

TUNNELLING IN SWITZERLAND: FROM LONG TRADITION TO THE LONGEST TUNNEL IN THE WORLD

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ABSTRACT

Switzerland, where the main north-south European traffic streams cross the Alps, is called up to provide adequate transportation routes. The necessity to cross the mountains originated a great tradition in tunnel construction. Since the second half of the 19th century, through several eras, very long and deep traffic tunnels have been built. They were, for a long time, the longest tunnels in the world, like the Simplon rail tunnel, 20 km, opened to traffic in 1906, the Gotthard road tunnel, 17 km, opened to traffic in 1980, as well as the longest traffic tunnel in the world so far, the Gotthard Base Tunnel, 57 km, presently under construction and scheduled for operation in 2015.

Viewing back on the long rail tunnels of the late 19th and early 20th century, the Gotthard, 15 km, the Simplon, 20 km and the Lötschberg, 14,6 km, we recall some interesting aspects of the related excavation techniques and the use of equipment and manpower.

During the early 60ties the first generation of the important alpine road tunnels has been realized (Grand St. Bernard, 5,8 km, San Bernardino, 6,6 km), during the same time as the Mont Blanc Tunnel (11,6 km) in the West, between France and Italy. They were followed, 15 years later, by the classical highway tunnels along the main north-south highway route, the Seelisberg Tunnel (double tube of 9,3 km each) and the Gotthard Tunnel (17 km), both opened to traffic in 1980. Within the same period road tunnels with similar dimensions were built in the neighboring countries, such as the Fréjus Tunnel between France and Italy (12 km) and the Arlbergtunnel in Austria (14 km).

Since more and more people and goods are crossing the Alps, Swiss government decided in 1995 to create the new alpine Transverse with two flat high speed rail lines, in order to upgrade the existing mountain rail lines and to provide a highly performing and modern passenger and freight link within the new European rail system. The two related main tunnels, namely the 34,6 km long Lötschberg Base Tunnel and the 57 km long Gotthard Base Tunnel, are at present both under construction. Whereas the excavation works in the Lötschberg are entirely finished and the tunnel will be opened to traffic by 2007, the works in the Gotthard are about half way. In the overview of these two impressive works, one notes the particular aspects related to their extraordinary dimensions, as well as the headings through the geologically difficult zones with high overburden.

In the conclusion some typical approaches are summarized to specific problems that arise in alpine tunneling. Appropriate solutions depend on a proper technical knowledge and a careful and wide-sighted design. It is a challenge for tunnel engineers to move on the development of the essential technical aspects of tunneling, that has already last for 150 years, such as excavation and support techniques, starting with the first use of dynamite in the Gotthard tunnel in 1872, up to the application of modern TBM installations on the presently running sites in the Gotthard Base tunnel.

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INTRODUCTION

Not like the beautiful island of Taiwan, Switzerland is an inland, about the same size and not less admirable, but situated in the middle of the European continent. In one particular aspect, Switzerland can also be defined as an island: It is surrounded by the countries of the European Union, of which it is not a member. Nevertheless this fact does not relieve the country to provide adequate transportation routes in order to meet the need for the increasing traffic streams through Europe, mainly the north south route. What the two countries have in common are the mountains and the variable geological composition of the underground. These are two essential points that make both countries especially interesting for tunnelling engineers.

REVIEW ON THE MAIN PIONEER WORKS OF THE LATE 19TH CENTURY

The economic development at the beginning of the 18th century created also the need for better transportation across the Alps. This was only possible by means of tunnels. The first known example for a road tunnel in the Alps is the so-called "Urnerloch" near Andermatt (Fig. 1). It has been constructed in the year 1707 by Pietro Moretti of Cerentino and allowed to substitute the formerly existing dangerous chain-bridge across the gorge of the Schöllenen. Some say that it is the first road tunnel in Europe, if not to say worldwide. Even if this may appear as an exaggeration, it certainly is the first traffic tunnel in the Gotthard region.

A century later began the era of the railways, with the realization of tunnels with so far unreached dimensions.



Fig. 1: The "Urnerloch", 1707, the first traffic tunnel in the Gotthard region.

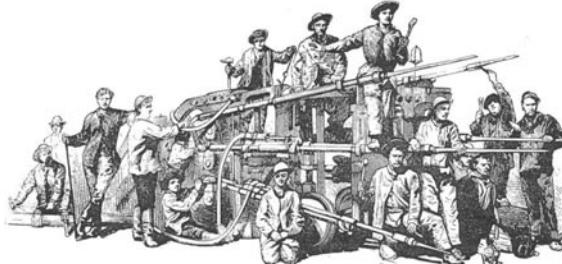


Fig. 2: Tunnel drilling machine at the Gotthard rail tunnel (1873).

The two main rail tunnels of this epoch are the Gotthard tunnel, with a length of 15 km and a total of about 30 additional tunnels, respectively another 11 km of tunnels along its northern and the southern access lines. The main tunnel works took place between 1872 and 1882, some years later than those of the Fréjus tunnel between France and Italy. These works initiated an enormous progress in technology, as the systematic use of explosives and the mechanical drilling of the holes for blasting. By that time drilling by compressed air has been invented, followed by the mounting of the drilling machine on carriages (Fig. 2), as predecessors of the later jumbos.

Compared to subsequent works, like the Gotthard road tunnel, and nowadays tunnel works, like the AlpTransit scheme, the overall construction time of the old Gotthard rail tunnel, which has been attacked from the two portals only, was not so long. On the other side the construction at that time required a great number of manpower, up to 2000 at each portal, and also an consecutive high amount of fatalities, 177 in total. It is obvious that in the meantime the safety in tunnel construction has radically increased. The fatality rate has been cut down to a tenth by the construction of the Gotthard road tunnel in the seventies, whereas current tunnel sites, like AlpTransit, tendentially present even a better safety record than comparable general construction works above ground.

Switzerland's second big alpine tunnel of that generation, the Simplon tunnel, has been constructed 20 years later. Opened in 1906, it was the longest railway tunnel of the world for more than 80 years, until the opening of the Seikan tunnel. The Simplon tunnel still holds a primateship because of its high overburden, which reaches up to 2200 m. During the works, many struggles related to the difficult conditions during excavation had to be overcome. The classical excavation method in difficult rock was characterized by various stages of headings in the cross

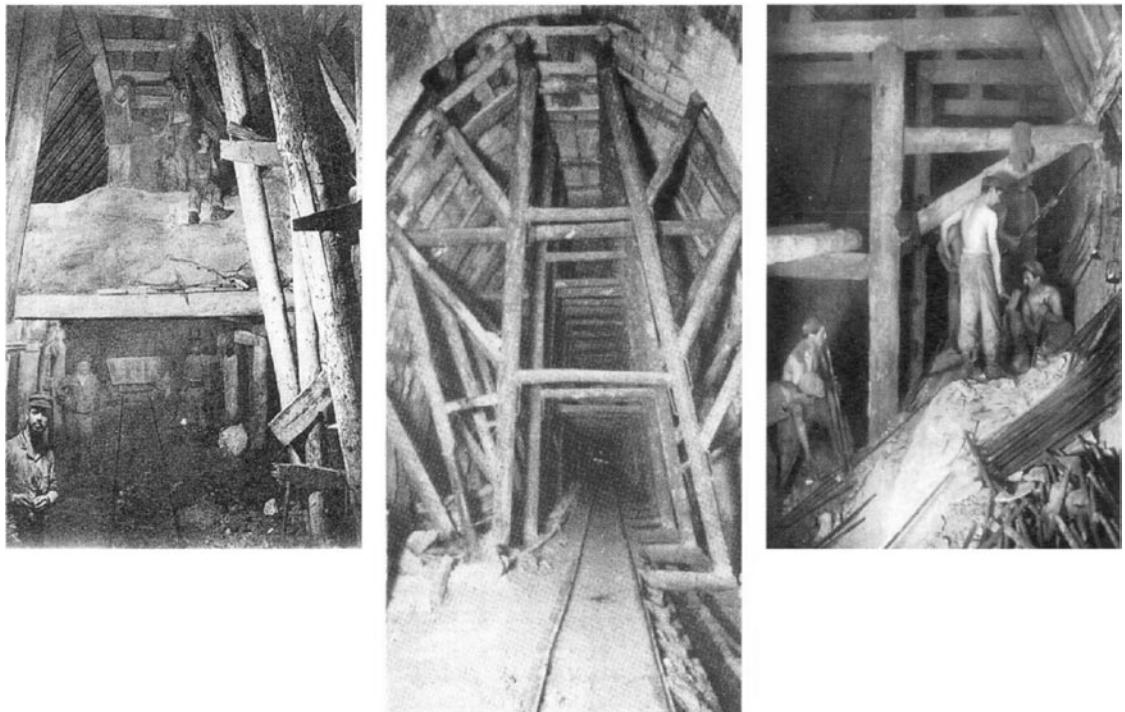


Fig. 3: Timbering in the tunnel.

section, using abundant timber support (Fig. 3). This kind of support, that offered evident advantages due to its yielding behavior, was common up to the first half of the 20th century.

The main difficulties derived from the sectors with squeezing rock and other sectors of the tunnel with heavy water inflow, up to 200 liters per second in the pilot heading. All these problems have lead to further technical innovations, like the measures to fight against high rock temperatures, which climbed up to more than 50 °C for a great part of the tunnel, reaching a maximum of 56 °C. A cooling system that was very advanced for that time, has been installed, spraying water for evaporation by fine valves for evaporation. But also outside the tunnel the works brought important innovations, like the realization of a proper hydraulic power production plant, to supply electric energy for moving the various machines. Another achievement of that time has been the development of an extended triangulation system on the surface, as a base for the underground surveying works.

In the period between 1940 and 1970 numerous water power plants in the Alps have been planned and constructed. For their realization a large number of water galleries and underground powerhouses were necessary. The usual cross section of water tunnels seldom exceeds 30 m², but many of them reach up far more than 10 km in length. At present there is a total length of 800 km of water tunnels in the Swiss Alps, apart from other related underground works like access galleries, power caverns



Fig. 4: Gotthard road tunnel; starting excavation in 1970.

THE FURTHER ERAS OF DEVELOPMENT

Water Tunnels for Hydroelectric Plants

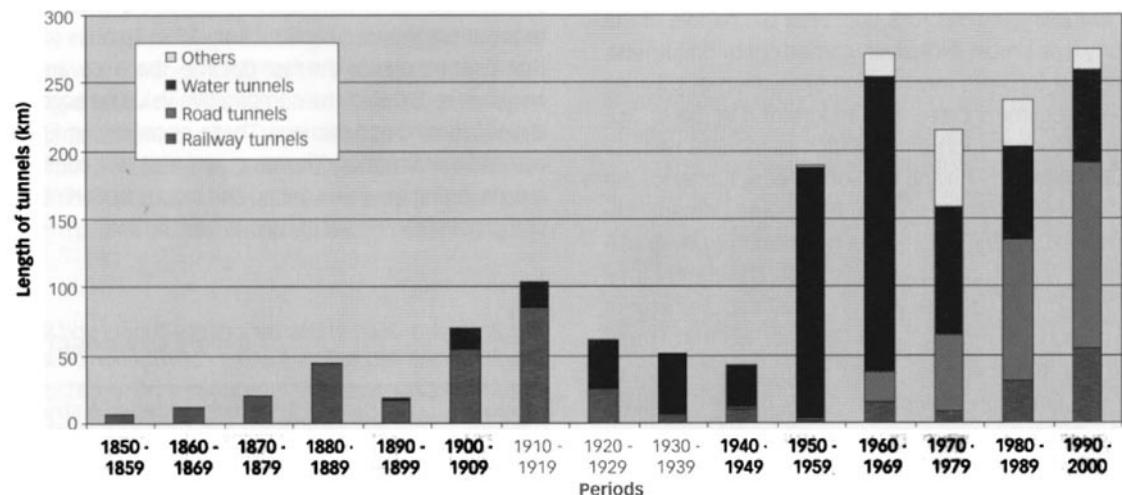


Fig. 5: Total length of the tunnels and galleries, classified according to categories and decade of opening.

and surge chambers.

Highways Through the Mountains

In the second half of the last century, the construction of highway tunnels for the National Highway Network assumed a great importance. Today, 90% of this highway system, which sums up a total of 1850 km, is in operation. The large part of it are highways with four or more lanes. There are 257 tunnels, which make up 15% of the total length of the highway system. Obviously the great percentage of tunnels is due to the mountainous shape of the terrain. On the other hand more and more, the tunnels became necessary because of the dense land occupation, where urban and suburban highways have to be built, whereas new tunnels arise nearly exclusively because of environment considerations.

On a chronological review one can define three groups of the classical Swiss mountain tunnels:

- * The era of the first generation of alpine road tunnels, constructed and opened to traffic in the sixties: apart from some smaller tunnels, we mention the tunnel of the Gd. St. Bernard (5,8 km) in the West, and the namesake San Bernardino tunnel (6,6 km) in the East. Both tunnels are single tubes and can look back on a long period of successful operation. Actually works are carried out for their upgrading.

- * The second group consists of the tunnels in the Swiss-German Jura region, mainly for the connection between the German und French highways in the

north with the Swiss plateau, across the Jura range. The three representative works are the Belchen, the Arisdorf and the Baregg tunnel, all opened to traffic in the year of 1970. They are of medium length, between 1,1 and 3,2 km, but built with twin tubes for an elevated traffic capacity.

- * Ten years later (1980), along the north-south highway through the Alps, the two main tunnels have been opened to traffic: The Gotthard tunnel with 17 km in length (Fig. 4) and the Seelisberg tunnel with 9,3 km. The Gotthard tunnel, at 1100 m above sea level, is the culmination of the transit axis, whereas the Seelisberg forms a direct line along the northern access, parallel to the lake of Lucerne. Both tunnels have a remarkable 25 years old traffic record, and this in terms of capacity as well as in terms of security and operation economy. The Gotthard road tunnel, where 132 Mio vehicles have passed so far, still holds the worldwide championship in length. Thanks to the continuous parallel safety gallery, that has proved its important function at several occasions, the Gotthard road tunnel has an excellent safety reputation. However, increasing traffic and heavy use increase the risk for troubles or even unforeseen interruptions; therefore the political decision to complete the tunnel with a second tube should not be withheld much longer.

Many more mountain tunnels have been realized since then, mainly those along and across the Jura mountain range in the north-west of the country and others on the access ways north and south of the Alps. Today new long alpine crossing road tunnels are not planned and are even

banned by a law, introduced upon popular vote.

Road Tunnels for Decongestion of Urban Areas

During the last 20 years tunnel construction was focused in and around the urban areas. The first big tunnels have been built in the Zurich region (Gubrist, Milchbuck, opened in 1985), followed by tunnels in other towns (St. Gallen, 1987 and Neuchâtel, 1990). As already mentioned tunnels are more and more built, not to overcome natural obstacles, but to meet the request for better protection of landscapes, as well as the protection against noise and pollution. Therefore we find new tunnels in the Swiss plateau where urban spread opposes to new open highways.

Underground Solutions for Special Purposes

Beside the transportation tunnels for water and traffic, we can make out underground solutions for many other purposes, like wine cellars, churches, car parks, shooting stands and various kind of laboratories. A relatively unknown but considerable asset of underground infrastructure belongs to the army, starting from ancient fortresses to the more recent armed defense systems, up to the protected headquarters, reservoirs and store caverns.

However, the most remarkable special underground project is the particle acceleration ring at the CERN (European Center of Nuclear Research), near Geneva. It consists of different circuits of galleries and a rough dozen of test caverns along the galleries. The first test rings have been initiated in 1960 by the cut and cover method, followed by the underground SPS system with a total length of 7 km and 4 points with shafts and caverns. The latest generation, the LEP/LHC project, is a circular system of galleries, with a circumference of 27 km. Along the ring there are 8 points with extended shafts and caverns. The main gallery is embedded in the Leman Molassic basin, a type of rock, which made it favorable for TBM headings. However, some 4 km of the scheme are situated in the limestones of the Jura range. This part was very delicate to carry out, by means of drill and blast headings, under steady risk of violent water inflow from karstic voids.

Summarizing from the Past to the Present

To summarize the development of Swiss tunnelling

during the last 150 years, it is interesting to have a look at the statistics of Fig. 5. showing the overall tunnel "production" in the different fields:

- * The classical alpine rail tunnels (1880 – 1920)
- * The water tunnels of the hydro-electrical schemes (1950 – 1975)
- * The highway tunnels (from 1975)
- * The new rail tunnels (from 1990).

The total length of existing Swiss traffic tunnels, including road, Federal and private small track rail ways, amounts to about 550 km. Since the highway system approaches to its completion, the overall percentage of rail tunnels will clearly increase in the next future.

THE NEW CHALLENGE: ALPTRANSIT, A HIGH SPEED NET THROUGH THE ALPS

Beside the growing high-speed rail system, called Rail 2000, which contains important new tunnels in the Swiss midland, the existing transalpine rail routes through Switzerland no longer meet the requirements of ever-increasing rail-traffic between north and south. The actual rail routes are in fact mountain railways: the northern and the southern access ramps of the Gotthard – with a maximum speed of 80 km/h and with a maximum decline of up to 2.2% - climb up to about 1,100 m a.s.l., where the old Gotthard rail tunnel is located, approximately 900 m higher than the city of Milan.

The Swiss government has decided to create the new alpine Transverse with two rail lines (Fig. 6). The Swiss population did confirm this decision and with his vote, expressed their will in favor of transferring transit traffic from road to rail, and gave the required authorization to deliberate the money for this important investment.



Fig. 6: New transalpine rail routes through Switzerland.

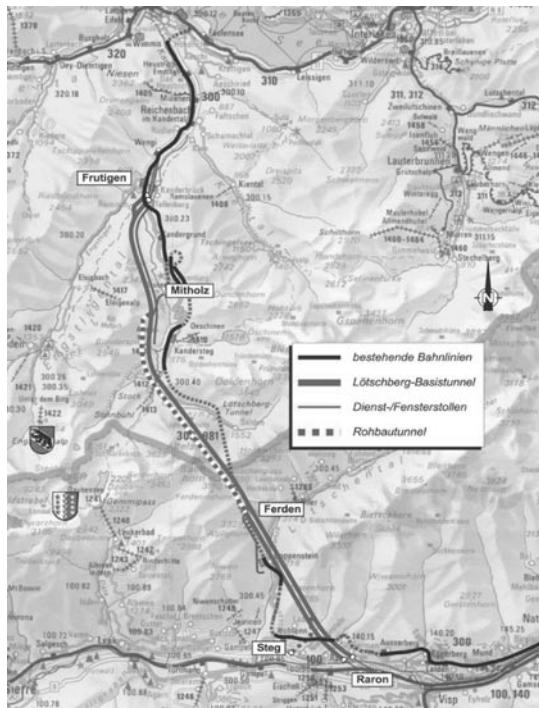


Figure 7: Situation Lötschberg Basetunnel.

The first line to be built is the Lötschberg, crossing the Alps in the West, between Berne and Raron in the Valais and forming the connection to Milan, together with the existing Simplon tunnel. The base tunnel is 34,6 km long and is located at a height between 660 m and 830 m (Fig. 7). It is designed as a double tube tunnel, but at first will partially be operated with a single track.

At the time, the excavation works, which have been carried out from the two portals as well as from two intermediate attacks, are entirely finished and concrete works for the inner lining are going to completion (Fig. 8). Installation of rail equipment and electro-mechanical parts are under way, so that the tunnel can be opened to traffic by the end of the year 2007.

The other transalpine rail route "Gotthard" will rely the city of Zurich with the city of Milan, interesting a catchment's area of over 20 million people in Germany, Switzerland and Italy.

Shorter traveling times – an hour less between Zurich and Milan, for example – will mean that rail travel across the Alps will be able to compete with flying and permit to optimize connections.

The AlpTransit Gotthard line requires the realization of three important tunnels: the Ceneri Base Tunnel in the

southern part (15 km long), the Zimmerberg Base Tunnel in the northern section (total length 20 km) and the Gotthard Base Tunnel in the heart of the project (57 km).

THE GOTTHARD BASE TUNNEL

The most impressive part of the new traffic route through the Alps is the Base tunnel under the Gotthard, which is planned to handle mixed traffic, that is high speed passenger trains (up to 250 km/h) as well as slower freight trains (up to 160 km/h). Once complete and operating, the Gotthard base tunnel will be the longest tunnel in the world. It will run through the Alps at approx. 500-550 meters above sea level. Its highest overburden will be approx. 2'300 m. With a minimum Radius in curves of 5,000 m and with a maximum slope of 0.70% the Gotthard base tunnel will be the first flat railway trough the Alps.

Overview of the Tunnel Design

The base tunnel stretches from Erstfeld in the north to Bodio in the south (see Fig. 9). It consists of two parallel single-track tubes with a diameter varying from 9.0 up to 9.5, which are linked by cross-passages every 300 meters. At two positions, one-third and two-thirds along the base tunnel, are located multifunction stations for the diversion of trains via the crossovers to the other tube, for the installation of electro-mechanical installations, and for the stop of trains and the evacuation of passengers in an emergency case.

Detailed and sophisticated evaluation demonstrated that this tunnel system was the most suitable for long alpine tunnels. To shorten construction time and for ventilation purposes, the tunnel will be driven from several sites simultaneously. To this end, the tunnel has been divided into five sections.



Fig. 8: Lötschberg Basis Tunnel, the inner lining will be finished soon.

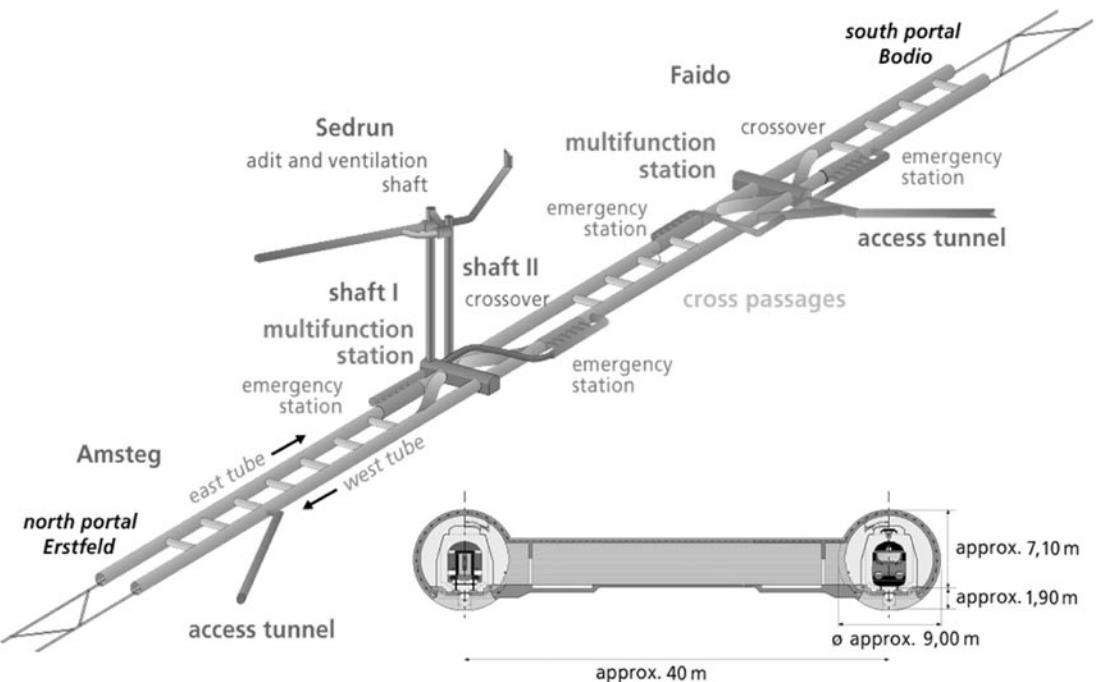


Fig. 9: Scheme of the tunnel-system.

Excavation will take place from the portals as well as from three intermediate attacks in Amsteg, Sedrun and Faido.

Facing the Geological Conditions

From north to south, the 57 km long Gotthard Base Tunnel passes through mostly crystalline rock, the massifs which are divided by sedimentary tectonic zones. The 3 crystalline rock sections are the Aar-massif in the north, the Gotthard massif in the middle and the Pennine gneiss zone in the south (see Fig. 10). These zones are unlikely to cause any major technical difficulties during construction and, apart from their extreme hardness, they are quite favorable for tunneling. They consist mainly of very strong igneous and metamorphic rock with high strength. More than 90% of the total tunnel length consists of this type of rock. The main danger is the risk of rock burst caused by the high overburden, the instability of rock wedges and water inflow.

One criteria during the initial planning phases focused on the choice of an alignment, which allows cutting through the different fractured and sedimentary zones at their narrowest points and not under excessive overburden wherever possible. The high mountain overburden of up

to 2,300 m, and more than 1500 m over 20 km of tunnel length, had to be taken into consideration in deciding the heading concept and the rock support design. It means also, that operating temperatures in the tunnel can reach 35-40 C. In order to maintain the required air conditions in the different working areas, a continuous cooling system is required.

Main Tunnel by TBM

In the crystalline massifs the parallel main tubes are

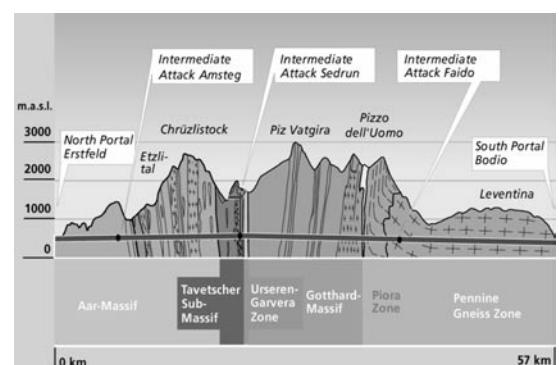


Fig. 10: Geology of the Gotthard Base Tunnel.



Fig. 11: Tunnel Amsteg, east tube, TBM cutter-head.



Fig. 12: Tunnel Bodio, installation of the TBM in an underground chamber.

driven by TBM. In the sectors of Bodio in the South and in Amsteg in the North (Fig. 11), the TBM drives have already passed more than half way of their 17 km, respectively 15 km long trip. Other TBM headings will follow: the one from the North portal at Erstfeld and the continuation of the South drive restarting from the multifunctional station of Faido.

The TBM's, with excavating diameters ranging between 8.8 m and 9.6 m, are open hard rock machines with a short finger shield. They have been installed in underground chambers (Fig. 12). Performances in average rock conditions vary between 17 and 22 m per working day.

Both drives have encountered some fault zones: In

Amsteg the predicted Intschi fault has been successfully penetrated and overcome. On the other hand, the Bodio drive met an unpredicted flat lying fault zone, which followed the tunnel tubes for more than 500 m in the eastern and some 60 m in the western tube. The penetration of this fault caused great overbreak and required extensive rock support right above the shield. The average heading rate in the fault zone was approximately 2.45 m per day.

Conventional Tunnelling for Intermediate Attacks, Multifunctional Stations and Sedrun Sector

The access works and the multifunctional stations in Sedrun and Faido have been excavated by drilling and blasting. In Sedrun, which is the most complicated section of the base tunnel, for logistical and geological reasons, the adit (1 km), the inclined ventilation shaft (450 m), the cavern at the top of the first shaft and the 835 m-deep vertical access shaft have been completed in several preparatory construction lots. The entire logistic supply for the heading of a total tunnel length of 2 x 6.8 km (4 simultaneous tunnel drives, together with other minor drives) has to be done through the access tunnel and the double shaft system.

At the beginning of this year the most difficult section of the new tunnel, the so called (old crystalline) Tavetsch intermediate sub-massif in the Sedrun stretch has been reached. This steeply inclined, sandwich-like sequence of soft and hard rock, which consists of phyllites and shales, is located between the Aar-massif and the Gotthard massif. According to the calculated results, based on previous investigations by means of long exploration drillings (Fig. 13), one expects to deal with radial deformations of up to 70 cm. Intensive support with steel arches, anchoring and face support are necessary. With a minimum distance between each double steel ring of only 0.33 m, the ultimate

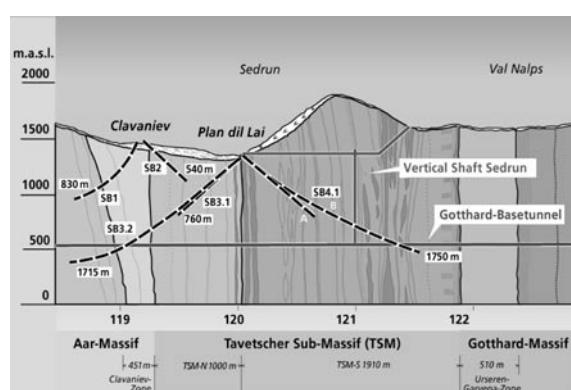


Fig. 13: Investigations in the Sedrun section.

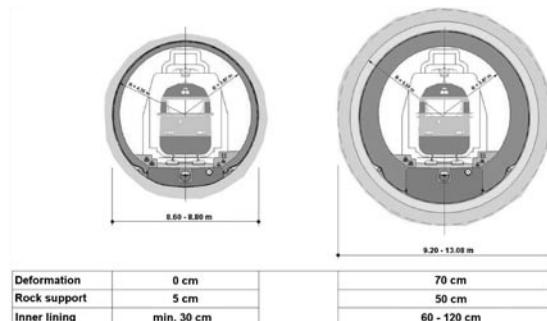


Fig. 14: Tunnel Sedrun, variable cross sections.

expected resistance of the support of the strongest cross section (including rock bolts) will hold back a rock mass pressure of about 1.80 MPa. The final support concept is based on a combination between a controlled yielding primary support and a resistant final concrete lining.

Obviously, under these severe conditions, the cross section of the single tubes increases from about 80 square meters in normal conditions up to more than 130 square meters (see Fig. 14) and the daily advancement rate falls down to 80 cm.

In the Faido section, the Piora syncline, which is another sedimentary cone reaching as deep as the base tunnel, has been deeply investigated in the second part of the nineties. It has been found, that the rock at tunnel level is formed by hard and dry dolomite, whereas 200 meters above the tunnel, the same geological formation consists of sugar grained dolomite, mixed with water under high pressure (up to 100 bars). In that way the Piora investigation system, as complex and expensive it was, allowed to optimize the design and the alignment, and above all it allowed confirming the feasibility of the tunnel as a whole.

The multifunctional station at the base of the inclined, 2,7 km long access gallery of Faido was planned according to the geological prediction in favorable rock conditions.

Totally unexpected, in summer 2002 an intensive fault system has been met. It passes through the large caverns of the multifunctional station at a very acute angle. An intensive investigation program was carried out to define the best place for the huge cross over caverns with cross sections up to 260 square meters – and that with an overburden of nearly 1,500 m. As a result of these investigations it was possible to adapt the layout of the multifunctional station and to place the large caverns in better rock conditions in the southern part. To the present,

about 6.7 km of tunnels and galleries and two cross over caverns have been successfully excavated.

The northern headings in the single track tubes had to be driven within the fault zone and required very intensive rock support. The yielding steel support has proved to be a good system in these rock conditions, where more than 40 cm of radial deformations have occurred.

Current State of Construction Works

Work on the Gotthard Base tunnel has been proceeding for many years, e.g. in Sedrun work has been in progress since 1996. On the other hand, in July 2004 the last construction site, the one at the northern portal of Erstfeld, has been opened, followed by the preparation works, before proceeding for the main work on the tunnel. Actually in all construction sites (portals and intermediate attacks) the works for the base tunnel are proceeding. Up to March 2005, about 60 km of tunnels and galleries or nearly 40% of the entire project (153.3 km) have been excavated. These are shown in red and green on the 3-dimensional picture in Fig. 15.

According to the progress made in the different sections, the actual overall time schedule shows that the excavation works of the tunnel will be finished in March 2010 and the first train will run through the Gotthard Base Tunnel in mid 2015.

SOME SIGNIFICANT FEATURES OF LONG AND DEEP TUNNELS AND THEIR APPROACH

In this final part three typical and significant aspects of long tunnelling in the Alps are briefly exposed. They deal with exploration, tunnel concept and optimization. There are of course many other interesting features, specific to long tunnels, like the special criteria for the size and the shape of the cross profile, the peculiarities of rock mechanics with high overburden, the dealing with elevated rock temperatures and all the problems related to the management of big tunnel sites. Furthermore the approach to the safety precautions has to be done in a much profounder way for the long tunnels, somehow parallel to the increasing general consciousness in that matter.

Geological and Hydrological Exploration

It is obvious, that for long and deep tunnels, explorations from the surface are limited. Time and cost for deep

Gotthard - Basetunnel

State of excavation, March 2005

- excavation and lining accomplished
- already excavated tunnels
- tunnels still to be excavated

Of the total of 153.3 km of access passages, shafts and main tunnels 59.7 km or 38.9 % have already been excavated.

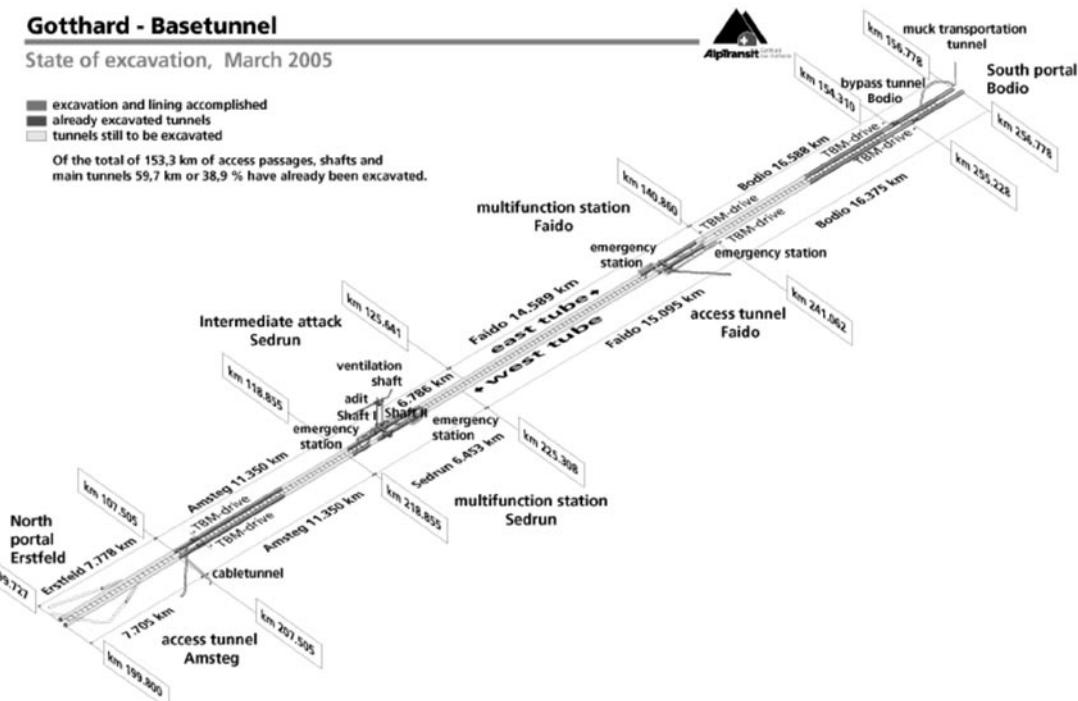


Fig. 15: State of works

investigations have to be compared with the desired degree of reducing uncertainty about the geological risks. Since there is a great number of variable and individual factors involved, this problem has to be solved for every singular long tunnel in its own way.

For the example of the Gotthard base tunnel, a first positive fact for geological forecast was, that the underground in the interesting area is already quite well known from a great number of existing tunnel works, whenever not at the desired depth, like rail tunnels, road tunnels, water tunnels and underground military works. Another advantage is the generally subvertical position of the geological formations. It allows easier extrapolation to the tunnel level. On the other side the main risk factors were, and still are to a certain extent, the unknown behavior of the deep sedimentary submassifs, the Tavetsch massif and the Piora syncline, situated north and south of the central Gotthard massif. In both zones really difficult rock has been forecasted, deep under the surface. Therefore, beside the usual and current investigations near the portals, deep investigations by means of drillings have been carried out in Sedrun, where the tunnel lies 1000 m under the surface. The Piora has been explored by means of an

exploration gallery, situated 300 m higher than the future tunnel, and subsequent long drillings down to the tunnel level (Fig. 16).

Since especially in long tunnels the uncertainties cannot be sufficiently reduced with explorations from the surface, successful tunnelling relies on advanced probings from the current headings and the preparation (in terms of technical design as well as from the contractual point of view) of adequate procedures to react to unforeseen situations. This concept is successfully applied at different sectors of the Gotthard base tunnel (Fig. 17).

How to Match the Time Factor: Intermediate Attacks and Excavation Method

We know that long and deep tunnels are not just single tubes from one point to another; they are systems, composed by parallel tubes, safety galleries, access adits, shafts, cross-over caverns, cross connection galleries, ventilation galleries and underground equipment rooms. This multitude of single project elements are linked with each other and the execution sequence has a high degree of interdependence.

For a long tunnel, which is driven from different points, the

Profil durch die Piora-Mulde Azimut (15° N - 195° S) mit projizierten Sondierbohrungen

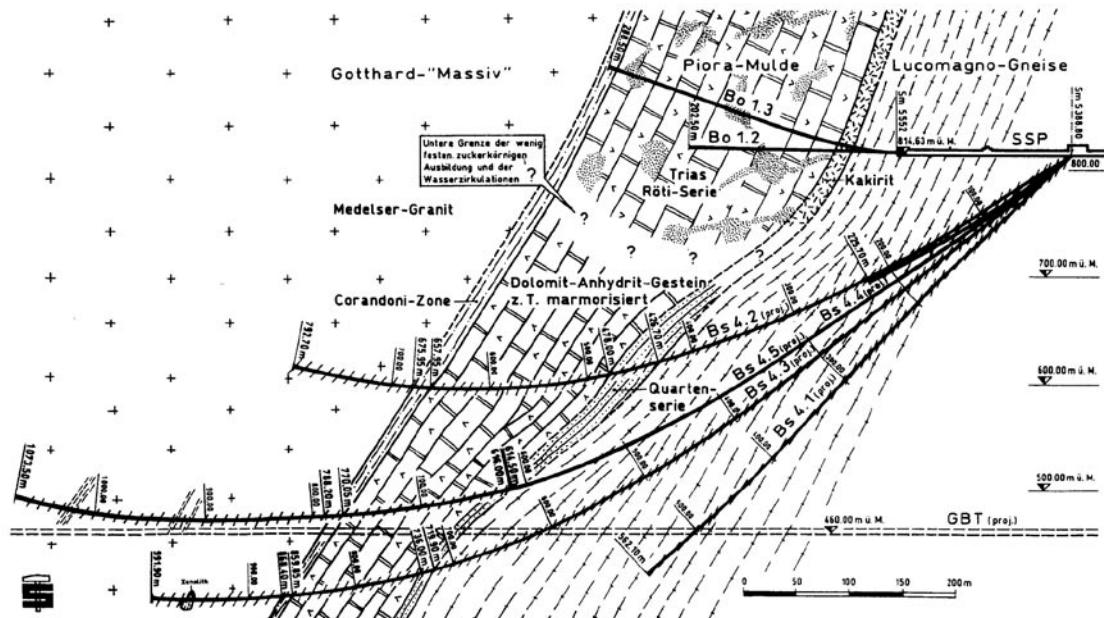


Fig. 16: Exploration of the Piora syncline: long range drillings from the end of the exploratory gallery.

finding of best possible overall heading concept is a very demanding task and requires a large and solid experience. It depends on a great number of influence factors. For everyone of them its own uncertainty has to be taken into account. Some important factors are:

- * Extent and evolution of preliminary exploration
- * Geological environment (limits between geological formations, position and kinds of faults, amount of water inflow)
- * Requirements from environment protection, sensibility of surface surroundings
- * Aptitude of excavating method (TBM versus drill&blast) and prospected heading speed
- * Minimizing falling headings (water evacuation, safety for staff)
- * Administrative conditions and risks for delayed project approval
- * Access possibilities and volume of surface transports, availability of muck deposit areas

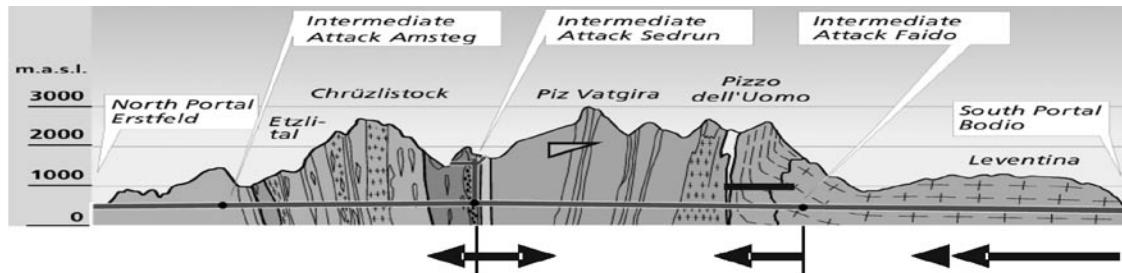
* Inopportune design modifications due to new standards and guidelines

* Composition and extension of the different construction lots

* Overall construction cost.

It is self-evident, that aside all the technical and temporal criteria, a cost-conscious design is preponderant. Therefore one has to have a clear idea about the degree of reliability of the cost prediction.

What the excavation methods are concerned, Swiss tunnelling is known for the early and frequent application of TBM drives. A lot of pioneer work has been done in the past by courageous and long-sighted contractors and their machine suppliers. In fact, already during the construction of the Gotthard road tunnel, in the year 1974, the designer incited the use of TBM's, preparing a corresponding design and specification alternative for the bid. Whereas two deep shafts have been realized by TBM, the proposal for the main tunnel has been disregarded, since large diameter TBM's for the hard Gotthard gneiss were not yet considered feasible at that



Sector	Sedrun	Piora	Bodio
Tunnel element	running tubes, 4 headings	exploratory gallery	running tubes, 2 headings
Method	drill & blast	TBM	TBM
Cross profile	circular/horse shoes, variable size	\varnothing 5.00 m	\varnothing 8.83 m - 9.03 m
Main scope	controlled approach of instable faults, prevention of uncontrolled water inflow from near-by reservoirs	safe approach, investigation and crossing of undrained dolomite, with 150 bar of water pressure	detection of fractured fault zones, prevention of TBM blockade by loose rock parts
Schedules	works started in 2004	works finished 1997	works actually ongoing

Fig. 17: Different types of advanced probings from the heading fronts in the Gotthard Base tunnel.

time. But in the same period the Sonnenbergtunnel, a twin tube road tunnel under the Molassic hill in Lucerne, has been excavated by a TBM with the 3-stage reaming method. Many others followed, mainly with full face TBM's. As the statistics on Fig. 18 show, mechanical excavation was largely preponderant for the last decade and will take even more importance in the future.

Optimal Alignment

The first long alpine tunnels, like the Gotthard and the Simplon, have been drawn in a straight line, following evidently the shortest way between two defined portals. The Lötschbergtunnel was meant to be straight as well, but as it encountered – on the way going – an unexpected deep sill of loose soil, the final alignment took a large curve around that critical area.

The choice of the alignment of the tunnels in the later periods has been subject to more complex criteria: Especially for road tunnels, one has to consider the requirements related to the ventilation, mostly achieved by a transversal ventilation system which requires air ducts along the traffic space. Since the construction volume due to the ventilation (longitudinal ducts, fan stations, shafts and adits) can reach up 1/3 of the total volume of a traffic tunnel, and the ventilation sectors cannot exceed a reasonable length, it is indispensable

to optimize the tunnel layout, which means to find the best solution among all the possible configurations of alignment, cross profile sizes and shafts.

The optimization process has to be applied primarily on the whole project, but also on every single element of the project by itself, because it is quite clear that the overall design cannot be considered optimal, if one or more of its elements can still be improved.

In economic terms, the total cost is understood not only by the initial investment due to the construction cost, but includes also the operation and maintenance cost, either in absolute figures or referred to a yearly cost. In order to fit all the cost elements to the same scale, the presumed future yearly costs have to be capitalized. This presumes that one has to know, or at least to assume with a certain reliability,

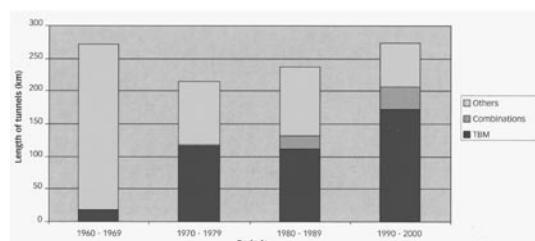


Figure 18: Types of excavation; preponderant TBM application

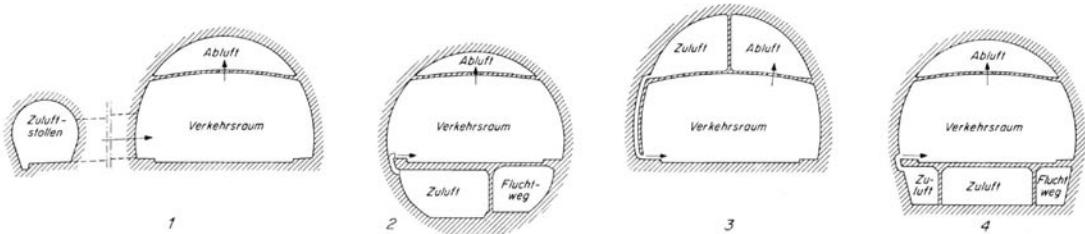


Figure 19: Examples of discrete variables for the optimization of a long road tunnel: different types of cross profiles.

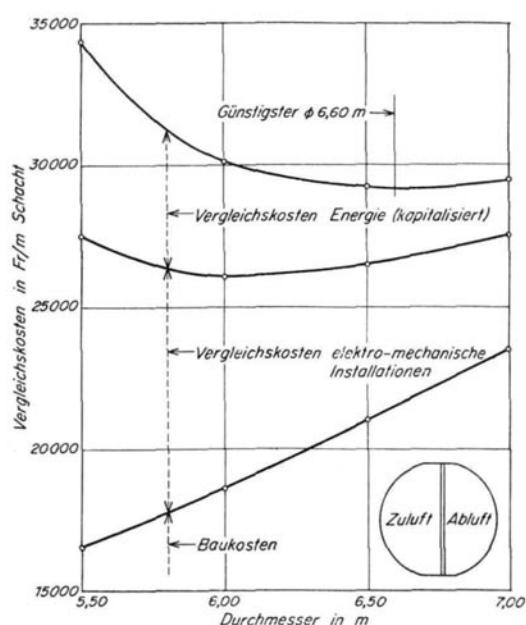


Figure 20: Gotthard road tunnel: optimisation chart for the Gumpisbach vertical shaft

the future operation cost, which is the most difficult task in face of the uncertainties, especially concerning the future pattern and volume of traffic, as well as the future cost of manpower and energy.

Among the numerous variables to take into consideration, there are discrete ones (number of tubes, number of attacks and shafts, ventilation system and number of sectors, type of cross profile, Fig. 19) and continuous ones (free air surface in a rail tunnel, diameter of a ventilation shaft).

As an example, one can see, on Fig. 20, the chart of the total cost per m of a ventilation shaft, in function of its diameter. It is known, that in a big shaft, for a given air volume, air velocities are low, which requires a small

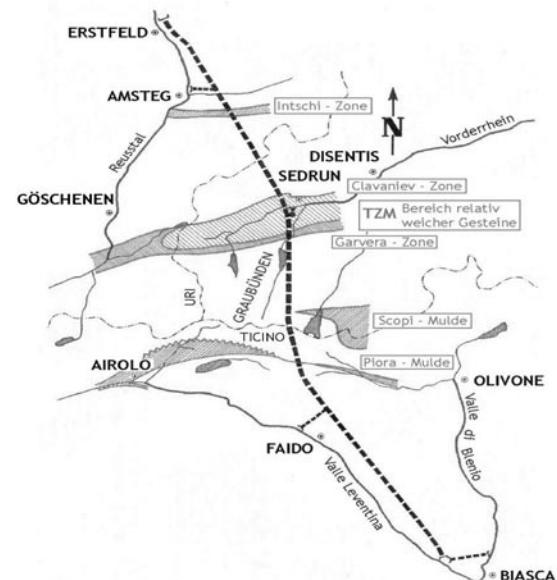


Figure 21: Determinant geological criteria for the alignment of the Gotthard base tunnel

power input for the fan and a limited energy input. With a small and cheaper shaft however, energy cost and investment for electromechanical equipment are higher. The minimum of the curve corresponds to the optimal diameter from the economic point of view. In practical cases it often occurs, that the minimum lies within a rather extended flat part of the curve.

Although the operation to work out the optimal solution may be satisfying from the intellectual point of view, one has to be aware of its limits. Not only because of the uncertainties of the future evolution of the variables (e.g. energy costs), but also in front of different and unmeasurable factors, like the public sensibility to safety and risk, which has a great impact on the project configuration and on the cost of safety equipments.

To come back on the question of the alignments, one understands why the long tunnels are no more aligned in a straight way. The reasons are manifold, but the shape of every project can be lead back to an optimization.

So the alignment of the Gotthard road tunnel ended up in a large curve to the West, partially due to some geological restrictions, but mainly to the result of the analysis in search for the minimum total cost design. In fact, the tunnel follows the pass road, which was suitable for the construction of the four ventilation shafts. By the way the longest sector between two shafts, which came out with 5,6 km, has been divided in two straight lines by introducing an "artificial" curve, with the intention to break the monotony for the user. This was a typical discrete optimization element.

Coming back to the present, we see that the 57 km long Gotthard base tunnel forms an S (Fig. 21). With this alignment one could fulfill the following main criteria in the most appropriate way:

- * Shortest line following the most suitable combination of inclined and vertical intermediate attacks
- * Crossing the delicate geological formations at their narrowest points
- * Avoiding maximum overburden when crossing the Alpine crest
- * Avoiding passing under existing reservoirs.

Vertical alignments were traditionally chosen between a minimum and a maximum slope in order to achieve climbing headings; this to facilitate gravitational water evacuation. For long and deep tunnels, where excavation not only occurs from the portals but also from one or several intermediate attacks, descending heading concepts and shaft sinking have to be taken in account. These concepts require carefully studied safety systems, with appropriate escape scenarios in case of flooding and fire.

CONCLUSION

Like in all fields of activities we are surrounded by an immense quantity of laws, standards and guidelines. But within this frame, it should not be the role of a conscious engineer to solve a technical problem alone by following the standards. Big works like deep and long tunnels are unique and need a certain amount of technical creativity and a realistic and careful optimization. But beware, not to mistake optimization by maximization. It means

to find the best possible configuration within the given boundary limits (minimum profiles, portal positions, access possibilities to attack points, respect of banned zones). In a more broader sense, an optimization means "the most economic way" and not necessarily the most perfect way.

The finally the scope of our works is to meet the increasing need for communication and transportation, and this not only in terms of quantity, but with a better quality and with the deemed consciousness for the preservation of the natural environment.

In this sense the ultimate reason of the deep transalpine tunnels is to win on environment.

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