The Alpine Tunnels and their Geotechnical Difficulties

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ISRM - President 1999-2003

Abstract: The crossing of the Alps by railway and road tunnels was among the major technical achievements of civil engineering in the second half of the nineteenth century and the twentieth century. The construction of theses tunnels faced a great number of difficulties. Most of them were due to geological and geotechnical hazards : inflows of water and debris, rock squeezing, rock bursting ...The analysis of these difficulties is carried out taking into account the progress of knowledge in rock mechanics. From these case histories, lessons may be drawn ; they may be useful for the future of deep tunnelling in mountainous areas.

1. Introduction

From the Genova Gulf to the Brenner Pass in Austria, the Alps are an almost continuous mountain belt between the northwestern ant the southeastern parts of Europe (Fig.1). Many summits have an altitude over 3000 m and the Mont Blanc reaches 4808 m. For centuries, the Alps were a natural barrier limiting the exchanges between the Alpine countries. The routes followed the valleys and went through the most accessible passes at an altitude over 1800 m : Mont Cenis, Grand Saint Bernard, Simplon, Gotthard. In the second half of the 19th century, to face the increasing demand of larger exchanges between Alpine countries, railway lines including tunnels with portals at a moderate altitude were built.

Fig. 1. The Alps : a natural barrier in Europe.

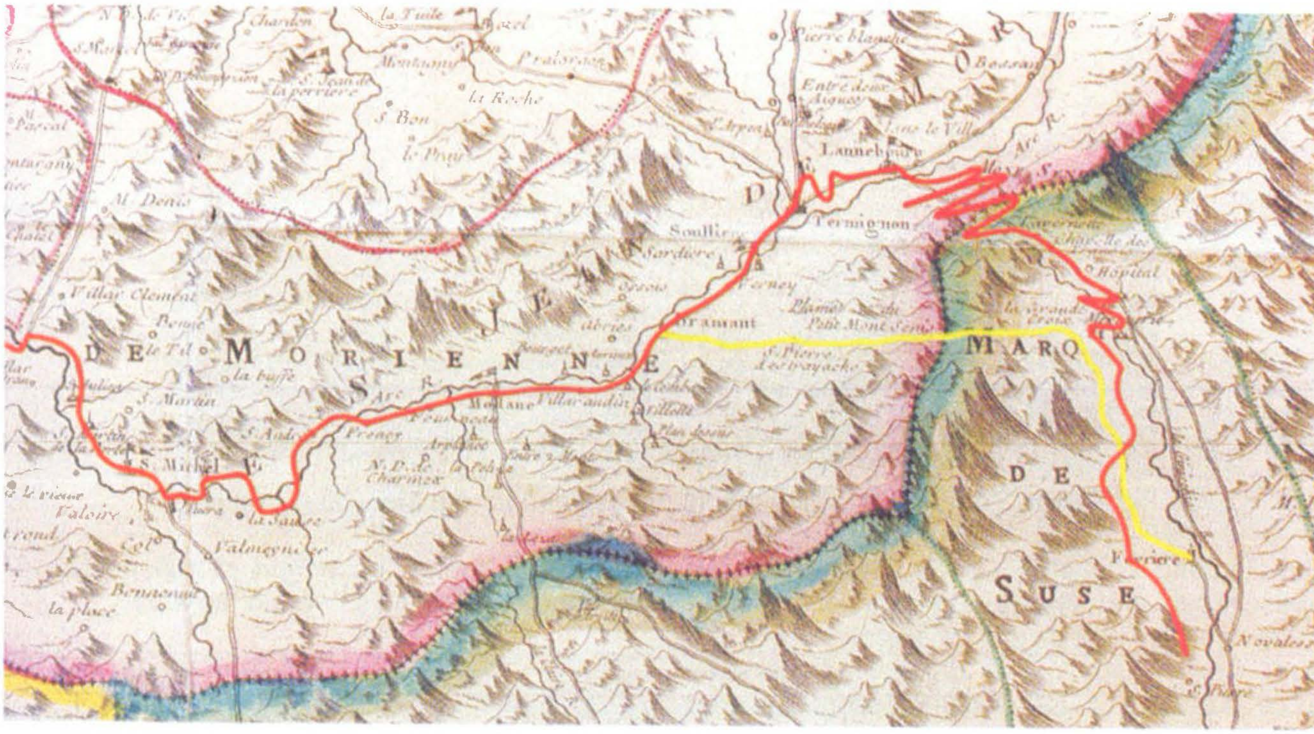

Fig. 2. Map of the Mont Cenis road in 1792

Tunnel	Period of construction	Situation	Length (m)	Maximal overburden (m)
Mont Cenis	1857-1871	Modane- Bardonecchia	12700	1600
Gotthard	1872-1881	Göschenen-Airolo	14980	1800
Arlberg	1880-1884	St Anton-Langen	10250	715
Simplon I	1898-1906	Brigue-Iselle	19730	2135
Lötschberg	1906- 1913	Kandersteg-Goppenstein	14500	800
Simplon II	1912-1921	Brigue-Iselle	19730	2135

Table 1

The first transalpine railway line Vienna-Trieste was built between 1848 and 1854 with a small tunnel, only 1500 m long, under the Semmering Pass. Then, the Alpine countries constructed several deep and long railway tunnels.
The table above (Table 1) gives the most important features of these tunnels.
Those tunnels are considered as landmarks in the history of tunnel building. They brought about many innovative technologies and methods in the tunnel construction.
The first major Alpine rail crossing was the 12.7 km long Mont Cenis Tunnel between the Maurienne Valley in France and the Dora Riparia Valley in Italy. It was built in 1857-1871. At the beginning, the rate of excavation was very slow, an average of 25 cm per day. The drill holes were perforated by hand tools. Fortunately, a new technique to drill the blastholes was introduced. G. Sommeiller, the chief engineer, designed the first air-compressed drilling machine. It was a major step in tunnelling technology. However, ten more years were necessary to join the two drifts. It may be noted that the link was realized with a surprising topographical accuracy, about 1 m.

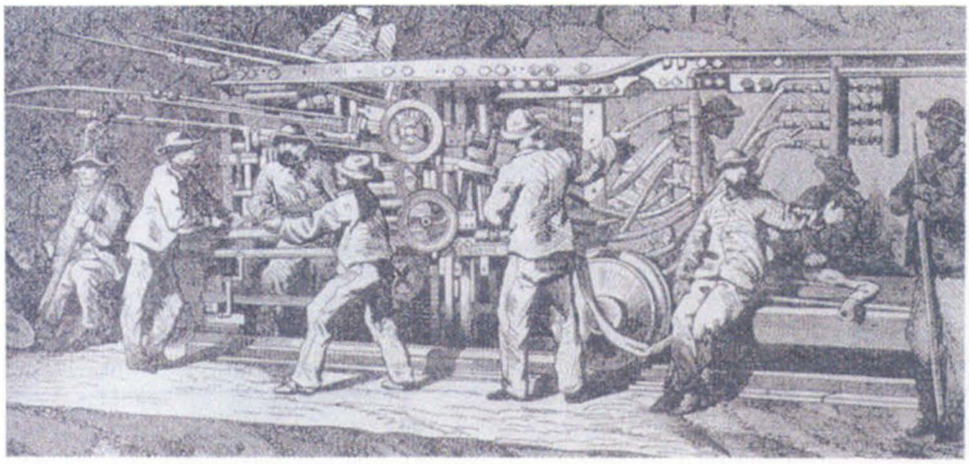

Fig. 3. The Sommeiller drilling machine designed for the Mont Cenis tunnel.

The Gotthard Tunnel is 14 984 m long between Goeschenen and Airolo. The main engineer L. Favre took advantage of the experience of the Mont Cenis Tunnel. The drilling material was improved with the use of compressors powered by hydraulic turbines. The dynamite replaced the black powder. Unfortunately, adverse geological conditions brought about many injuries and an average of 25 dead per year. The construction lasted nine years.

The most remarkable early Alpine railway tunnel was the 19,8 km long, double-tube, Simplon Tunnel between Italy and Switzerland . The first tube was built in 1898-1906 and the second one was finished in 1921. The engineer Brandt had designed a rotative driller which proved to be very effective. The engineers and the miners faced a great number of difficulties : high rock temperatures (up to 55,4°C) and various geological and geotechnical hazards.

The construction of the Arlberg Tunnel began in 1880 and ended in 1884, one year before the anticipated date. The average daily advance was 8 m instead of 5 m for the Gotthard Tunnel and 2.5 m for the Mont Cenis Tunnel..

The Lötschberg Tunnel, opened to the traffic in 1991, was the last great railway Alpine tunnels up to the present very important projects.

The decline of the railways and the increase of the road traffic brought about in the second half of the 20th century a period of construction of important road tunnels through the Alps.

Fig. 4. A postcard of the Simplon Tunnel.

Tunnel	Period of construction	Situation	Length (m)	Maximal overburden (m)
Gd St Bernard	1959-1964	Bourg St Pierre-Aoste	5800	700
Mont Blanc	1959-1964	Chamonix-Courmayeur	11600	2500
San Bernardino	1962-1967	Splügen-San Bernardino	6596	500
Gotthard	1969-1980	Göschenen-Airolo	16322	1800
Seelisberg	1970-1980	Altdorf-Beckenried	2x9300	1300
Tauern	1971-1975	Flachau-Zederhaus	6400	1567
Arlberg	1974-1978	St Anton-Langen	13970	715
Fréjus	1974-1979	Modane-Bardonecchia	12870	1800

Table 2.

The 11.8 km long Mont Blanc Tunnel driven between the Chamonix Valley in France and the Courmayeur Valley in Italy was built between 1959 and 1964. It was a new challenge for the engineers because of the large overburden which reaches 2 500 m under the Aiguille du Midi.

Fig. 5. The Mont Blanc Tunnel: the portal in the Chamonix Valley

The other important Alpine road tunnels constructed in this period were the Saint Bernard Tunnel, the Gotthard Tunnel, the Seelisberg Tunnel, the Arlberg Tunnel and the Frejus Tunnel.

A great number of lessons may be learnt from the history of the construction of all these Alpine tunnels. Most of the difficulties met during the construction of the Alpine tunnels were due to geological hazards and to geomechanical problems resulting from the large overburden.

The geology of the Alps is extremely complex. A great number of units are to be distinguished : crystalline basement rocks, mesozoic or tertiary sediments. During the Alpine orogeny, these units were strongly deformed, folded, sheared into complicated tectonic structures with large regional overthrusts. The rocks were metamorphosed at variable grades. Then the Alps exhibit a great variety of geological formations : granites, gneiss, micaschists, calcshists, limestones, shales, mudstones, sandstones, quartzites, anhydrite and gypsum, mollasses, alluvial and morainic formations...

Many geological studies of a great value have been carried out in the Alps by the geologists among the most famous of this century. Many valuable geological maps have been drawn by very competent geological teams of the Alpine countries. The general geology of the belt may be considered now as well understood. However, geological hazards are still to be expected for every tunnel to be driven at great depth in the Alps.

The main geological and geotechnical hazards which may happen during tunnel construction at great depth are :

- large water inflows
- large debris inflows
- squeezing ground
- rockbursts

These hazards may be well illustated by the cases histories of the construction of Alpine tunnels. From these cases histories, it is possible to draw lessons for the important future underground works under project in the Alps.

2. The Water Inflows

Groundwater may enter a tunnel in different ways. It may drip from the roof and turn into a veritable rain. It may flow from the walls. But the most severe situation is met when the waters under heavy pressure break in as a gusher. These inflows of water are all the more dangerous when they are sudden and unexpected. They brought about many casualties and delays in underground works at great depth.

Such an accident occurs when the excavation is advancing in a low permeability formation and come close to a waterbearing fault or fissure under high pressure ; suddenly the slab of rock separating the wall of the excavation and the discontinuity fails within the water pressure and the water rushes into the tunnel.

Many large water inflows were reported during the construction of Alpine tunnels.

During the construction of the Mont Blanc Tunnel, J. Renaud described two sudden inflows of water on the French drift :

"...

On 16th march 1962, at the metric point 4977, during the drilling of blastholes, the face burst in under the water pressure, throwing in rock blocks and injuring five miners, two of them very severely. The initial flow output was 55 l/s and decreased down to 19 l/s.

On 27th march 1962, at the metric point 5032, during the drilling of a 60 mm diameter borehole, the drilling rig was violently pushed backward and a 80 m waterjet prevented to approach the face. The initial output was about 200 l/s; after a few days, it was stabilized at a value of 60 l/s.

..."

The largest inflow occurred on the Italian drift at the metric point 3660 with an initial output of 1000 l/s. The floor of the tunnel was covered by a 40 cm water layer. The permanent output was about 300 l/s to 400 l/s.

The record of the outputs of large inflows is rarely carried out with sufficient care to make possible a detailed analysis of the hydraulic behaviour of a discontinuity waterbearing on a great height. It is necessary to distinguish two different hydraulic situations :

- if the discontinuity is connected with a large reservoir, for instance a lake, the hydraulic head may be considered as constant, the permanent outflow may be evaluated with the expression:

$$Q_\infty = \frac{2\pi H}{\ln \frac{2H}{R}} T$$

where,

H is the hydraulic head,

R, the equivalent radius of the tunnel section,

T, the hydraulic transmitivity of the discontinuity.

the transient output at time t after the beginning of the flow is given by :

$$\frac{Q(t)}{Q_\infty} = \frac{2 \ln \frac{2H}{R}}{\int_{\frac{R^2}{\lambda t}}^{\frac{H^2}{\lambda t}} \frac{\exp(-x)}{x} dx}$$

where λ is the hydraulic diffusivity of the discontinuity.

Then the hydraulic behaviour is characterised by two hydraulic parameters, its transmissivity and its diffusivity.

- when the discontinuity is not supplied by water, it is progressively drained and the output remains approximayely constant since the hydraulic gradient is constant. The inflow stops when the discontinuity is empty.

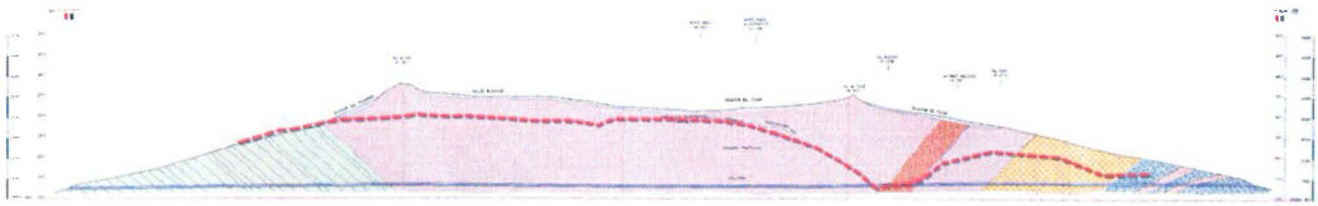

Fig. 6. The longitudinal temperature profile along the Mont Blanc Tunnel.

For tunnel at great depth; the rock temperature at the tunnel level is high because of the geothermal gradient when there is no groundwater flow. The record of the temperatures along the tunnel may also give information about the proximity of discontinuity connected with the surface at low temperature.The sudden decrease of the temperature in the temperature profile along the Mont Blanc Tunnel was due to the presence of a fractured zone connected with the Glacier du Géant.

On the Italian drift of the Simplon Tunnel, the rock temperature reached 56°C. Between 4.4 km and 4.5 km from the portal, the total output of the water inflows was 1200 l/s at a temperature of 12°C. The progress of the work was stopped several times. One of the water springs was used to cool the tunnel atmosphere.

3. The Debris Inflows

A debris inflow occurs when the tunnel is about to come close to the boundary between a watertight rock formation and a section of loose cohesionless soil or of highly fractured or weathered rock under high groundwater pressure. The sudden blow out of the face brings about a flow of cohesionless materials which may fill in the drift on a great length.
Such accidents happened at the crossing of faults with cohesionless fillings, of crushed or

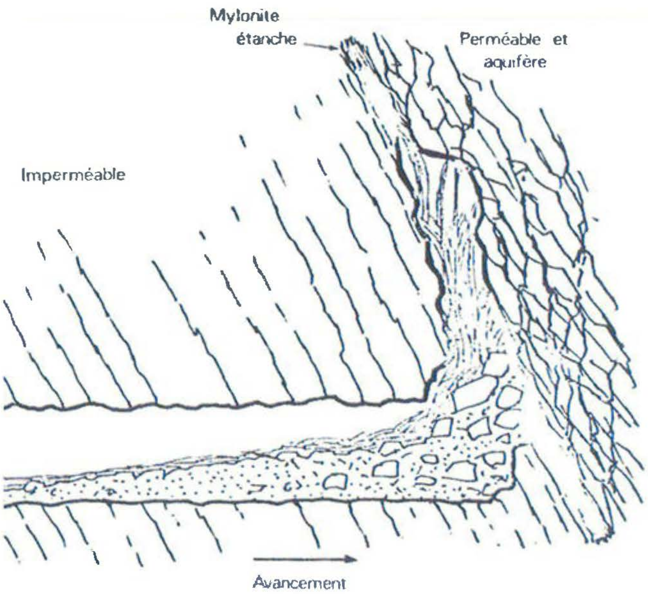

Fig. 7. A debris inflow into a tunnel

mylonitized zones in granite and gneiss, quartzite or sandstones, limestones and dolomites, or at the vicinity of valleys or karstic or glacial channels.

J.L. Giafferi described several accidents of this type during the construction of hydraulic galleries driven in the Alps for hydropower plants.

Another example is given by the Tunnel des Hurtières on the French motorway A43 in the Maurienne Valley. It is a 1180 m long double-tube tunnel expected to be entirely driven in Precambrian schists. But the western tube met at 310 m from the North portal a deep and narrow glacial channel with a complex shape.

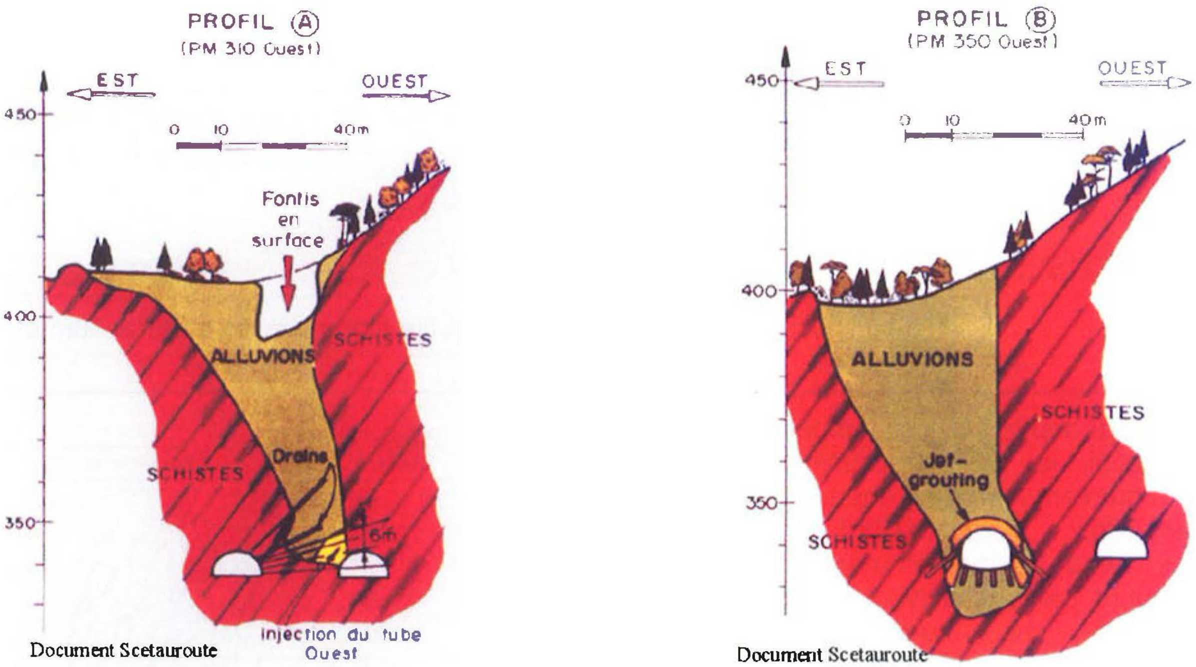

Fig. 8. Tunnel des Hurtières : debris inflow due to a glacial channel. (Scetauroute)

A debris flow stopped the progress of the work. Detailed geological investigations were necessary to determine the exact location and shape of the channel. Drainage, grouting, jet-grouted prevaults, and consolidation of the faces were used to cross this zone. 15 months were necessary to overcome this geological accident.

But the most memorable and tragic debrisflow in the history of Alpine tunnelling occurred during the construction of the Lötschberg Tunnel on july 24th 1908. Under the Gastern Valley at 2675 m of the Kandersteg portal, when the face of the tunnel entered into waterbearing alluvial deposits, a flow of mud and gravels filled in the tunnel on a length of 1800 m. After the collapse, a crater 3 m deep with a 80 m diameter appeared at the surface of the valley. 24 miners could not escape and died. The geologists had wrongly assumed that there was a cover of 100 m of limestone between the roof of the tunnel and the alluvial deposits. The alignment of the tunnel was modified in this section . This change explains the present curve of the tunnel on the North entrance.

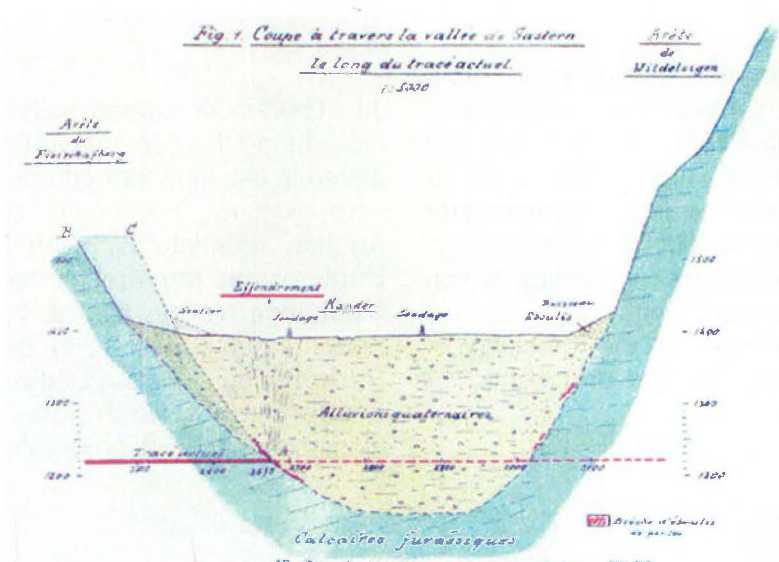

Fig. 9. The Lötschberg Tunnel : the collapse below the Gastern Valley. The longitudinal profile of the initial alignment.

4. The Natural State of Stress

The analysis of the behaviour of an underground excavation at depth requires the knowledge of the natural state of stress. But the determination of the natural state of stress at great depth is one of the most difficult challenge in rock mechanics.

Theoretical considerations are not a great help to assume the natural state of stress and may only give a posteriori explanations. In some areas of the world, some maps show the regional stress pattern resulting from the critical analysis of all the data available. B. Müller & al. published a map for Europe and more specifically for the Alpine area. The orientation of the principal stresses may be related with the tectonic deformations due to the collision between the African and European plates. However, at a level above the valleys, it seems that the state of stress is primarily due to the gravity. In some areas, residual stresses due to the permanent strains acquired during the tectonic deformations may subsist.

Different techniques have been developped to measure the state of stress in rock masses. The two most used are the overcoring technique and the hydraulic fracturing.

The overcoring technique measure the strains due to the relief of the stresses by overcoring around a bidimensionnal (doorstopper technique) or tridimensionnal strain cell (with two coaxial boreholes). Favorable conditions relative to the behaviour of the rock and to the homogeneity of the rock mass are necessary for the realization and the interpretation of these tests. Their main drawback is to measure the state of stress corresponding to a small volume of rock which is not representative of the scale of the volume of excavation. In many instances, the measurements are scattered and it is necessary to carry out a great number of tests.
The technique of hydraulic fracturing has been developped in the oil industry to improve the production of the wells. The fracture initiation pressure, the shut-in pressure, the fracture orientation give most useful informations about the natural state of stress. The most obvious one is the direction and the magnitude of the lowest principal stress. The determination of the stress tensor from hydraulic fracturing is much more difficult and controversial. The technique HTPF (Hydrofracturing Tests on Prexisting Fractures) developped by F. Cornet consists to reopen natural fractures intersecting the boreholes with various orientations. Inversion techniques are used to determine the state of stress and its variation along the borehole.

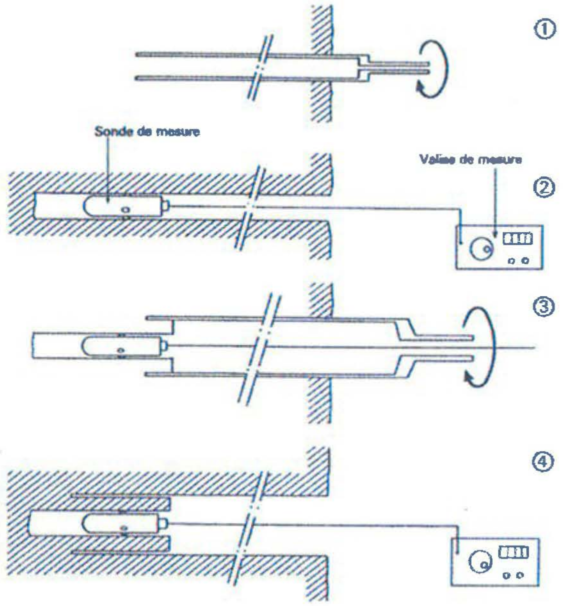

Fig. 10. The principle of stress measurement by the overcoring technique.

The drilling of boreholes brings about very valuable informations about the natural state of stress. They may be inferred from :

- the breakouts which occur on the walls of deep boreholes and which may be observed with a good resolution, with the borehole televiewer (BHTV),
- the measurement of the ovalization of the boreholes with a diameter logging technique,
- the core discing which occurs in the high-stressed zones.

The back analysis of the behaviour of underground works (convergences, nature and type of failures) located in the same area and, if possible, in the same geological formation, may give very useful informations about the natural state of stress. In many situations they are the most pertinent ones for the design of new tunnels because they are at the adequate scale.

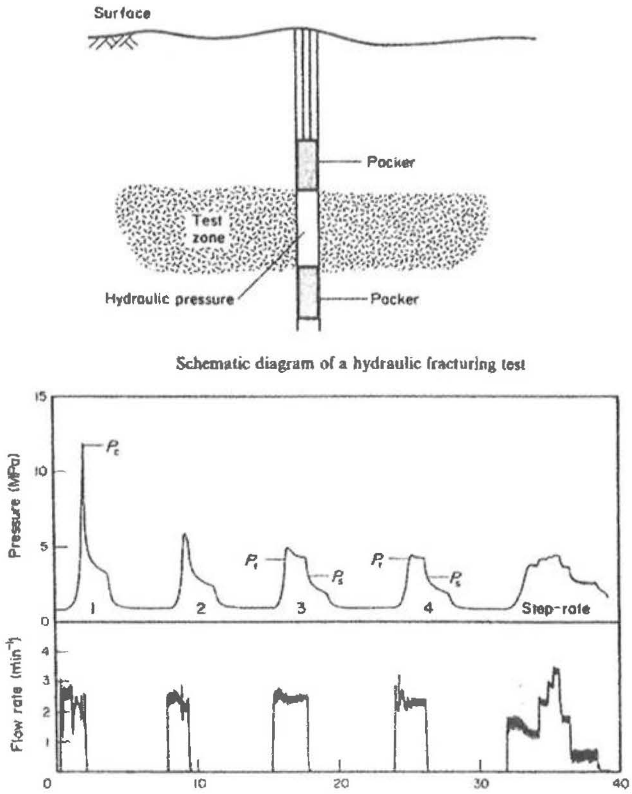

Fig. 11. The principle of stress measurement by the hydraulic fracturing technique (After Haimson)..

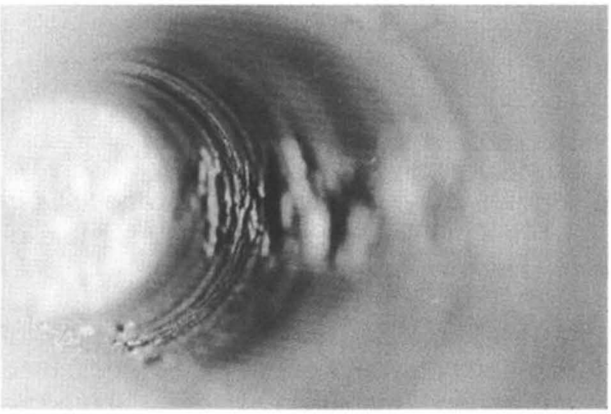

Fig. 12. Breakouts along a horizontal borehole (Mont Blanc Tunnel)..

In most cases and particularly for the study of deep Alpine tunnels, the combination of all the data and informations obtained by these various approaches are the only way to make valid assumptions about the natural state of stress to be used for the analysis of the tunnel behaviour.

In order to analyse the risk of rockbursts in the southern section of the Lötschberg Base Tunnel, now under construction, a fair evaluation of the natural state of stress was necessary.

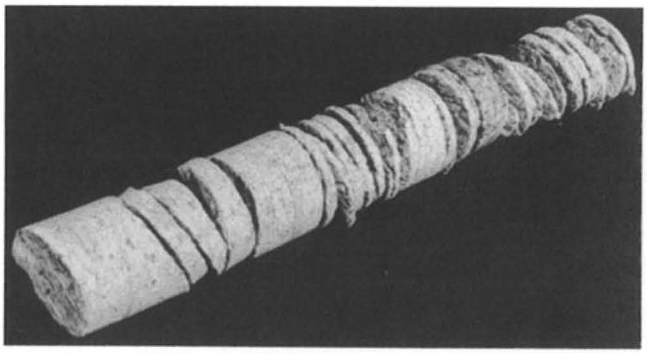

Fig. 13. Core discing in boreholes (Mont Blanc Tunnel).

In this section, the tunnel passes through the Bern Oberland granitic mass with summits (Doldenhorn, Bâlmhorn) over 3700 m. The level of the tunnel varies between 634 m and 827 m. The distribution of the stresses in the rock mass due to the gravity was determined by a tridimensionnal finite element model reproducing the topography on a large area. The results of the models were compared to all the available data:

- the measurement of in situ stresses by the hydrofracturing techniques,

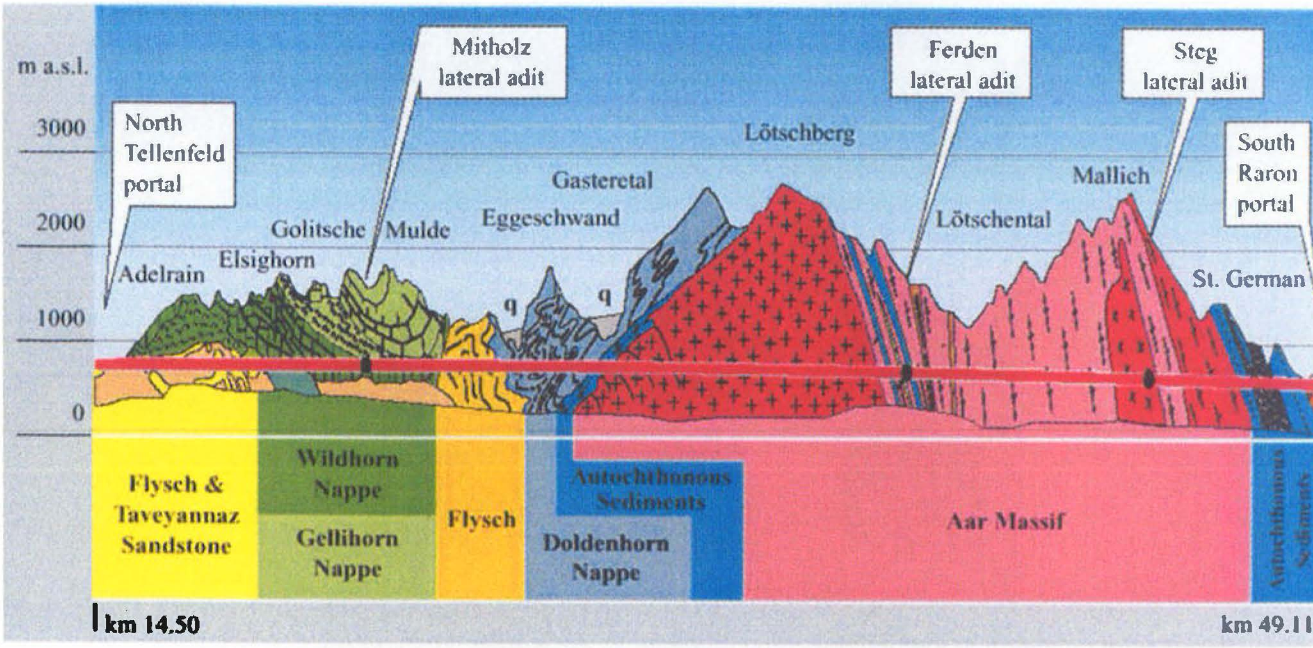

Fig. 14. The geological longitudinal section of the Lötschberg Base Tunnel.

- the analysis of core discing in some boreholes,
- the back analysis of the behaviour of the railway tunnel driven in the same geological formations about 500 m above the level of the Lötschberg Base Tunnel.

The validation of the numerical model was considered as acceptable . It gave the basis for analysis of the probability of rockbursting.

5. Tunnelling in Squeezing Grounds

According to the Commission on Squeezing Rocks of the International Society of Rock Mechanics,
" *rock squeezing in tunnelling is the time-dependent deformation which occurs around the tunnel and which is essentially associated with creep caused by exceeding a limiting shear stress. The amount of tunnel convergence, the rate of deformation and the extent of the yielding zone around of the tunnel (away from the tunnel perimeter and ahead of the tunnel face) depend on a number of factors such as the geological conditions, the in situ stress relative to rock mass strength, the groundwater flow and pore pressure and the rock mass properties."*

Tunnelling in squeezing rock at great depth is a challenge which was experienced during the construction of the Alpine tunnels. The Simplon Tunnel, the Furka Tunnel and the Vereina Tunnel in Switzerland, the Tauern Tunnel and the Arlberg Tunnel in Austria, the Frejus Tunnel between France and Italy are well documented examples where rock squeezing conditions were the cause of very large difficulties during construction. The difficulties increased very significantly the delay and the cost of construction of these works.

Very heavy squeezing conditions prevailed during the construction of the first tube of the Simplon Tunnel at 4.45 km of the South portal. According to Pressel (1906) :

"*...One entered in a rock mass where heavy pressures were exerted from everywhere. It was like a paste , made mainly of calcschists ...Every attempt to drive with the usual mining methods, the support consisting in side by side, 50 to 60 cm diameter, wooden struts made of larch, proved unsuccessful. The supports failed. Even those made of 50 cm x 50 cm oak timbers broke, although the section of the galery was not over 2 m high and 1.95 m large..."*

Finally a steel support was used. The crossing of the 42 m long section lasted almost seven months. To build the masonry lining a temporary masonry arch was erected. The vault of the final lining made of gneiss stones is 1.67 m thick and the invert is 2.50 m thick.

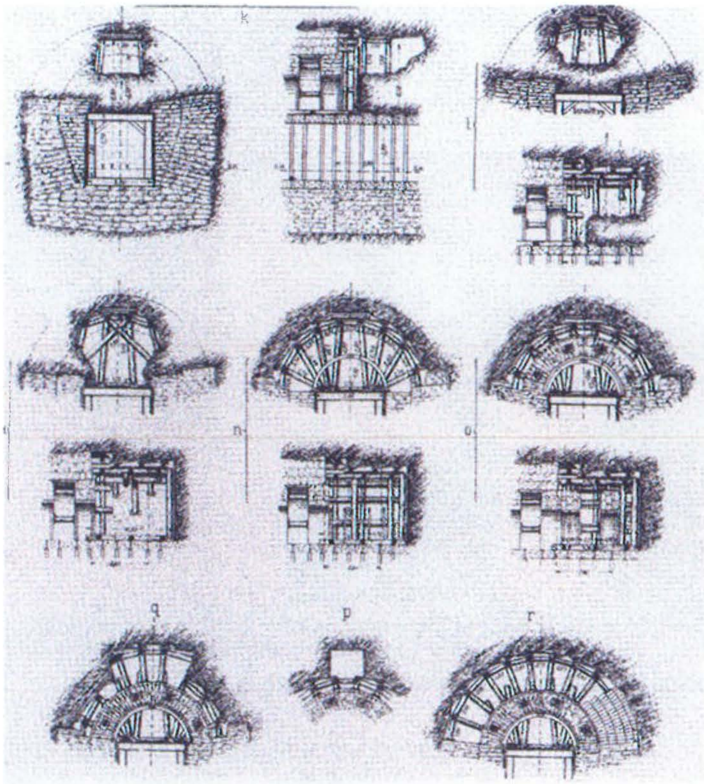

Fig. 15. The mining method used in the heavy squeezing rock conditions of the Simplon Tunnel.

The highway Frejus Tunnel was constructed on almost all its length (12.6 km) in a calcschist overthrust. The strike of the schistosity is parallel to the axis of the tunnel and its dip may vary between 20° and 60°. Very large convergences occured inward in the direction perpendicular to the schistosity. Large convergences which exceeded 50 cm were measured. It may be remarked that the convergences measured in a gallery perpendicular to the tunnel were low.

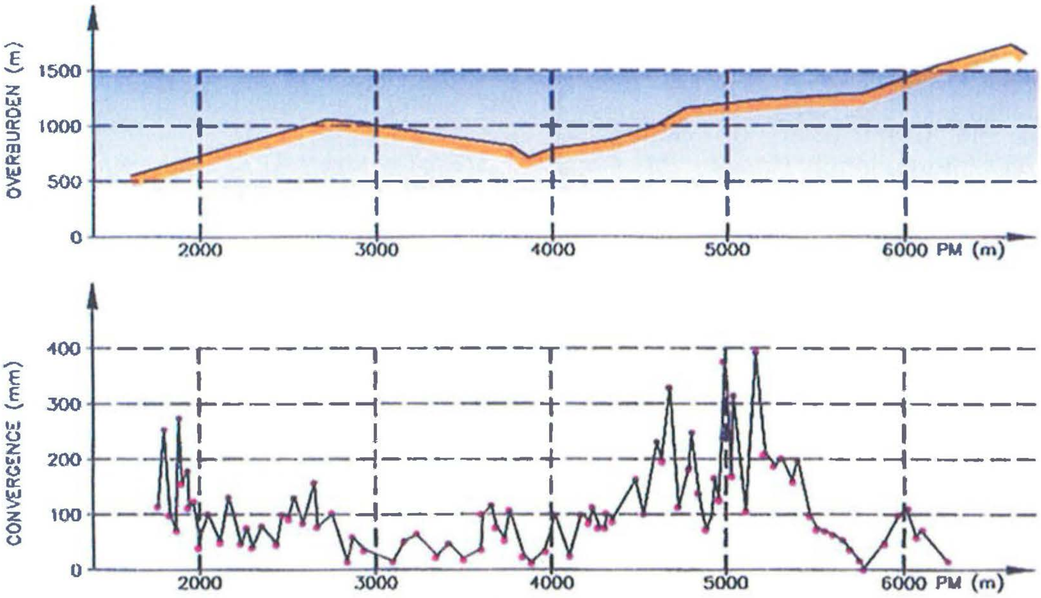

Fig. 16. Frejus Tunnel : Convergences measured one month after the excavation of the section on the French drift.

The Fig.17 shows that there is no obvious relationship between the magnitude of the convergence and the overburden. The magnitude of convergence may be related to petrographic variations of the rock, even if the variations of the petrography in an apparently monotonous formation like the calcschists may not be evidenced by a simple examination.

The rock deformation was time-dependent and the convergences increased during all the time of measurement, up to the installation of the final concrete lining.

On the French drift, the tunnel was supported by point-anchored rockbolting and a strong steel mesh. Some rockbolts failed. It was necessary to adapt the rockbolt support technique to the large convergences. The attempt to use a shotcrete support was given up because of the failure of the shotcrete shell. The fissuration of the shotcrete appeared when the radial deformation was over 2 to 3 x 10^{-3} and it failed progressively when the convergences increased. The use of very heavy support with closed steel arches and poured concrete was also unsuccessful.

Fig. 17. The Frejus Tunnel : The failure of heavy support with steel arches and concrete.

In the Alpine tunnels, rock squeezing conditions were most often encountered in schistous rocks where the strike of the schistosity is parallel to the axis of the tunnel. Because of the orthotropy of the behaviour of the rocks, there are large stress concentrations around the tunnels in the zone where the shistosity is tangent to the walls. The large convergences in these zones are mainly due to the buckling failure of the schistous layers.

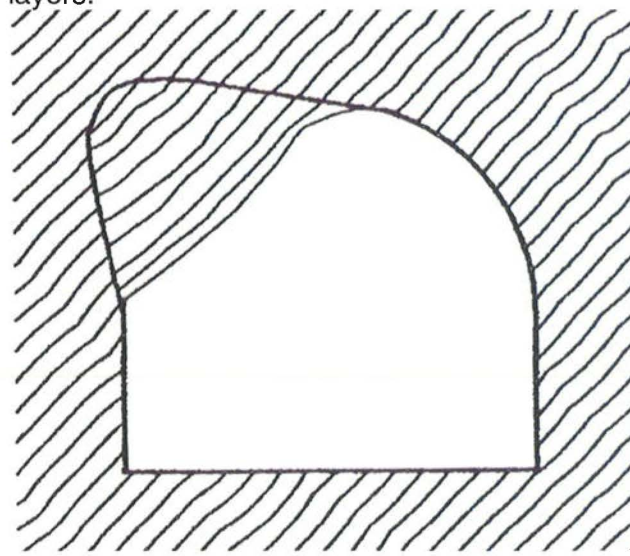

Fig. 18. The buckling failure of schists in tunnels.

The stability of the face must also be analyzed carefully, even if no failure occurs at the face. P. Lunardi proposed to measure the extrusion at the face by sliding micrometers.

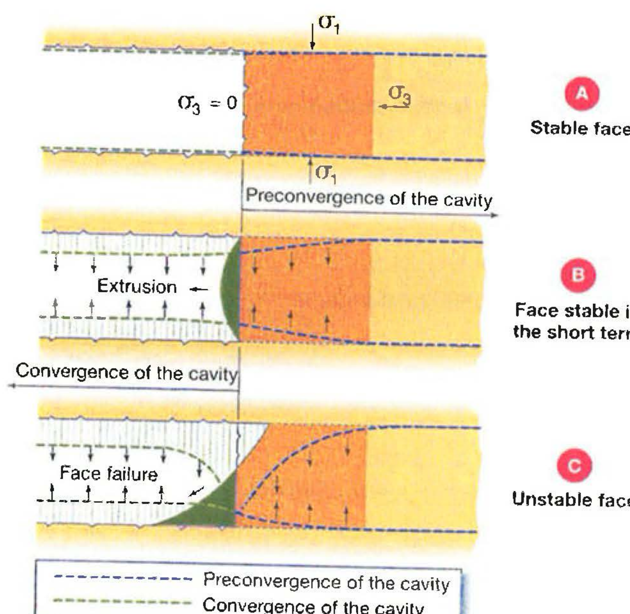

Fig. 19. The various behaviours at the face of a tunnel (P. Lunardi).

A large extrusion evidences a development of the yielding zone ahead of the face. Various techniques as grouting, presupport or prereinforcement have been proposed to control the extrusion and therefore the convergence of the tunnel. A presupport may be achieved by the old technique of forepoling, by a reinforced ring ahead of the face with suhhorizontal grouted bars or jet-grouting piles or by mechanical precutting. The prereinforcement of the core may be obtained by using glass-fibre structural elements. In many cases, mixed techniques of presupport and prereinforcement of the core are used.

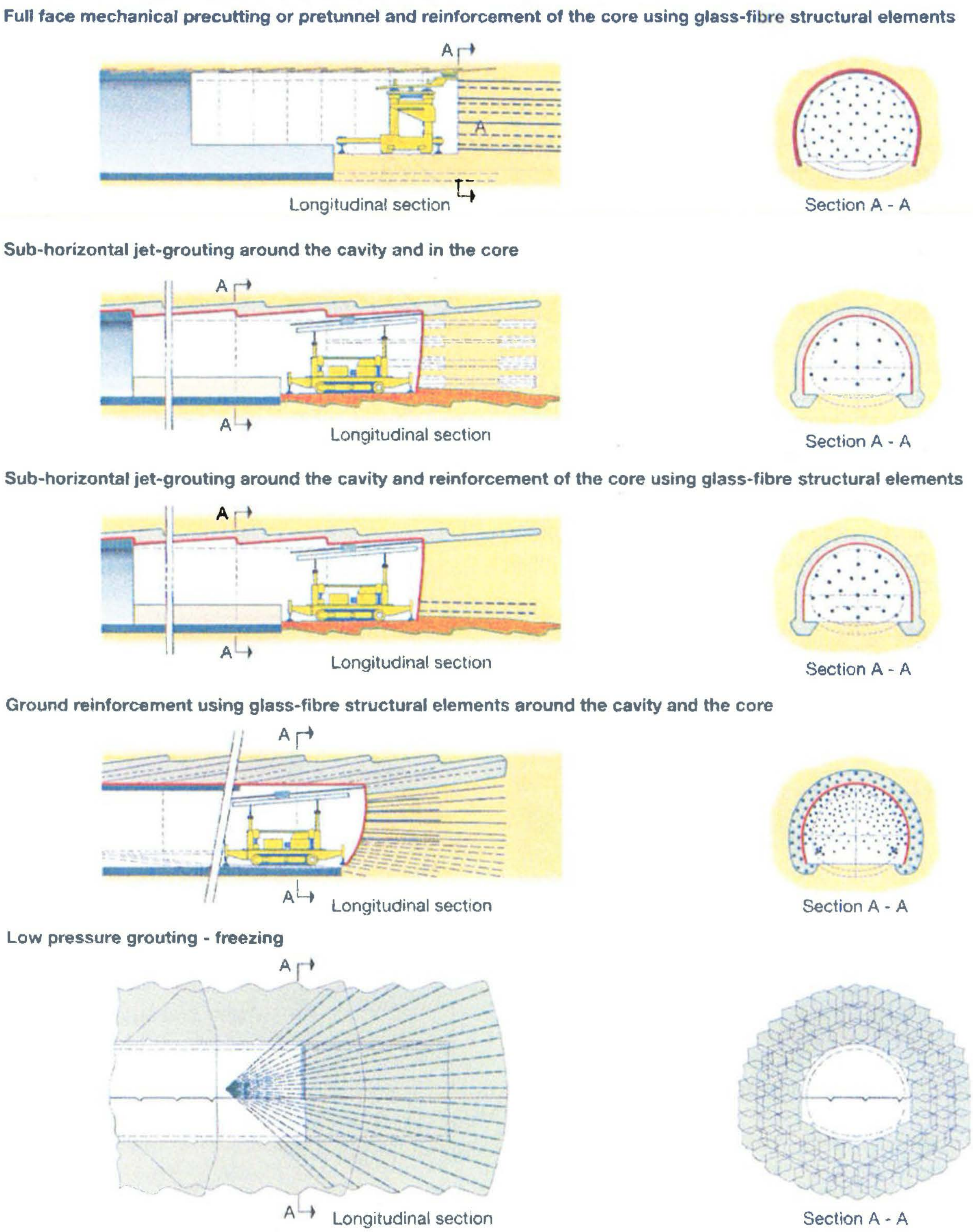

Fig. 20. Mixed techniques of presupport and prereinforcement of the core (P. Lunardi).

Up to now, the full-face excavation method with mixed techniques of presupport and core reinforcement were applied with success to tunnels at moderate depth (P. Lunardi). Its effectiveness for tunnels at great depth exhibiting large convergences are still to be proved. However the analysis of the behaviour of the core ahead of the face may allow a much more pertinent definition of the technique of construction and reinforcement around the face.
Theoretically, the convergence-confinement method may be used to anticipate the magnitude of convergences and support loads . The largest difficulties do not arise from the computational methods but from the difficulty to determine the rock mass characteristics. For example, the strain softening behaviour of the rock mass is a very important factor. It is very difficult to characterize this post-failure behaviour and, therefore, it is rarely taken into account.

The large convergences of squeezing rock masses are time-dependent. Up to now, no rheological model has been able to predict correctly the time dependent behaviour of the rock mass in squeezing conditions. From a detailed analysis of the convergence curves versus time and distance to the face, a semi-empirical law of convergence was proposed:

$$c = A_1 f(x)[1 + A_2 g(t)]$$

where,

$$f(x) = \left(\frac{x}{x+X}\right)^2$$

$$g(t) = \left(\frac{t}{t+T}\right)^n$$

X is related to the distance of influence of the tunnel face and therefore to the development of the yielding zone.
T and n are parameters dependent on the rheological behaviour of the rock mass.
For the Frejus Tunnel, the convergence curves were approximated with a noteworthy accuracy with the following parameters :

X=13 m, T= 3,75 days, n=0.3, A_2=4

On many others tunnels, these expressions were used with success.

6. The Rockbursts

The brittle behaviour of rock may be observed during compression tests at low confining pressure. In a uniaxial compression test, beyond the maximum strength, the stress-strain curve is decreasing rapidly.

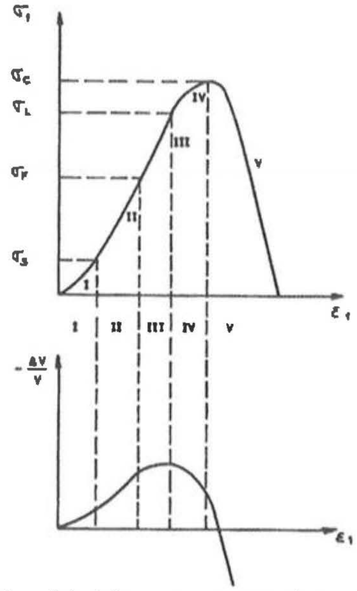

Fig. 21. The stress-strain curve of a brittle rock in a uniaxial compression test.

If the press used for the test is not stiff enough, the behaviour of the sample beyond the maximum resistance cannot be tested ; the post-failure deformation is no more controlled and the sample bursts. This unstability of the system is due to the steep downward slope of the load-displacement curve. The sample cannot control the energy which was stored in the soft press during the loading and which is restored too brutally.

The same type of unstability may be observed on the wall of a tunnel driven in a brittle rock mass under high natural stress. At the wall of a tunnel, the stress path due to the excavation brings about a low confinement and a high deviatoric stress.

This uncontrolled process of failure at the walls of a tunnel is called rockbursts. Rockbursts have been observed in many underground openings at great depth, for example in the South African gold mines. Violent rockbursts occurred also during the construction of Alpine tunnels, most of the time in sections in granitic or gneissic rocks under a large overburden.

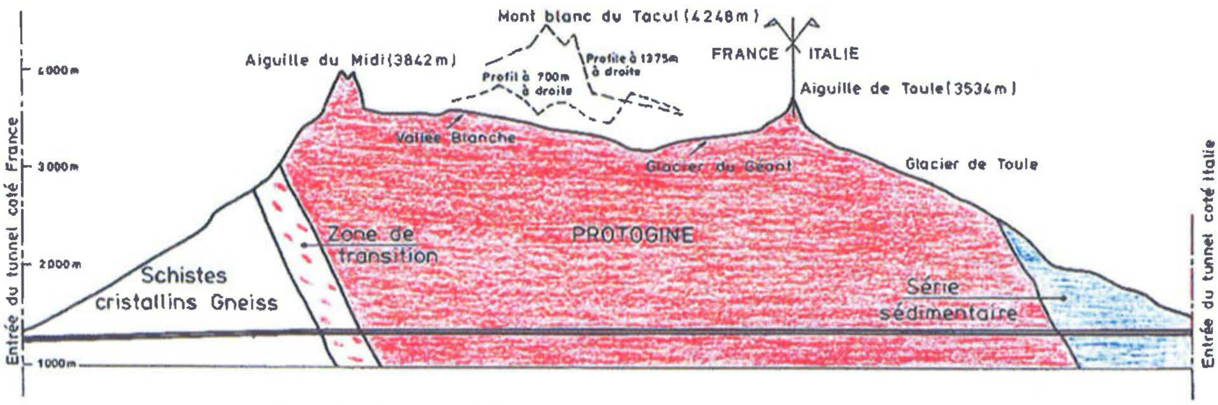

Fig. 22. The route of the Mont Blanc Tunnel.

In its central section and on most of its length, the Mont Blanc Tunnel was driven in a metamorphic granitic rock called protogine. The overburden of this tunnel is very large and reaches 2500 m under the Aiguille du Midi (alt : 3850 m). But the natural state of stress at the tunnel level is also influenced by the proximity of summits with an altitude over 4000 m. The tunnel crosses successively sections of mylonitized rocks, sections of fractured rock mass with subvertical fractures and sections of massive rock mass where the rockbursts happened.

Between the metric point 4502 and the metric point 4545 (from the French portal), at proximity of the summit Mont Blanc du Tacul (alt: 4400 m), the rockburts were very violent. In the geological report of the Bureau de Recherches Géologiques et Minières, J. Gutefin gave the following description :

"... The initial rather massive appearance of the rock mass has entirely changed during the three or four days after the blasting. It was completely modified by a strong and violent decompression. The rockbursts are very impressive.
These phenomena occur mainly on the tunnel walls at mid-height. The rock is extremely distorted, spalled, broken in every direction. The rock bursts violently in wide plates or is decompressed in unbonded slabs..."

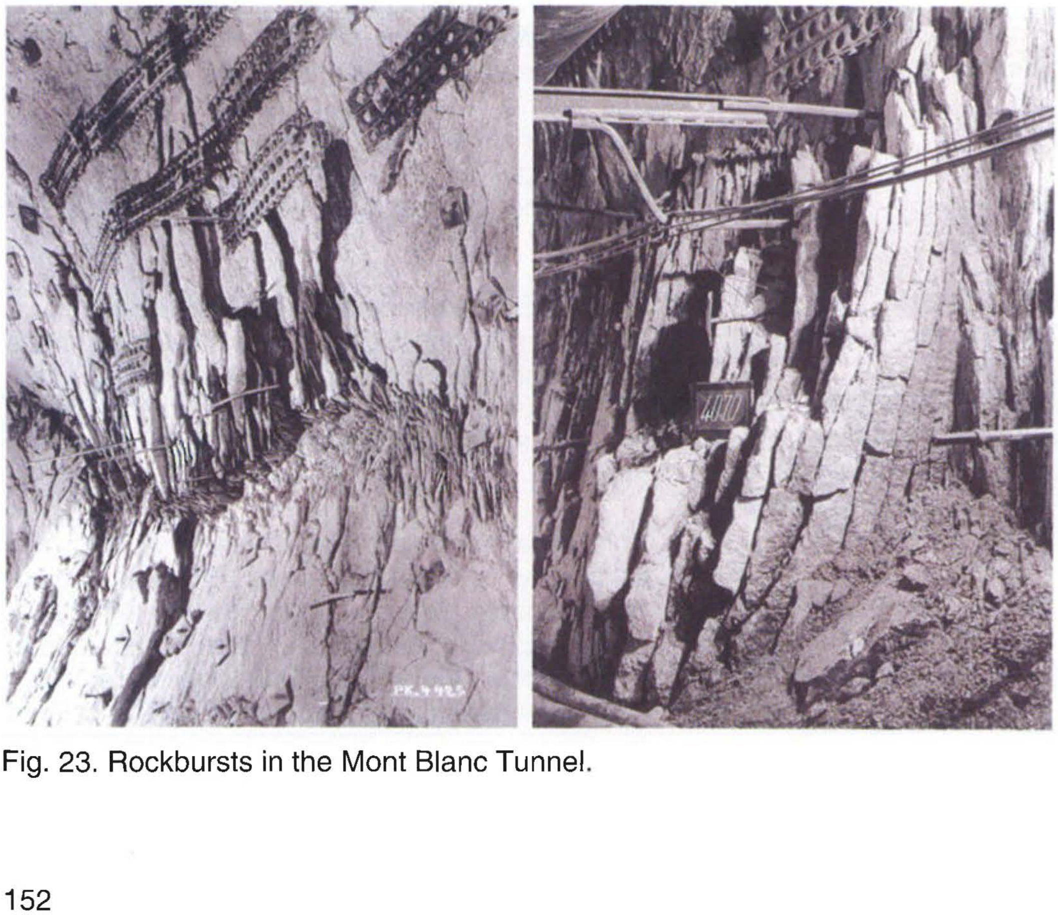

Fig. 23. Rockbursts in the Mont Blanc Tunnel.

In some sections where the natural state of stress was the highest, some rockbursts occurred on the face of the tunnel and it was necessary to install some rockbolts at the face before drilling the next blast round.
For a long time, it was assumed that rockbursting happened when the tangential stress at the wall of the opening was close to the uniaxial compressive strength. More and more available data pointed out that slabbing may occur around underground openings for stress level smaller than the uniaxial compressive strength. The more recent studies on brittle failures around tunnels were carried out to analyze the classical "dog's ears" failures observed in the experimental gallery for the storage of radioactive waste in Canada (Mine-by tunnel of the Underground Research Laboratory at Pinawa in Manitoba).

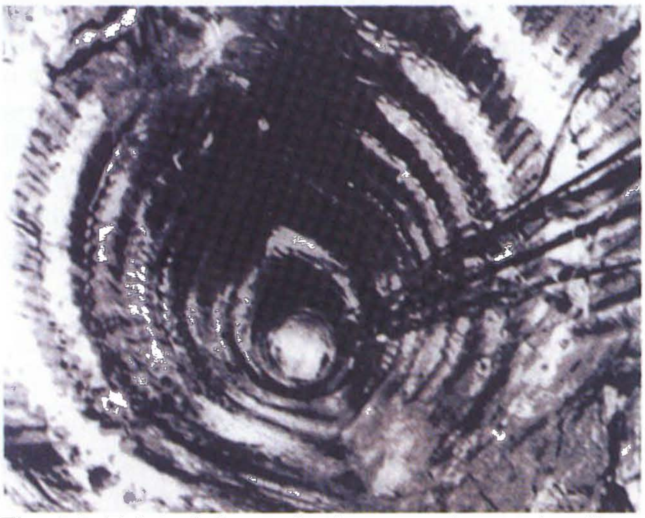

Fig. 24. Brittle failures in the experimental gallery of URL (Canada).

The process of rupture of a brittle rock begins at a low level of stress. The damage may be detected by a non linearity of the volume strain or by acoustic emission. For brittle rocks like granite, the crack initiation appears for deviatoric stress equal to one third to one half of the maximum deviatoric stress (the unconfined compressive strength in a uniaxial compression test). When this threshold damage is exceeded, crack coalescence leads to axial splitting with fractures parallel to the maximum parallel stress, if the confinement is low, $\sigma_1/\sigma_3 > 10$. When the confinement is higher, it leads to a macro-scale shear failure.
The localization and the shape of the failures were reproduced in a very satisfactory manner by the particle flow code PFC developped by Cundall or by damage model in a finite element code. However, all these models are still unable to predict the unstable character of the failure.

7. Future Projects - how to reduce the Geotechnical Hazards

An important network of high-speed railway lines is being built in Europe. The construction of this system will lead to a new generation of tunnels between Alpine countries. To limit the grade of the lines, the portals of theses tunnels lie at a lower altitude than the older ones. Then, they are longer and have a larger overburden. They are called Alpine base tunnels.

The largest present projects are :

- The AlpTransit Lötschberg Tunnel on the line Bern-Milano (43 km long),
- The AlpTransit Gotthard Tunnel on the line Zurich-Milano (57 km long),
- The AlpeTunnel on the line Lyon-Torino (50 km long),
- The Brenner Tunnel on the line Innsbrück-Verona (60 km long).

All these tunnels intersect several of the tectonically complex units of the Alpine mountain chain and are likely to meet every type of geotechnical hazards described above. The feasibility and design studies aimed at the selection of the most suitable routes to limit these hazards. They have been investigated by all the more pertinent techniques considering the unfavourable in situ conditions met the most often : intense geological mapping, structural analysis based on aerial photographs and satellites images, geophysical surveys, vertical or inclined boreholes, some adits. One of the main purpose of these investigations are to detect at depth, the contact zones between the geological units, the main faults and discontinuities in the geological structures, the waterbearing fractured and cohesionless rocks, the high-stressed zones.

From the preliminary study of the Gotthard Base Tunnel, the Piora Zone appeared as a major hazard. This zone consists of a sedimentary sequence of anhydrite and dolomite.

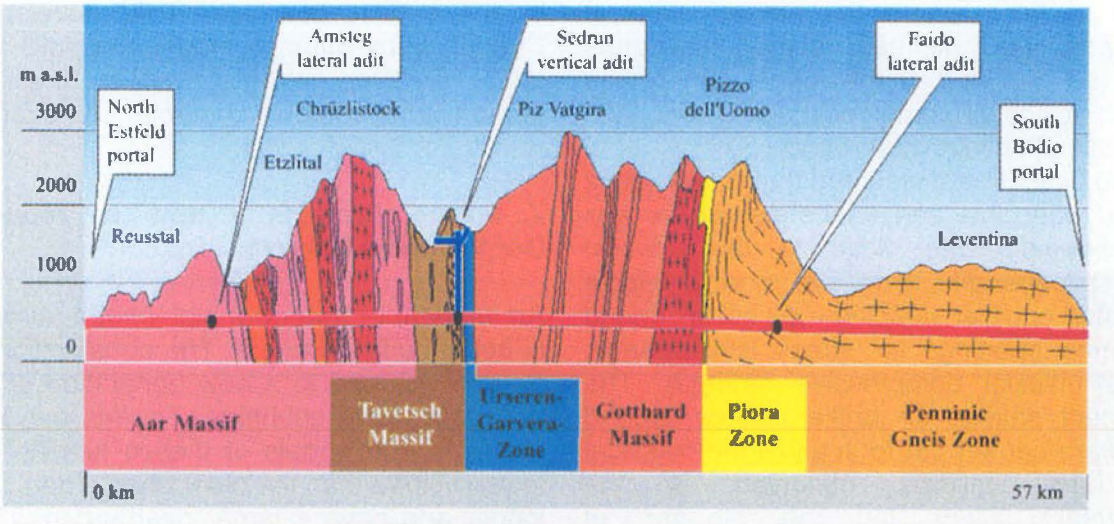

Fig. 25. Longitudinal geological profile of the Gotthard Base Tunnel (after Schneider 1999).

From surface observations and experiences in previous underground works, the rocks of the Piora Zone could have a sugar-like, cohesionless structure. Due to the water pressure which could be associated with an overburden of about 2000 m, a very large debris flow difficult to control could be anticipated.

In order to investigate this major hazard, an exploration adit was drilled, 350 m above the level of the base tunnel. Ahead of the face of the adit, systematic horizontal boreholes were carried out. During the drilling of the last borehole, a blowout which amounted to 600 l/s occurred. The water pressure was estimated to be about 12.5 MPa. A plug was concreted at the end of the adit and several horizontal and inclined boreholes were drilled to investigate the Piora Zone. They show that, at depth, the sequence was made of compact layers of dolomite and anhydrite. The transition between the cataclastic zone and the compact zone have not be defined very precisely but, fortunately, is located well above the base tunnel level.

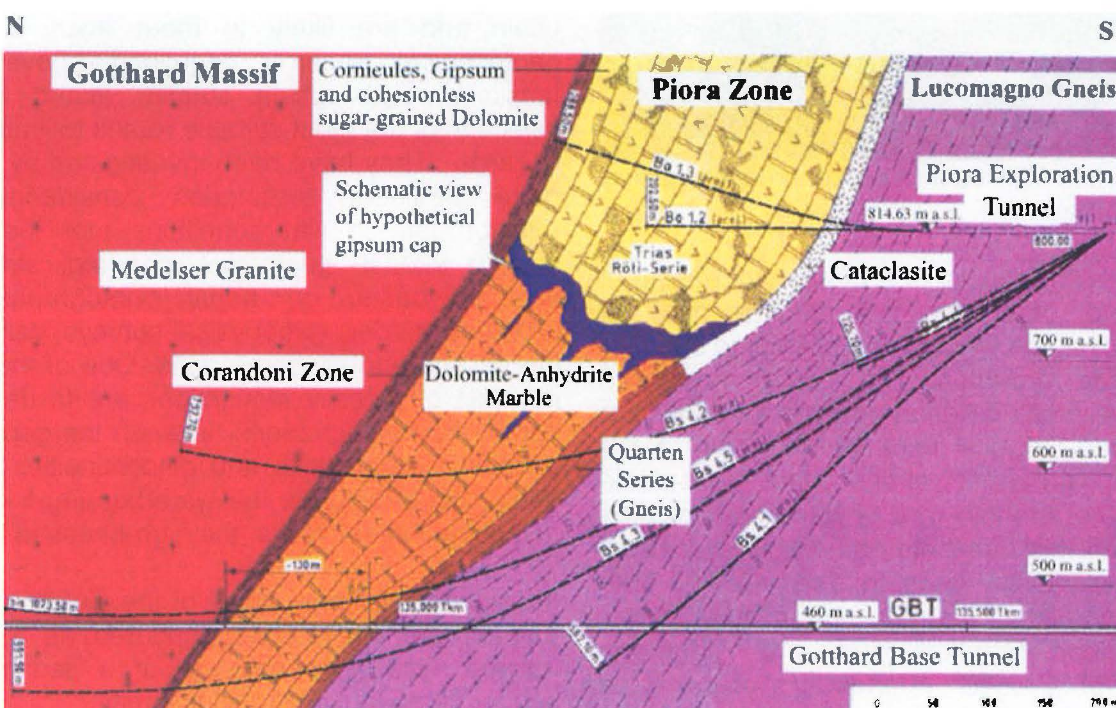

Fig. 26. Geological structure of the Piora Zone as determined by horizontal and inclined boreholes (after Schneider, 1999)

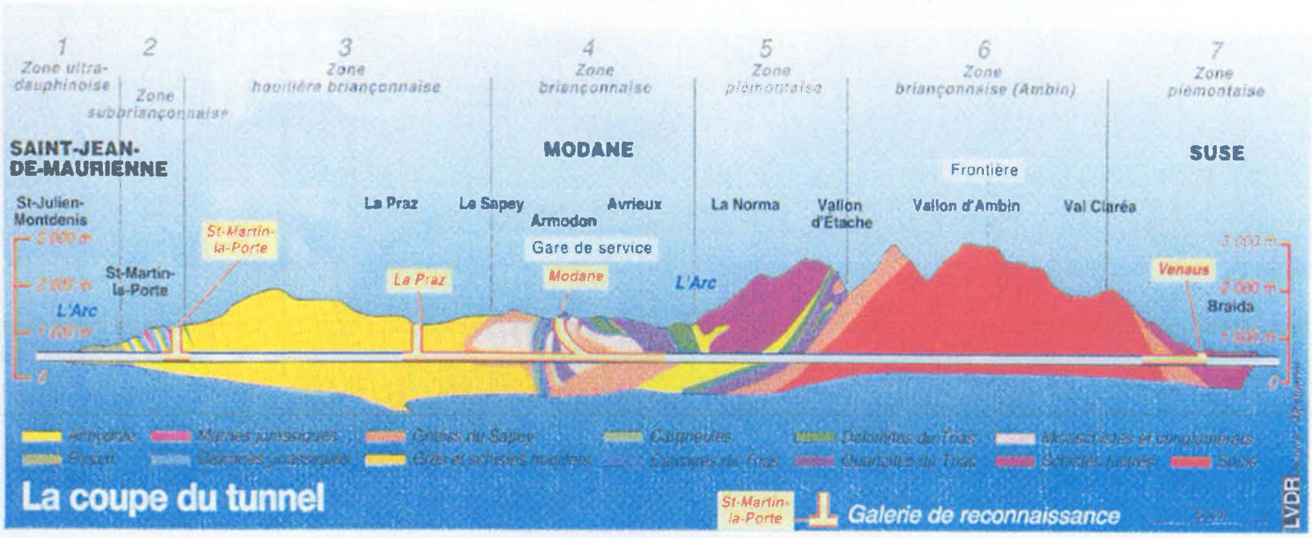

Fig. 27. Geological longitudinal profile of AlpeTunnel.

A detailed geological mapping of the Alps between the Maurienne Valley in France and the Suza Valley in Italy has allowed to draw a geological longitudinal profile of the future AlpeTunnel.
This preliminary profile emphasizes the complexity of the geological structure and all the associated uncertainties. The tunnel may intersect major geological discontinuities which may represent the main hazards for the tunnel construction : difficult ground conditions with possible water or debris flows. Several vertical or inclined boreholes were drilled to intersect and to characterize these structures. Extended reach drilling (ERD), a technique developped in oil engineering, was also used for the first time in a civil engineering project. This technique allows to deviate a vertical or inclined borehole to drill in the horizontal direction parallel to the axis of the tunnel.

The objective of the ERD Avrieux borebole was to investigate under the Arc river the contact between two major Alpine geological units : the Briançonnaise unit, and the Piemontaise calcschist overthrust with its triassic gypserous bed layer. The length of the borehole is 1822.5 m ; the first 290 m of the borehole are straight and inclined at 40° ; the build-up was made between 290 m et 867m and the last part, between 867 m and 1822.5 m, was drilled subhorizontally in the direction of the tunnel axis.

Conventionnal destructive drilling was used for the first inclined linear section down to the kick-off point where the deviation starts. The build-up section was drilled by a down-hole equipment. The deviation is, at most, 1.5° per 10 meters.The last horizontal section was mainly cored with a wire-line technique in order to recover cores of more than 47 mm diameter. The drilling started in June 1999 and finished in February 2000.

The drilling parameters were recorded. Many logs were carried out in the borehole by the following techniques : electrical logging (laterolog, induction and microresistivity) – sonic logging (sonic full wave) – nuclear logging (gamma ray and spectral gamma ray) – fluid logging (temperature, conductivity, flow-meter) – multibutton dipmeter – acoustic scanning – trajectometry by gyroscopy. Nine DST (Drill Stem Test) water tests were performed. The nature of the rocks was identified from the cores or from the cuttings. The structural data obtained from the acoustic scanning log and from the cores have been analyzed.

All the data obtained from this borehole lead to draw a modified longitudinal profile of this section of the tunnel.

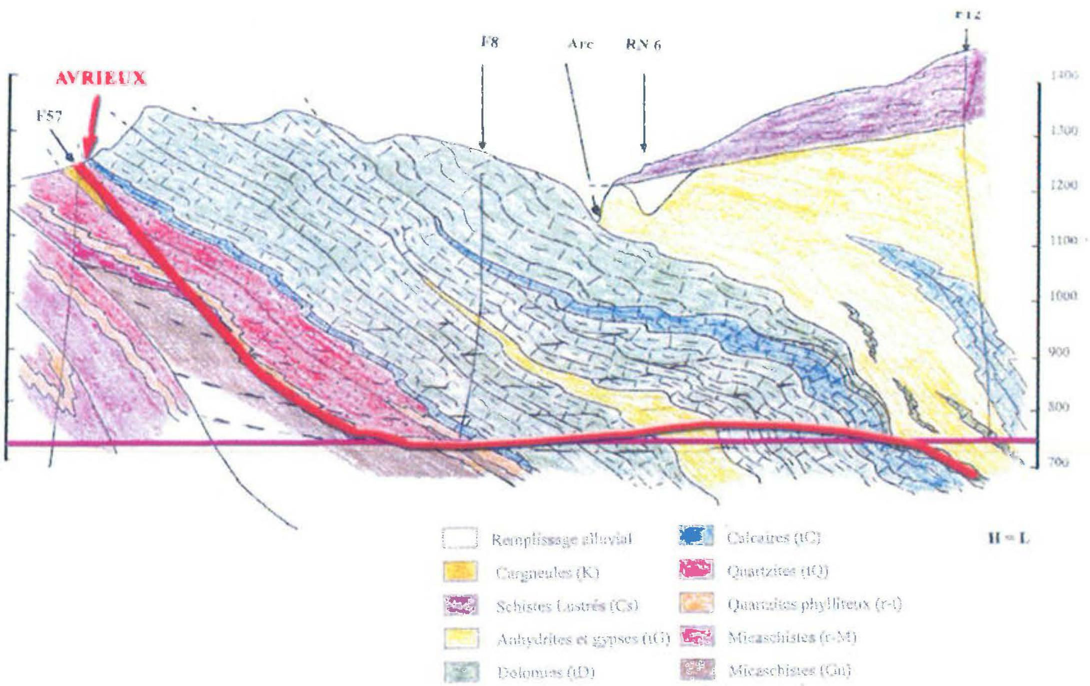

Fig. 28. AlpeTunnel. The Avrieux extended long reaching borehole.

In spite of the recent improvements in the investigation techniques at great depth, mainly transferred from the oil engineering, every Alpine tunnel project at great depth, involves a great number of geological and geotechnical uncertainties, with very large consequences on the cost and the delay of construction.

The combination of all these uncertainties bring about to consider many possible situations ; they differ from the geological longitudinal profile, the various options of construction (number and type of intermediate accesses), the methods of construction (full face, heading and bench, multi-drift), the method of excavation (drill and blast, tunneling machine, road header), the type of initial and permanent support (steel arches, bolting, shotcrete, segments, concrete lining). Methods of risk assesment have been developped to take account of all the geological, geotechnical and constructive uncertainties and analyse a large number of inferred situations.

The DAT method (Decision Aids for Tunnelling) was initiated by H.H. Einstein at the Massachussets Institute of Technology in Boston and was developped in collaboration with the Laboratory of Rock Mechanics of the Swiss Federal Institute of Technology in Lausanne. A simple law of probability is determined for all the uncertainties. Each considered situation is obtained by applying Monte-Carlo procedures. A very large number of situations are to be analysed to produce the cost-time scattergram.

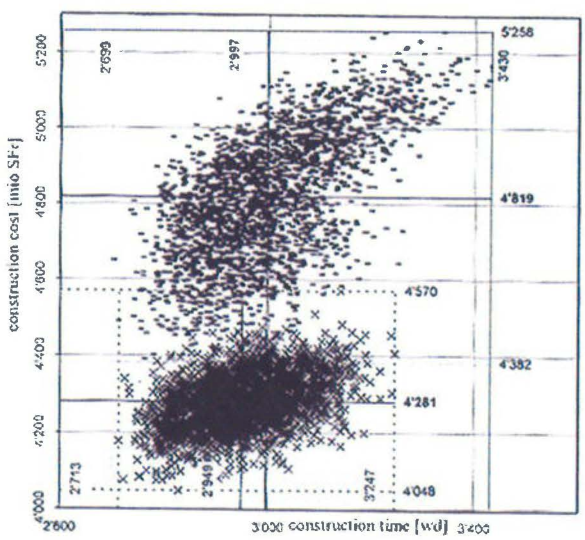

Fig. 29. Time-cost scattergrams for the Gotthard Base Tunnel.
Case "without Piora" **X**. Case "with Piora" **-**
(After J.P. Dudt, F. Descoeudres & H;H. Einstein).

The DAT method has already been used for several projects of Alpine tunnels : the Gotthard Base Tunnel, the Lötschberg Base Tunnel, The AlpeTunnel.

These methods may be considered as a new tool for geotechnicians to analyse the tunnelling projects with their everexisting uncertainties. They may also help to find better solutions to share the risks between the owner and the contractor.

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