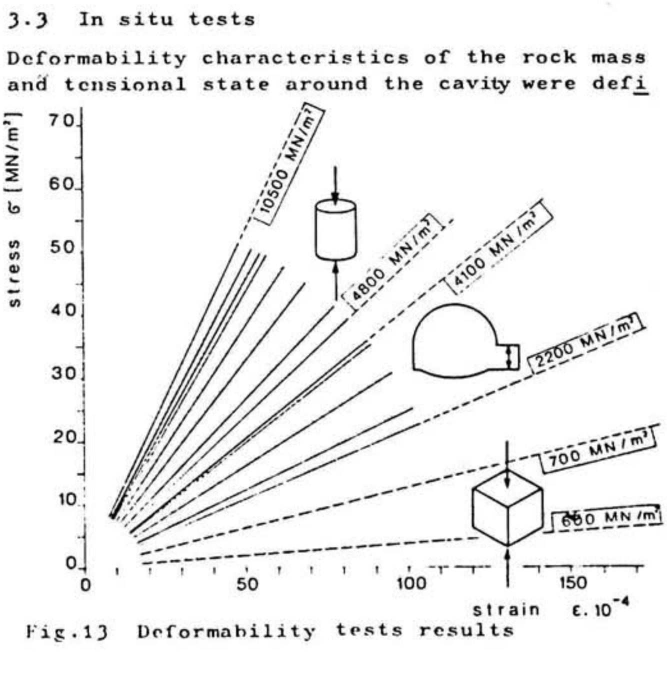
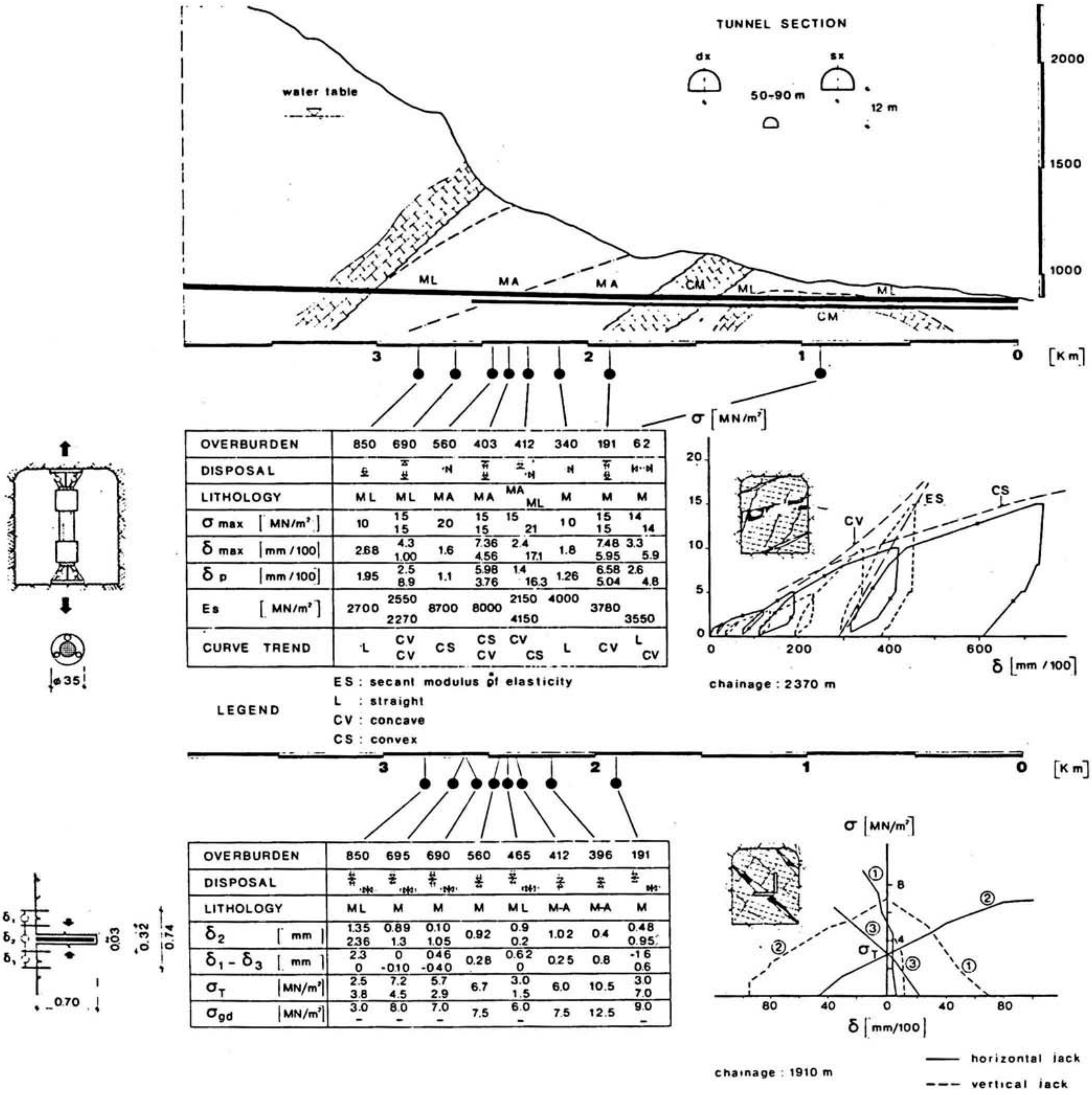


Fig.13 Deformability tests results



OVERBURDEN	850	690	560	403	412	340	191	62
DISPOSAL								
LITHOLOGY	ML	ML	MA	MA	MA ML	M	M	M
σ max [MN/m²]	10	15 15	20	15 15	15 21	10	15 15	14 14
δ max [mm/100]	2.68	4.3 1.00	1.6	7.36 4.56	2.4 17.1	1.8	7.48 5.95	3.3 5.9
δ p [mm/100]	1.95	2.5 8.9	1.1	5.98 3.76	1.4 16.3	1.26	6.58 5.04	2.6 4.8
Es [MN/m²]	2700	2550 2270	8700	8000	2150 4150	4000	3780	3550
CURVE TREND	L	CV CV	CS	CS CV	CV CS	L	CV	L CV

LEGEND
ES : secant modulus of elasticity
L : straight
CV : concave
CS : convex

OVERBURDEN	850	695	690	560	465	412	396	191
DISPOSAL								
LITHOLOGY	ML	M	M	M	ML	M-A	M-A	M
δ_2 [mm]	1.35 2.36	0.89 1.3	0.10 1.05	0.92	0.9 0.2	1.02	0.4	0.48 0.95
$\delta_1 - \delta_3$ [mm]	2.3 0	0 -0.10	0.46 -0.40	0.28	0.62 0	0.25	0.8	-1.6 0.6
σ_T [MN/m²]	2.5 3.8	7.2 4.5	5.7 2.9	6.7	3.0 1.5	6.0	10.5	3.0 7.0
σ_{gd} [MN/m²]	3.0 –	8.0 –	7.0 –	7.5	6.0 –	7.5	12.5	9.0 –

Fig. 14 Cylindrical and flat jack tests

ned by means of numerous cylindrical and flat jack tests, along 3 km of tunnel. The cylindrical jack tests, were operated in little openings, a few metres far from tunnel wall. Gradually applied loads, up to 20 MN/m², gave rise to very high deformations. Structural heterogeneity of the rock caused a different run of deformation curves, from convex to concave shape (Fig.14).

A large amount of deformation occurred, particularly for laminated marl, due to first locking of chips; for higher loads failure effects of single layers appeared evident from well defined steps on relative graph (Fig.15). Comparison among results of deformability tests obtained from tests of different type, is shown in Fig.13. According to Schneider classification (Fig.16) marly rocks mainly fall into anelastic field (Zone B), except arenaceous marl which is often to consider as compact rock. Measurement of tangential stresses, at tunnel wall, carried out by 70x70x3 cm flat jacks, gave values of 7÷10 MN/m² for arenaceous marl, and of only 2÷3 MN/m² for marl (Fig. 14).

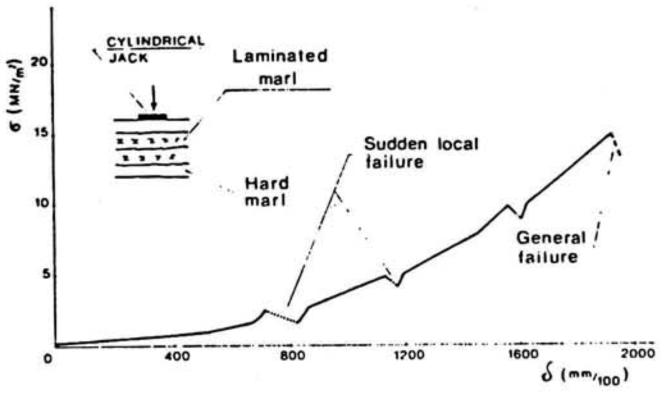


Fig.15 Typical behaviour of complex formation in compressive test

Strength of laminated rock mass, obtained by the same jack tests, until failure, was found to be only about 10% higher than mentioned tangential stresses, evidently for previous collapse of rock at excavation border.

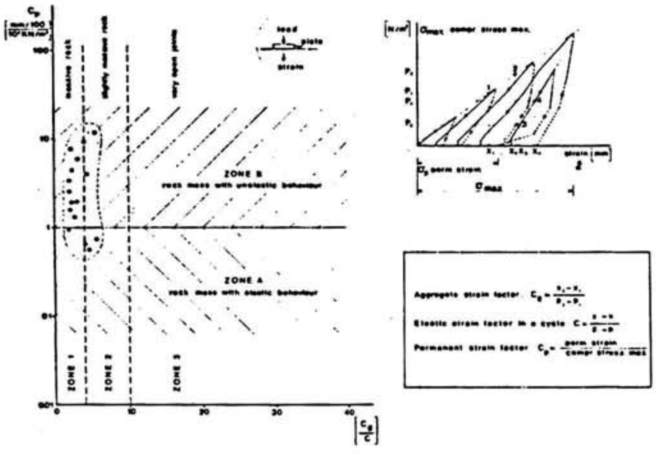


Fig.16 Schneider classification

For that reason no important relation appeared between measured tangential stresses and overburden.

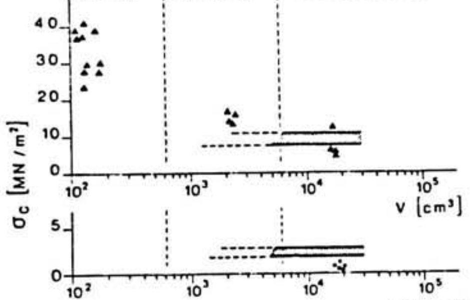


Fig. 17 Compressive strength versus sample volume and type of tests

Rock mass strength by flat jacks was in average 30% of value from matrix tests for marl and practically near to values from complex block tests (Fig.17). Any trials were operated, which are still outstanding, to determine primary stresses in the rock. Large difficulties, due to nature of the formation, and particularly to complex and tectonized structure, didn't yet allow a positive conclusion on this point. Some remarkable results by flat jack tests clearly indicated horizontal stresses higher than vertical ones, probably in connection with tectonics of the massif.

4. TUNNEL EXCAVATION

4.1 Behaviour of formations

The excavation of the two tunnels was carried out on full section by traditional methods; as provisional support steel ribs, slaked by a shotcrete prelining, were put in service immediately after tunnel advance.
The lining construction followed at distance of 200-300 m from the front.
Preceding main tunnels, in first 2600 metres section the excavation of a small service tunnel was made, which effectually allowed a direct advanced investigation.
Rock behaviour at the excavation corresponded (Fig. 23) to following remarks.

1. Marly limestone

The excavation of the tunnels was relatively rapid, with advancements of 2,00÷2,50 metres per blasting. The stability of the opening as a whole was satisfactory also for the particularly favourable bedding of banks.
No phenomenon was observed associated with increasing of overburden variable from about 40 to 200 metres. Only failures of fragile type due to blasting occurred in about 1 m thick ring around cavity and were checked by boroscope.

2. Marl, arenaceous marl

Rocks behaviour at the excavation was different along the tunnel axis.
In general, average advancements were made of about 2,00 metres per blasting, but, for important sections of the tunnel safety reasons reduced that advancement even to 50%.
The opening was mostly stable, both on the heading and on the perimeter of the cavity, for overburden up to 300 metres, while with higher overburden, local phenomena of instability took place, with small rock failures at hunches and calotta.
The fractured ring in average extended up to a thickness of 1,50 m.
In particular, in correspondence to compact and stratified marly facies, between ch.1900÷2250, with overburden 300÷500 metres, phenomena of sudden and violent enucleation, at

the heading, of rock elements up to some cubic meter in volume were observed.
Failure surfaces were conchoid shaped and involved various banks, which apparently showed good stability.
Loads on supports were more or less symmetrical, and appeared appreciably increasing in relation to overburden.

3. Laminated marl

The excavation in this type of rock didn't present any stability problem in Zone A.
Instead, under the high overburden (Zone C), stability appeared precarious, and only advancements not exceeding 0,80÷1,00 m were possible. In the most difficult conditions, immediate supports on the whole perimeter of the excavation, including the face, were necessary while heading showed a tendency to assume a concave shape.
Phenomena of plastic failure over whole edge of the cavity were evident. They radially extended on inside of the rock mass up to many metres, and seemed to be stabilized only some months after excavation.
As a consequence, very important deformations occurred, gradually increasing with overburden which caused cracks in prelining, especially at crown, and required supports reinforcement. Pressures on the prelining generally appeared to be uniformly distributed around edge of excavation and made often urgent the invert execution.

4.2 Field measurements

Field measurements essentially consisted of :

1. sonic logs in borehole;
2. deformation measurements with multianchor extensometer;
3. convergency of opening by invar tape extensometer;
4. deformation measurements with short rod extensometer;
5. pressure measurements behind prelining with hydraulic pressure cells.

As a rule, mechanical or hydraulic devices were used, since more sophisticated and delicate instrumentation was found to be unsuitable, due to difficulty of installation in the concerned formation, and too expensive in relation to foreseen frequency of measurement stations.
The sonic logs were carried out in a ∅ 75 mm, L = 40 m borehole, drilled from the service adit, and gave indications concerning rock before and after excavation of one of the main tunnels.
Results, collected in Fig.18 show:

- value of dynamic modulus E_{dyn} ;
- wideness of relaxed zones around the cavities
- relevant reduction of E_{dyn} (ch.2500) of mass between the service tunnel and the right-hand tunnel (Dx) already excavated, in comparison with that on the left, still to be excavated;
- high degree of relaxation of laminated marl beds, quite evident with regard to average behaviour of mass.

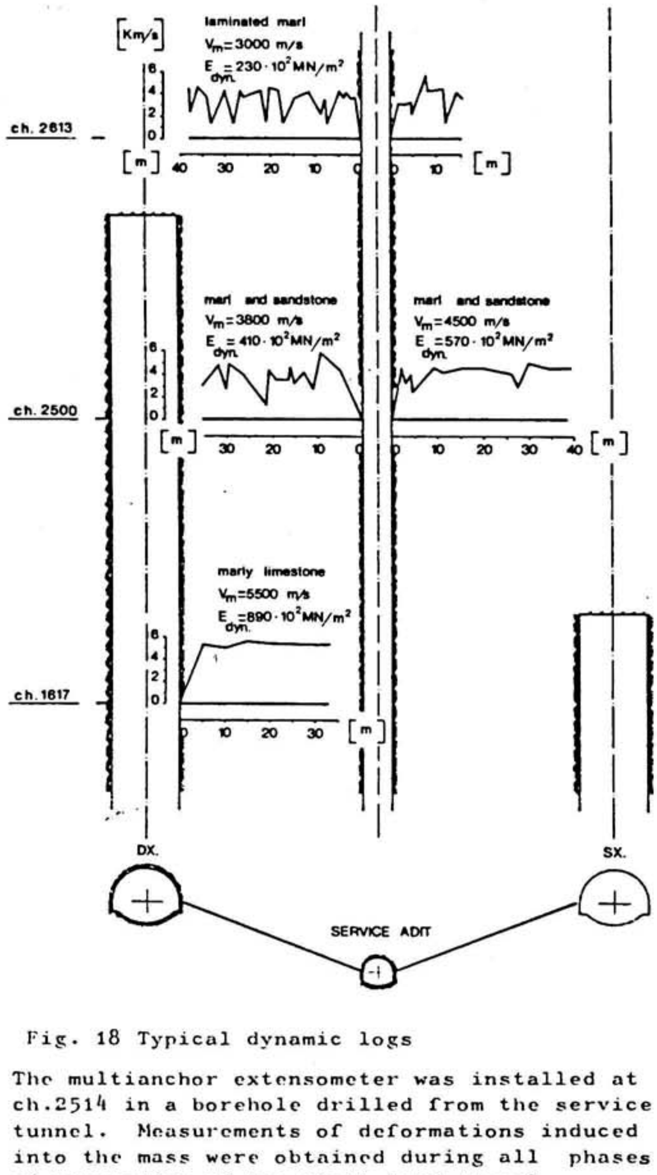


Fig. 18 Typical dynamic logs

The multianchor extensometer was installed at ch.2514 in a borehole drilled from the service tunnel. Measurements of deformations induced into the mass were obtained during all phases of excavation of the right-hand tunnel.
Results, summarized in Fig.19, indicate that :

- radial deformations began about one diameter before arriving of heading, and percentage of them, before that arriving, was about 10% of total final amount;
- final relaxation was practically extended ,

even if lower and lower, from the main tunnel as far as the service adit;

- deformations curve largely vary till some diameter after excavation, and then stabilization of values, in the long run, is very slow.

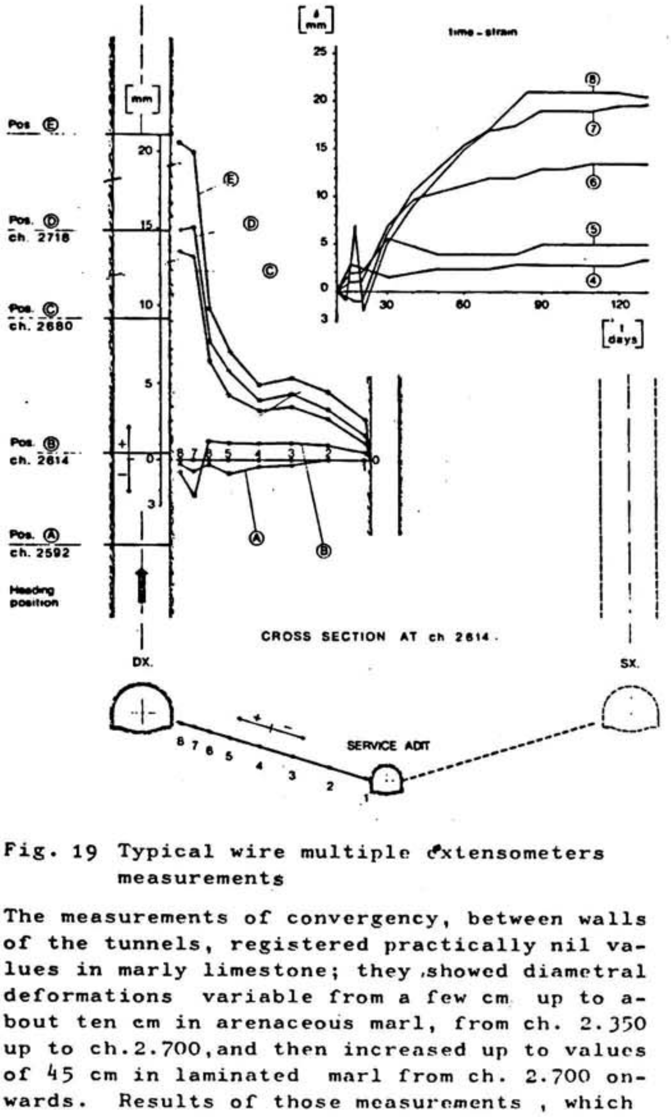


Fig. 19 Typical wire multiple extensometers measurements

The measurements of convergency, between walls of the tunnels, registered practically nil values in marly limestone; they showed diametral deformations variable from a few cm up to about ten cm in arenaceous marl, from ch. 2.350 up to ch.2.700, and then increased up to values of 45 cm in laminated marl from ch. 2.700 onwards. Results of those measurements , which are summarized in Fig. 20, show that:

- degree of tectonic alteration was a more determinant factor on convergency, than entity of overburden: that behaviour is made evident from comparison among results obtained for each of the two main tunnels;
- a large amount of total deformation occurred in phase heading was moving from zero to 30÷÷40 m distant from measurement point;
- deformation phenomena continued even when advancement of excavation front was stopped at a few tens of metres from the measurement point; that is a demonstration of presence, of viscosity effects in the rock.

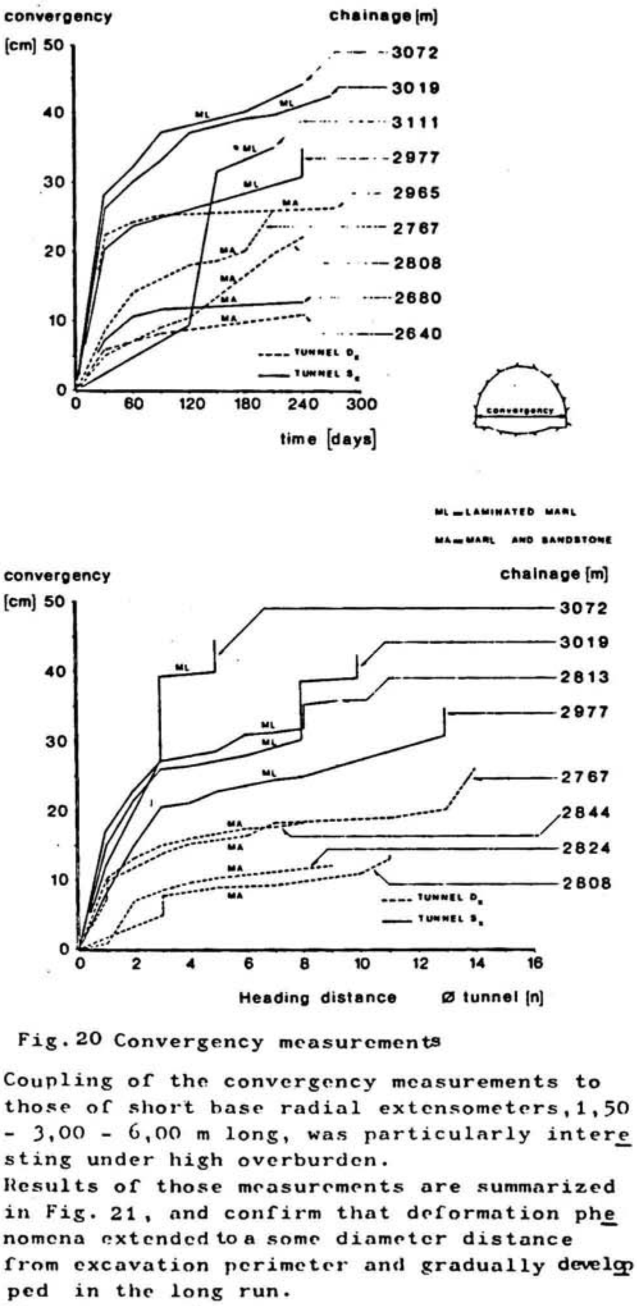


Fig. 20 Convergency measurements

Coupling of the convergency measurements to those of short base radial extensometers, 1,50 - 3,00 - 6,00 m long, was particularly interesting under high overburden.

Results of those measurements are summarized in Fig. 21, and confirm that deformation phenomena extended to a some diameter distance from excavation perimeter and gradually developed in the long run.

The measurements with pressure cells followed a very intensive programme.

Ten stations, set up according to scheme shown in Fig. 22, were put into operation directly at the front; devices were installed between rock and prelining.

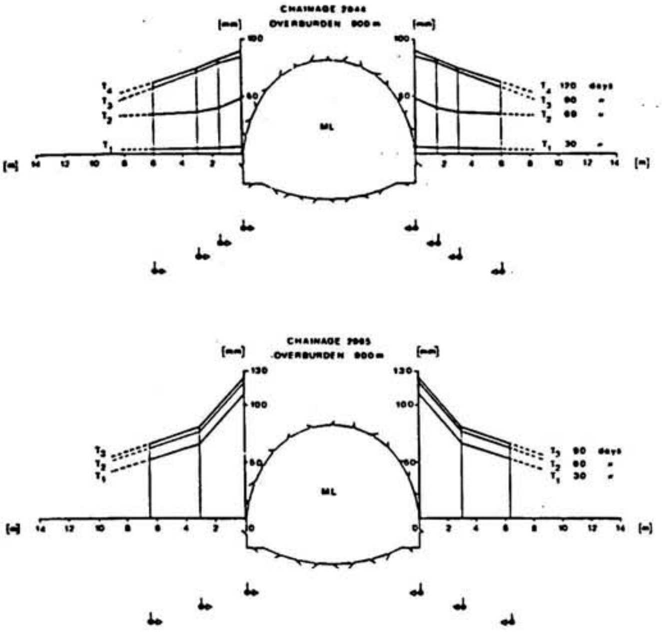


Fig. 21 Rod extensometers measurements

In marly limestone and in arenaceous marl under low and medium overburden, pressures were registered which didn't exceed 0,5 MN/m^2 mainly with asymmetrical distribution around edge. A prevalence of vertical pressures, which reduced with increase of the overburden, could be noted.

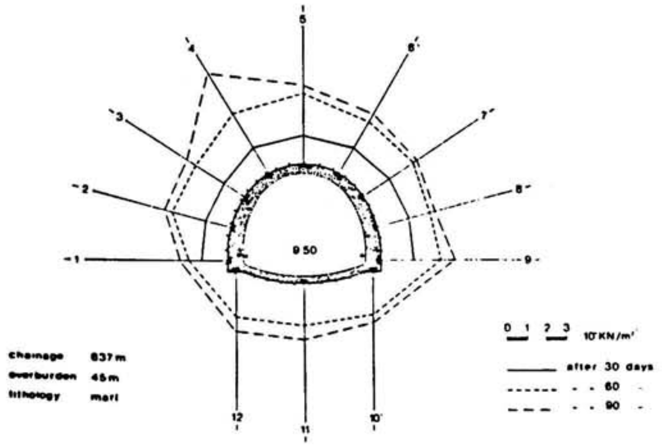
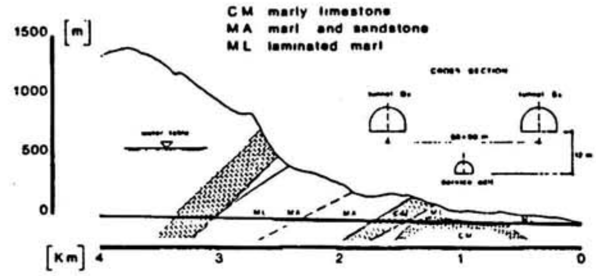


Fig.22 Rock pressures by hydraulic cells

In laminated marl, under high oberburden, pressures up to 1,2 MN/m^2 were registered, with uniform distribution around edge. However, in correspondence of max deformations, which caused a crisis of first prelining ring, hydraulic circuits of the cells went out of service, so that is was impossible to check eventual higher pressure values.



	C	B	A
Geological zones	C	B	A
Overburden	high	medium	low
Joints	strongly compressed		weakly compressed
Anisotropy	no	slight	marked
Convergencies [cm]	10÷45	0÷8	–
Wall failure	progressive and spread	sharp and localized	no
Load law on supports - $\frac{Ph}{Pv}$	0.85÷1.10		0.5÷0.85
Heading behaviour	considerable strains	rare failures	stable

Fig. 23 Rock behaviour under excavation

5. STATICS OF THE TUNNELS

5.1 General criteria

Difficulties to be usually faced when analysing static conditions of a tunnel were increased, in our case, by these essential factors :

a. complexity of formation, with consequent very hard identification of significant geotechnical parameters and models for design calculations;

b. an exceptional max overburden of the tunnels, 1000 m, related to softness of concerned rock;

c. probable anomalies in primary stresses of formation , due to effects of complex tectonics of Gran Sasso system, especially in correspondence to the highest overburden.

For approach to numerical problem it was then necessary to introduce, in project phase, many simplifications in hypotheses. At same time it was considered that, instead of concentrating studies on too sophisticated previous analytical researches, it was better to investigate rock behaviour gradually, while excavation of the tunnels proceeded from low to high overburden, and to use those results to adapt said hypotheses and to specify project lines.

5.2 Structural models

The various above considered facies, in which the formation was divided in geotechnical classification, were grouped, for static analysis, in three categories:

1) Limestone and marly limestone
2) Marl, arenaceous marl
3) Laminated marl

For the rock of category 1, whose behaviour clearly falls into field of rock mechanics , a traditional approach was considered to be acceptable.

There statics of the tunnels didn't present any problem, also because that rock was encountered only under low overburden.

The category 2 rock was excavated for an important length of the tunnels, under minimum to maximum overburden.

Layers of sandstone having a low percentage in mass, the behaviour of the whole was determined by marl. Its structure, could be compared to the classic discontinous rigid model which is typical of rock mechanics.

However, blocks themselves, isolated by joints, frequently presented an important deformability and a modest compression strength, due to presence of many internal weakness surfaces.

Consequently, for stresses level corresponding to low overburden, the discontinuous rigid scheme around tunnel could be considered still valid, but for loads which exceeded a certain value, said important modifications in rock structure were to be adequately taken into account.

Strike of layers resulted oblique in respect to axis of the tunnels and their dip was, on an average, inclined 30°-50° towards the inside of the montain.

Therefore the tunnel crossed the layers in a completely oblique position.

That fact determined particular structural conditions for it; actually, while the formation, as a whole, was considered to be anisotropic, especially where presence of the layers of sandstone was more important, the effect of obliquity, added to the intense fracturing and complexity due to tectonic effects, practically gave a large scale isotropic behaviour to mass, at least in zone close to excavation. Calculation parameters of that rock were fixed, on the basis of tests and fiels measurements, as it follows:

- density $\gamma = 2,5$ t/m^3
- friction angle $\varphi = 35°$
- monoaxial strength of mass $\sigma_{\varrho d} = 7$ MN/m^2
- corresponding to cohesion $c = 2.0$ MN/m^2
- undisturbed elasticity modulus $E = 6000$ MN/m^2

The category 3 rock consisted in locked together scaly elements, which rapidly lost density and compactness when they weren't laterally contained. Deformations were therefore due to variation of porosity which occurred in relation to actual different compressive stresses; failures were caused by reciprocal slip of scales, but also by crushing of weaker chips.

Behaviour of that rock seemed reconductable , less to the mechanic discontinuous rigid model, than to that of porous media, though crushing effects of chips inserted a series of discontinuity on stress-strain curve.

Average bedding of laminated marl was more or less similar to that indicated for marl; it was oblique, in space, in respect to tunnel axis.

However, continuous and often thick flexures and curls, complicated position of the whole , so that also for that category hypothesis could be considered as substantially valid isotropic in regard to tunnel statics.

Calculation parameters were defined as it follows:

- density $\gamma = 2,5$ t/m^3
- friction angle $\varphi = 30°$
- uniaxial strength of mass $\sigma_{\varrho d} = 3$ MN/m^2
- corrisponding to cohesion $c = 1.0$ MN/m^2
- undisturbed elasticity modulus $E = 2000$ MN/m^2

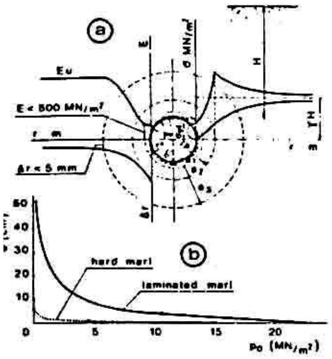
5.3 Deformations and supports

Analysis models for deep tunnels are generally based on hipothesis that a "plastic" ring originates at border of excavation as soon as equilibrium stresses around opening exceed intrinsic curve of rock. Stiffer supports or lining installed against excavation surfaces are and quicker execution is, less wide dimension of that ring results.

In our case, rock being prevalently weak or soft the purpose of limiting, as in classical design, plastic deformations at border, in order to guarantee provisional and permanent safety, found serious obstacle in exceptional pressures to support as a consequence of max overburden. In fact, with reference to Fenner-Kaster criterion, moving from strength of mass σ_{gd} and for pressures supportable by prelining, an important extension of plastic zone, was to foresee (Fig. 24 a-b).

On the other hand, block tests showed that if a rapid intervention was not made with suitable supports, excavation of the cavity would have reached serious conditions of instability since those rocks (Fig. 24 c) should be considered to have an unstable characteristic curve (Lombardi 1970).

In that condition conclusion was reached that it was absolutely necessary, immediately after excavation, to install a rather stiff prelining, which could be easily made stronger where necessary. It practically consisted in various spaced steel ribs incorporated in a shotcrete ring, in average stressed up to 10 MN/m². That fairly resistant ring was made more strengthening, when an excessive deformation appeared, by increasing shotcrete thickness , in a range from 25 to 50 cm, and doubling the steel ribs system with a second internal set.



ⓒ

Po = 1 MN/m²		OVERBURDEN		
		300 (m)	500 (m)	900 (m)
HARD MARL σgd = 7 MN/m²	a1 (m)	—		0.40
	a2 (m)	0.40	1.40	2.90
	a3 (m)	0.60	1.80	4.00
	rp/ro	1.07	1.24	1.49
LAMINATED MARL σgd = 3 MN/m²	a1 (m)	—	0.30	0.80
	a2 (m)	2.10	3.70	6.50
	a3 (m)	2.00	6.00	15.00
	rp/ro	1.34	1.67	2.20

Fig.24 Stresses and deformations around the tunnel

Otherwise, amount and law of increase of deformations were essence of the static problem: basical task was indeed to find the point, on " characteristic rock curve, where the ring had absolutely to be blocked, even with inverted arch, to avoid any danger of collapse of the cavity. On that theme on site measurements and analysis mainly concentrated during construction, leading to conclude that for marl radial deformation could be limited, to about 8÷10 cm without excessive pressure on supports, while in laminated marl that limit was to be fixed to exceptional value of 30-40 cm.

5.4 Analysis and structure behaviour

Analysis around the tunnels was carried out by various criteria, on the hypothesis of hydrostatic primary stresses (Heim) and of an elasto-plastic behaviour of rock; radial deformation was calculated for congruent rings, concentric with the tunnels, which were related to actual radial and tangential stresses.
Results of calculations made in that way were found to be sufficiently straight with field measurements for the part of the tunnel with smaller overburden. On the contrary, for the larger overburden, correspondence was found to be only partial. A careful examination of various experimental elements, indicated that reason for such a discrepancy was to be attributed to particular behaviour of the rock , which probably moves away from habitual model in a notable measure.
In effect, modification which construction of a tunnel causes in undisturbed rock structure, takes normally place around excavation only, in a plastic ring, where shear strains along joints occur; in our case, the phenomenon was complicated, because:

- in proximity to wall, under high tangential stresses, a failure occurred, not only due to shear strain along joints, but also to collapse of matrix and of laminar elements, with a consequent radical reduction of mechanical properties of the rock on the whole;
- in depth, even beyond the plastic ring, a wide zone was interested to excavation effects elastic modulus becoming there considerably lower than originally undisturbed one due to relaxation of laminated structure.

As a consequence a law of variation of the modulus E more extended than usually was to be assumed, from wall of the tunnel up to a great depth, in order to correctly interpretate various degrees of weakening of the formation. In practice surrouding rock was divided in 3 conventional zones, and a curve of the modulus E like in figure was adopted, minimum value for E being :

E_w = 1500 MN/m², at wall; for marl at low overburden

E_w = 400 MN/m², for marl at high overburden

E_w = 200 MN/m², for laminated marl.

It was so ascertained that provisional equilibrium of the excavation could be reached by means of prelining, but in spite of very important deformations. For final equilibrium a concrete ring was foreseen, about double in thickness respect to that in shotcrete, and it was admitted that the two rings could be considered statically unified; so after gradually transferring pressure from prelining to the total ring, long term concrete stress would be considerably less than the value accepted in provisional phase, and a reasonable margin would exist even with regard to possible viscosity phenomena.
In the light of results checked up until today, dimensioning of the structures seems to be sufficiently correct, the lining is made, since a long time, up to ch.2900 for the overburden which reach 950 m and which is not far from maximum value; at moment, pressures on the structure do not seem to exceed foreseen value, neither serious inconveniences were found.
As a whole, the hydrostatic hypothesis seems to correspond well to distribution of pressures on structures.
In spite of presence of a few layers of materials rich with active minerals, the formation does not seem to have produced real swelling phenomena.

6. CONCLUSIONS

Excavation of north block of the tunnels made it possible to improve knowledge of Gran Sasso and clearly showed stratigraphical succession of middle-upper Miocene,composed by marly limestone, arenaceous marl and high laminated marl. Starting from about ch.2300, overturned beds were put in evidence as a part of flank of anticlinal-synclinal structure crushed by overslip of calcareous dolomitic block.
Some interesting geotechnical results about complex marly formations behaviour under large overburden were collected.
Site investigation and laboratory tests appeared to be strictly complementary: in laboratory characteristics of each matrix element were clearly defined, whereas tests on large heterogeneous blocks were only partially successful, in spite of carefully performed sampling. In situ tests by cylindrical jack showed peculiar deformations characteristic of laminated rock, while those by flat jack positively specified peripherical stresses value after excavation, and mass failure process and strength. Field measurements, especially by convergency tape and by short bar estensometers, gave possibility to follow deformations systematically; those being always of considerable width,necessity was realized, more than of sophisticated devices, of a high frequency and rapidity system. A behaviour of the formation was found, which only partly corresponds to classic discontinuous rigid model: under heavy loads failure effects of matrix added to those of shear along pre-existing joints.
As a whole,deformations produced by excavations in the mass were extended up to some tunnel diameter from wall, with a remarkable reduction of modulus E, due to relaxation of laminated rock. Particularly mechanical properties collapse evidently occurred in proximity of tunnel walls.
In spite of that tendency, static behaviour under high overburden was found to be more favourable, at least on a short term, than it was foreseable from investigations and traditional analysis. That fact can be attributed to a pessimistic evaluation of characteristics of the rock on the whole.
In such formations a wide laboratory tests program on large size complex samples consisting of more than one lithotype is to recommend , in order to define large modifications of mechanical properties and, particularly, of deformation characteristics versus stresses level; comparison with in situ investigations, which can create little disturbance, and among those deep dynamic tests, seems advisable to verify law of said modifications.

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