Long tunnels at great depth

ITA Working Group n° 17
on Long tunnels at great depth

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1 >> Introduction

Recent projects of very long railway tunnels (from 20 to 50 km or more) at great depth (thousand meters and more) have only emphasized what has been recognized for many years with existing long railway and road tunnels (from 5 to 15 km or more): the work is a complex civil engineering system, to be designed under uncertain conditions with stringent requirements for safety during construction and operation.

Long and deep tunnels are consequently characterized by extreme conditions for risk assessment and risk management during the lifetime of the project. This refers to the early planning and ground investigations; the design, including the intermediate access shafts or adits; the rescue or multi-purpose chambers; and other safety features for construction and operation.

This report is intended to serve the international tunnelling community as a guideline for planning, design, construction and operation of long and deep tunnels. It recommends an approach or a methodology for solving the major problems involved. Specific reference is made to the following approaches and requirements:

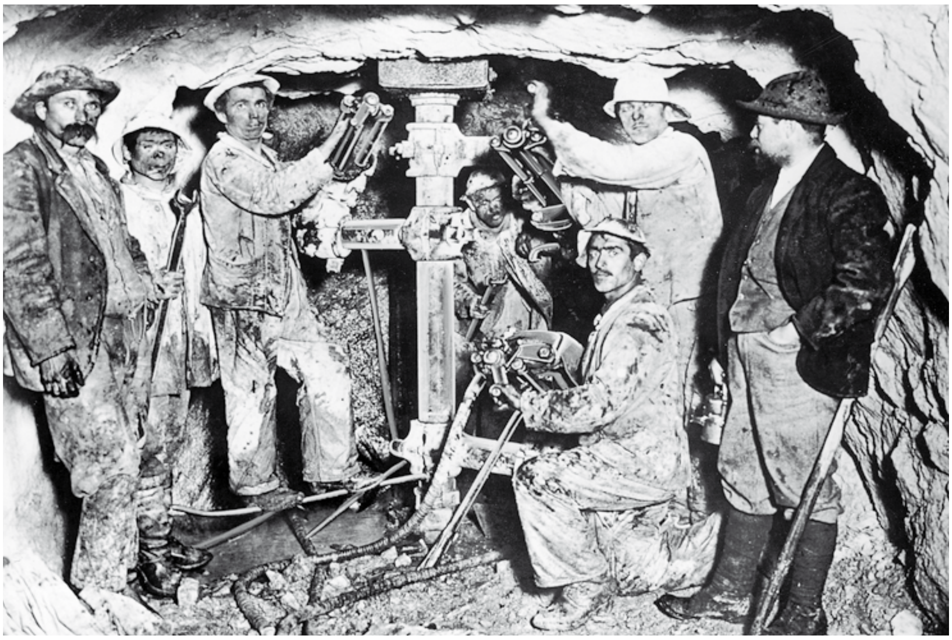
- The investigation methods for the geological, hydrogeological and geomechanical conditions of the ground, specially related to the great depth: high in situ rock stresse s, plasticity or squeezing, rock burst, fault and shear zones with high water pressure, high ground temperature, etc.
- The risk assessment and risk management process, mainly related to the great length, which implies: a long time extension of the design and of the construction process, even with intermediate accesses, a considerable amount of resources needed, a high social and environmental impact of the work and the need to assure a safe operation of the tunnel.
- The specific construction aspects for long headings, the logistics of site installations partly located underground, ventilation, haulage and transport of construction materials, as well as the control of the excavation advance rates, support selection, and performance.
- The safety requirements, in general for the construction, or specifically for railway and road tunnels operation, in relation with the traffic load.

2.1. GENERAL OBJECTIVES

The extension of the railways during the 19th century was an element of political unification in the old European countries as well as for the great new countries then in full development. The poor steel-wheel grip on the rail has given the possibility of pulling heavy masses with relatively low power. This advantage fostered the considerable growth in exchanges that are inherent in industrial growth.
But this poor steel wheel grip on the rail was also a handicap for crossing mountainous terrain. So, the first railway networks followed natural valleys to benefit from low grade slopes. The drawbacks are winding layouts and numerous tunnels the lengths of which were designed to be as short as possible. With such principles, the first alpine railway crossings were the result of a compromise: high altitude tunnels to reduce their length, relative winding layouts but steep slopes (25 or 30 mm/m over several tens of kilometres).
Today, with the increase in weight of trains, second-rate performances are noted, without considering loading gauge problems, particularly for transport of maritime containers.
In Japan, the construction of long and deep railway tunnels started about 1920 with the Shimizu tunnel (9.7 km) and the Tanna tunnel (7.8 km).

Great alpine crossings between 1860 and 1913
Fréjus 1871, 13.7 km, between France and Italy
Saint-Gothard 1882, 15 km, Switzerland
Simplon 1906 (1st tube), 20 km, between Switzerland and Italy (2nd tube in1922)
Lötschberg 1913, 14.6 km, Switzerland

The railway response to today's needs in freight transportation seems to require long tunnels at great depth, to cross mountainous barriers. This is true for the already industrialized countries with their equipment become obsolete, or for developing countries attempting to open themselves up.
From the middle of the 20th century, the railway development was replaced by the highway network arising. Long road tunnels, from 10 to 15 km, were of utmost importance to secure winter links through the Alps, for instance. The Mont Blanc tunnel, between France and Italy was opened in 1965, over a length of 11.6 km, followed by the Gotthard tunnel, achieved in 1980 with a length of 16.9 km, which remained the longest road tunnel for 20 years, with an increase in traffic from around 2 million vehicles per year in 1981 to over 6 million in 2000.
In other countries however, the railway development did not stop at the same time. In Japan for instance, over 70 long tunnels were constructed during the last 50 years, including the world famous Seikan tunnel, 53.9 km long.
More generally, long tunnels (not always at great depth) are frequently required by high-speed or high-capacity transport projects, with the following benefits:



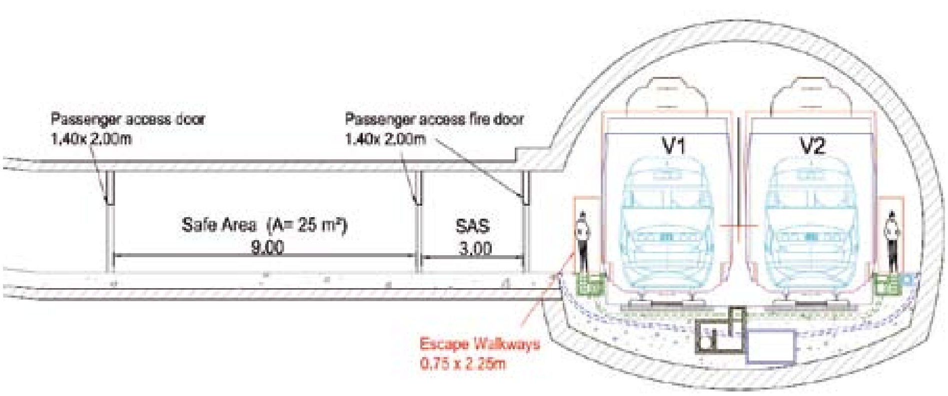
- Shortening of the route mileage and travel time.
- Improvement of the capacity of existing rail links by raising the train speed.
- Improvement of the safety and quality of travel, compared with old difficult routes involving many curves, up and down grades, and short tunnels.
- Reduction or mitigation of environmental impacts.

2.2. BASIC CONCEPTS

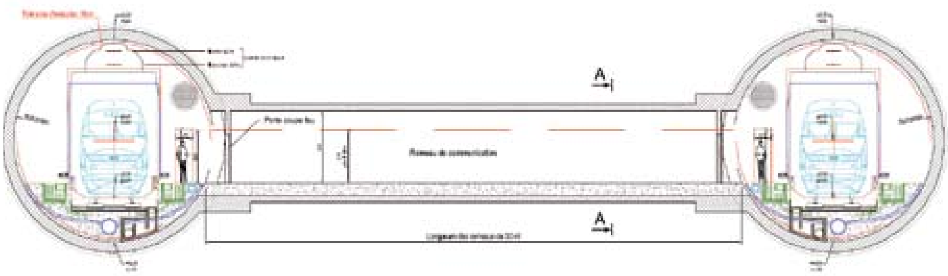
The choice of the system configuration for long tunnels at great depth, apart from the usual alignment trials and design of the cross section (including the clearance profile), should consider the required transport capacity, the construction aspects, and the equipment for operation and safety: ventilation, lighting, signalling, communications, cableway, and so on.

- **Tunnel system**

The possible tunnel systems for long tunnels are mainly represented by 4 options:
- Option 1: Single tube double track tunnel with intermediate rescue station.
- Option 2: Single tube double track tunnel with a parallel safety-service tunnel
- Option 3: Two parallel single track tunnels, with intermediate rescue stations
- Option 4: Two parallel single track tunnels, with a third service tunnel



Example Option 2: Project Lyon(F) – Torino (I)



Example Option 3: Project Lyon(F) – Torino (I)

Evidently, each option has advantages and drawbacks. As a matter of fact, the world's longest railway tunnels have different system options using:

- Seikan Tunnel (Japan, 54 km): Option 1 with two rescue stations.
- Channel Tunnel (France-England, 50 km): Option 4
- Gotthard Base tunnel (Switzerland, 57 km, under construction): Option 3 with two rescue or multi-purposes stations.

At the present time, safety requirements for railway tunnels become more and more severe, orienting towards the options **with two single track tubes (options 3 or 4)**. The same is equally valid for long road tunnels. Major traffic accidents with dramatic fires at the Mont Blanc in 1999 (Bidirectional single tube without service tunnel) and at the Gotthard in 2001 (Bidirectional single tube with a safety tunnel) can only strengthen the necessity of separating the traffic in **two tubes, with double lanes for each**.

In case of low traffic density however, exceptions are assumable. The bidirectional Laerdal Tunnel in Norway, the world's longest 24.5 km road tunnel, but only 400 vehicles per hour at the heaviest traffic and an average daily rate as low as 1000 vehicles, represents the major and most recent example of this category.

One shall not underestimate the problems linked to human aspects (claustrophobia, stress, etc.).

• Interval distance of cross passages between two parallel tubes

For safety reasons, cross passages between the tubes or between one tube and a service tunnel have to be constructed at an interval not greater than:

- 330 to 500 m for railway tunnels,
- 250 to 500 m for road tunnels.

• Length profiles

The minimal longitudinal slope should be at least 5 mm/m for dewatering and drainage. The maximum slope depends on the operation concept. As a general rule, the maximum slope must not exceed:

- 13 mm/m for long railway tunnels
- 30 mm/m for long road tunnels, in order to avoid a third lane for slow vehicles.

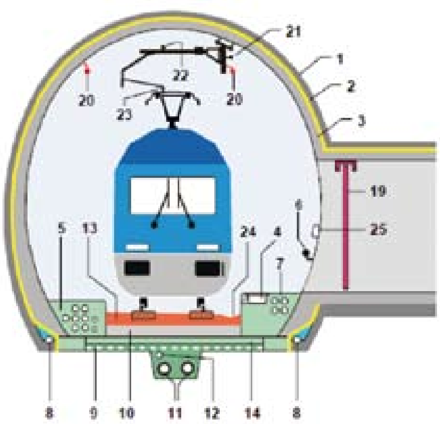
• Cross section

The shape is strongly dependent on the excavation method (circular profile with TBM, horseshoe with Drill and Blast or Road headers).

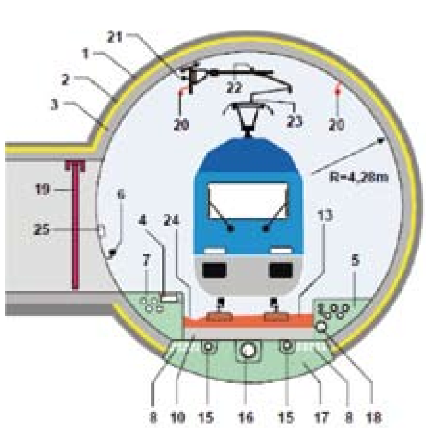
The geological and geomechanical conditions can also lead to quasi circular or circular profiles, for instance, in swelling and squeezing rocks.

For **railway tunnels**, the space to be secured above the rail level is settled by the loading gauge (clearance profile) and by the free section, depending on the train speed, the safety and the comfort of the passengers. For high speed trains, over about 160 km/h: numerical simulations with an aero-dynamical model including the shock wave occurrence and the tunnel length are necessary to design the free space, eventually combined with decompression shafts.

Cross section conventional



Cross section TBM



Example of cross sections: Lötschberg-Base Tunnel (CH)

Ventilation and safety concepts should be integrated in the preliminary studies for the construction and for the operation phases.
For long rail tunnel, a longitudinal ventilation system is usually required. The capacity is based on the critical velocity concept. Massive smoke extraction can be implemented at the location of rescue stations.
For long **road tunnels**, transverse ventilation is usually required, at least for bi-directional flow. The profile must include the air ducts for fresh and waste air, usually with a ceiling and a partition wall above t he clearance section in horseshoe profile.
In a circular profile, the space for ventilation ducts can be organized with fresh air in the invert and waste air in the roof.
The need for a cable duct or a utility duct should be carefully studied and planned in the invert, especially for horseshoe profile where space adaptations are often required. This is equally valid for railway tunnels.

• **Ventilation and cooling requirements**
This is a major concern for operating long and deep tunnels. Special studies are required, taking into account all technical, safety, operative and environmental aspects. The fire case is particularly relevant. The important chimney effect resulting from large pressure differences between shafts, intermediate adits and the tubes has to be prevented with screens, lock chambers, and over pressurization in rescue rooms, or similar devices.

• **Logistics**
The special construction-related needs are strongly related to the site conditions as well as length and depth of the tunnel:
- Equipments for ventilation, cooling system, de-gassing, dewatering and mucking.
- The maximum drive length from a portal is limited by logistic constraints and extension of time, thus requiring deep access shafts and/or construction access tunnels, which sometimes are also long and deep.
- Long access roads are often to be built, even for the site investigations.

2.3. PROJECT PHASES

Long tunnels at great depth are exceptional undertakings not only from a technical point of view, but also because the decisions are taken at the highest level of responsibility (often the government or even more than one government), with large time intervals between stages to go ahead or to stop the project.

• **Non-technical considerations**
These basic points are notably:
- The structuring characteristic of the project for a country or a continent depending on the political will which sometimes might be the opposite of economic logic (will to open up a part of a country, policies concerning major works, response to a forceful local request…).
- The project has to be part of the existing networks implying certain characteristics (gauge, traction means, signalling systems…)
- The great investments involved, which may either increase because of required improvement in performances or decrease if financing possibilities or the will to finance are limited.
- The generally difficult natural environment (thick overburden, complicated geology, harsh climate) is a source of many unforeseeable factors and of variations in the cost and the time required for construction, in spite of very serious studies.
- The system approach, needing a multiplicity of techniques and particular to a railway project (traffic forecast, running, maintenance, layout, signalling, traction, aerodynamic, civil work, safety…), involves mobilizing as many specialists as there are disciplines, and requires an excellent degree of co-ordination.
- During the long implementation time of a project, changes are quite common in :
  - the political, economical and social conditions;
  - the material and labour supply conditions;
  - the staff involved in the project, especially those assuming a management role, since it is generally difficult to expect that people will stay on the same project for a period of over 5 to 10 years.

• **Technical approach:** Project phases and corresponding requirements

The following steps are basically taken:

A – Strategic planning
Definition of basic goals and objectives
Identification of potential sources of funding

B – Technical feasibility study (preliminary study)
Feasibility and choice of the geographical situation Major constraints (known and potential)
Safety and functional criteria
Identification of alternatives and conceptual design
Constituents to be satisfied, use agreement
Legal regulations, requirements and restrictions
Strategic procurement policies
Estimates of project duration and cost

C – Preliminary design
Definition of the best solution from among the alternatives
First risk assessment – Environmental impacts and safety aspect
Procurement policy (option to continue with Final design or move to Design + Build, or Design + Build + Operation + Transfer) including the type of tendering process

D – Final Design
Detailed project
Equipments and defined accesses
Base for tender.

E - Tendering

F – Construction Design
Execution drawings
Project Management
Risk management (ITA Working Group 2 Report TUST 2004, p. 217-237)
Safety design and guidelines for operation.
More detailed requirements are given in the following table (as example Swiss tunnel code – General Basis – SIA 2002).

2 >> PROJECT SPECIFICATIONS

Project phases Types of services	B Technical feasibility study	C- Preliminary design For national Roads: general project	Administrative public inquiries and building permit For national Roads: execution project	D- Final design For national Roads: itemised project	E- Tendering	F- Construction Design
Operating system description, geometry of works	Operating concept. Identification of implantation requirement, operating convention.	Variant studies of the layout, definition of the works. Selection of a variant, accesses, adaptation of the operating convention	Detailed definition of works, ground, implantation, adaptation of the operating convention if required.	Detailed project, base for tender, places for building site equipment and defined accesses.	Execution project, excavation, timbering, covering, building site equipment, accesses, make out of execution variants.	Design and execution plans, adaptation to the actual conditions.
Quality management specific to the project PQM (see SIA 2007)	Objectives, basic conditions and determination of the project services.	1st assessment of risk, adaptation of the project if required.	2nd assessment of risk, adaptation of the project if required.	3rd assessment of risk, adaptation of the project if required.	Bases for PQM	Establish the quality convention, work out of quality plan.
Geology / hydrogeology	Preliminary study based on existing documents.	Identification of specific critical points, necessary information for the variants. Definition of the exploratory campaign.	Necessary exploratory for the definition of the works.	Complementary detailed exploratory for the design of the works.	----	Design and execution plans, adaptation to the actual conditions for execution.
Operation and maintenance	Definition of operating and maintenance concept.	Variant study and selection of operating equipment. Functional study of rooms.	Emissions qualification and noxious waste quantification, estimation of operating consumption (electricity, water, …)	Definition and design of electromechanical plants, definition of operating scenarios.	Tender for electromechanical equipment.	Control of execution plans and suppliers at factory. Operating test and reception.
Operation safety	Definition of safety concepts.	Integration of safety procedures, escape ways, smoke extraction, safety equipment.	Safety dossier, quantitative analysis of risk.	Integration of necessary adaptations for operation and maintenance in the project.	----	Safety dossier for operation.
Environment	Identification of critical points (environmental impact assessment phase 1).	Draft dossier for administrative public inquiries, procedures and contents (environmental impact assessment phase 2).	Environmental impact assessment, reuse of excavation materials, concept of disposal.	Adaptation of project to the requirements for building permit.	Environmental requirements for the construction phases.	Control of the accompanying measures and environmental follow-up of works and control of environmental measures.
Operating and safety plan	----	Definition of critical events presenting risk and dimensioning operating conditions, concept of drainage and watertightness.	Definition of risks, determination of all operating conditions, system of drainage and evacuation of water.	Selection of material and quality requirements, working out of process: check plan.	Special conditions for execution and control.	Adaptation to execution conditions.
Work hygiene and safety	----	Assessment of critical risks at site. Ventilation and cooling concept.	Measures study and their integration in the administrative public inquiries project.	Adaptation of the project to the requirements of the building permit and adaptation of measures.	Integral safety plan enclosed to the tender.	Integral safety plan worked out by the contractor and approved by the Safety Authority before the beginning of the works. Follow up and adaptation of the plan.
Construction methods	Identification of plausible methods.	Qualification of plausible methods of excavation, types of supports and number of adits.	Integration of constraints due to construction methods, noises, dust, vibration, ground in the project.	Selection of one or two project variant for the construction project. Clear definition of disqualified variants. Definition of constraints to be respected by the contractor for the construction variants.	Analysis of the construction variants.	Adaptation of the project to the selected method for the construction.
Estimate (quote) **Accuracy** [(1)]	Estimation based on existing works. ± 30-20%	Estimation based on existing works realised with similar conditions and methods. ± 20-15%	Estimation based on a precomputation of quantities with known prices of similar works. ± 15%	Estimation based on a precomputation of the main quantities with prices in order of ± 10%	Realistic precomputation of quantities for the tender.	Final accounting.
Construction planning	Estimation based on existing works.	Estimation based on existing works realised with similar conditions and methods.	Planning established on the base of existing construction time of works parts.	Detailed projected planning of construction.	Planning of construction and definition of contractual delays in tender. Construction planning of equipment.	Control and adaptation of delays.

[(1)] Requirements regarding accuracy of cost estimation are to be based on existing laws

Final remark

Project for civil work, equipment, logistic for construction (including ventilation and cooling system) have to be done in parallel.

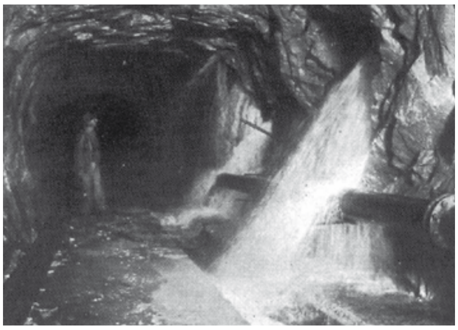
3.1. MAJOR CONCERNS AND CONSTRAINTS FOR LONG AND DEEP TUNNELS

Long tunnels at great depth are usually located in mountainous areas with limited infrastructures. Therefore, very little is known about the geological, hydrogeological and geotechnical conditions: the deeper the tunnel, the larger the uncertainties; the higher the probability of encountering adverse or unforeseen conditions for tunnelling, the greater the effort and the cost for site investigations to reduce the uncertainties.

• Adverse conditions for tunnelling

- High in-situ stresses, difficult to estimate (particularly the horizontal stresses) and not easy to measure (in deep boreholes with hydrofracturing or stress release techniques).

- Strong squeezing and high plastic deformations in rocks if the unconfined compressive strength is lower than the mean in situ stress (high convergences and strength softening).
- Rockburst in very hard rocks associated with high in-situ stress.
- Swelling and creep in argillaceous rocks (long time invert deformation).
- High water pressure and/or large water inflows



- Fault and shear zones, often associated with poor strength and high water pressures (face instability).
- High ground temperatures, which may require ventilation and even cooling during excavation.
- Seismic induced local displacements along active faults crossed by the tunnel.
- Heavily tectonised and fractured zones with poor mechanical and anisotropic conditions, eventually requiring pre-treatment ahead of the face.
- Environmental impact on underground water or large aquifers.

• Selection of the excavation method and support systems under conditions of uncertainty

- Uncertainty in construction parameters – apart from the uncertainty related to the many geological factors, there are uncertainties in the construction parameters which directly influence the construction time and cost of a given design-and-construction option. With deterministic estimates it is not possible to account for the various sources of uncertainties. Evidently, the variation of construction cost and duration will also influence the economic bases for decisions in a project. In this regard, cost-effective and risk-minimized engineering solutions need to be developed.
- Unforeseen geological conditions may lead to erroneous choices in the construction development, with dramatic consequences for the workers and the work. Site investigations should progressively reduce the uncertainties, as long as the unforeseen ground conditions are not actually unforeseeable !
- Use of systematic probe-drilling to prevent sudden face instability due to high water pressure or inflow and geologic anomalies.
- A cost-benefit analysis should be made for the design of the investigation scheme in terms of reducing not only the uncertainties of the geological, hydrogeological and geomechanical conditions, but also the construction risks related to these conditions.
- An integrated design of the investigations, the tunnel options and the construction methods, incorporating a multi-criteria decision making process, should be aimed at. This approach is necessary to justify the investment for investigations, acting against the tendency of limiting the expenses for reasons such as: the result of investigations will not change the amount of rock support actually required, the advance rate of a TBM depends mainly on logistical aspects and not on geotechnical ones, there are legal rules limiting the access to the site for drilling or adits, etc.

3.2. BACKGROUND INFORMATION AND SITE INVESTIGATION PROGRAM

At the beginning of a project, the information available is surely far from being sufficient for the Technical Feasibility Study (TFS) and, therefore, a specific and appropriate Site Investigation Plan (SIP) will need to be formulated and performed to integrate the existing data. To minimize costs the SIP should be prepared on the basis of a careful desktop study of all available information.

• Aerial photographs
If they do not exist, they should be taken by photogrametry over the Project corridor.

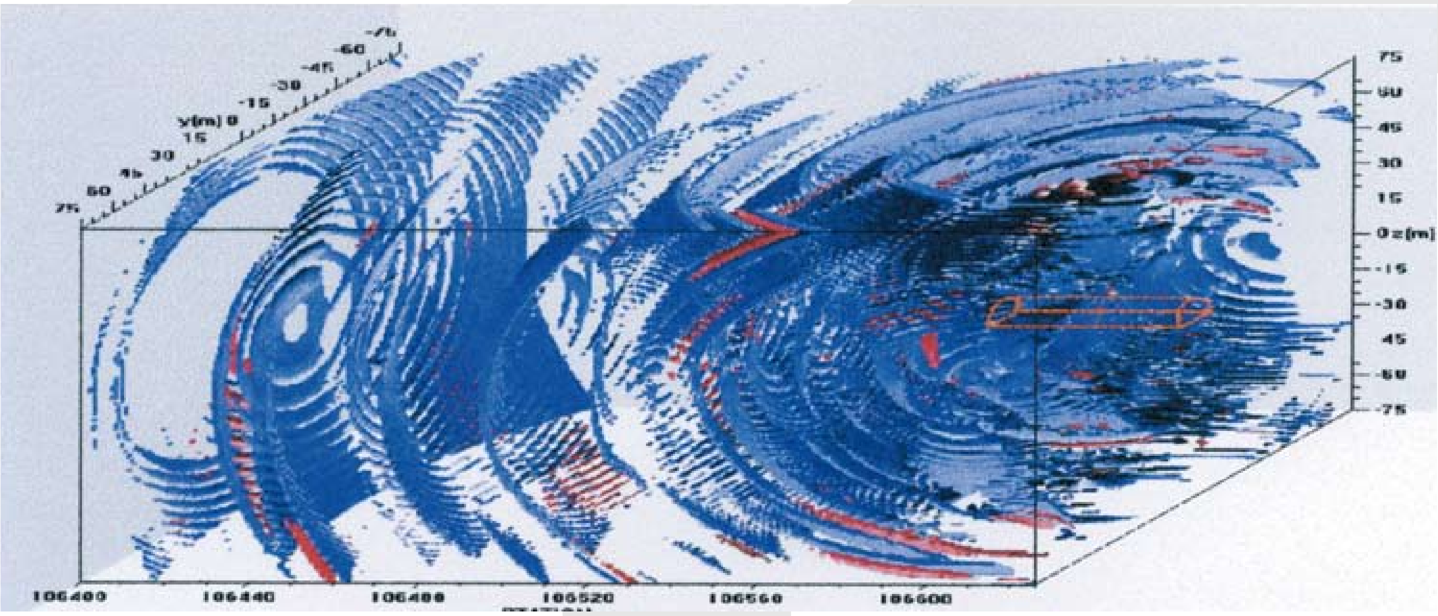
• Use of satellite images
All information should be organized into a comprehensive database for use with a Geographical Information System (GIS).

• Terrain systems mapping
A terrain systems mapping approach should be adopted within the Project study areas to form the basis for understanding the nature and distribution of potential engineering, geological, and environmental constraints to the design and construction of the tunnel. In essence, the terrain system is a scientific classification of a large area (into characteristic terrain units) based on topography, soils, rocks, and vegetation correlated with geology, geomorphology, hydrogeology and climate. Past experiences have shown that terrain evaluation techniques (such as DTM – digital terrain modelling) are readily available, cost-effective and appropriate in providing a reasonable number of preliminary alternative alignments within a given corridor for guiding the subsequent detailed investigations.

• Field mapping and study of the identified corridor
The scope is to study and map the geomorphology, geology, structural geology (faulting, folding, and jointing of the strata), hydrogeology, and natural hazards as well as any environmental constraints in the Project corridor. Specific efforts should be directed towards the identification of adverse ground conditions and risks for the design and construction of tunnels. The study should also deal with the availability of local sources of construction materials like fills and aggregates.

• Data on existing properties and utilities
All available data regarding the existing properties and utilities in the Project corridor should be collected for analysis of their potential interference with the Project. In case such data do not exist, specific surveys shall be made. In addition, effort should be made to interface with local authorities and planning organizations to collect information regarding any future developments in the Project corridor, such that due consideration can be given to them during the course of Preliminary Design (PD) development.

• Drilling and geophysical explorations supplemented by in-situ and laboratory tests
On the basis of the results of the field mapping and study, a program of drilling and geophysical explorations will be defined and executed to understand the ground structure in the vertical direction and its engineering behaviour. The in-situ and laboratory tests will be made to study the in-situ state of stress in the rock masses, their physical and mechanical characteristics (strength, deformability and permeability), the chemistry of the ground water, the pattern of circulation of groundwater, etc.

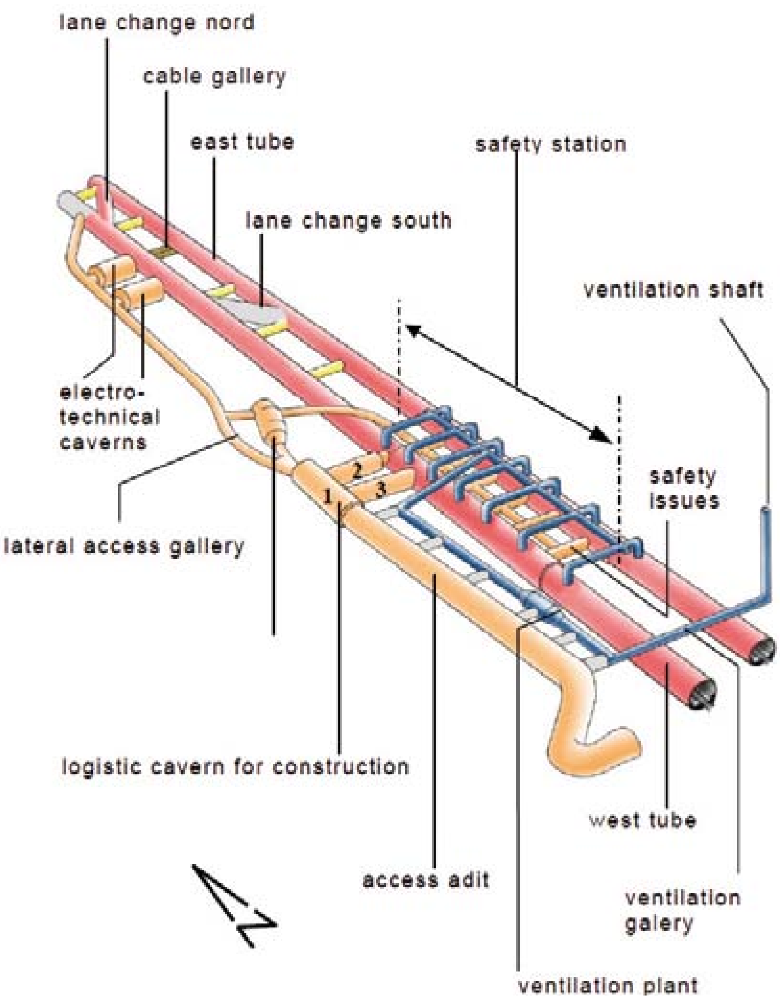


• 3-dimensional ground models
The combination of terrain models, the data obtained from the field mapping and study, plus the results of the drilling and geophysical explorations will permit a 3-dimensional modeling of the ground along the Project corridor, which will be of great help in testing the sensitivity of alignment variations.
Data obtained from the comprehensive SIP will be evaluated and used to:
- make engineering-geological and geomechanical characterization of each potential alignment for the Tunnel option;
- prepare various kinds of maps, sections, longitudinal engineering-geological profiles for the proposed TFS and PD;
- define the input parameter values required for the TFS and for the PD analysis;
- further indicate the need for additional investigations to be carried for the next phase of development of the Project, and
- prepare an Environmental Impact Assessment of the Project.
The variation (or uncertainty) in the available information can be quantified statistically to obtain the parameters (with their upper and lower bounds) for input to comparative analyses of the alternatives.

• Investigations for the final design
At this stage, depending on the complexity of the geology, it can be of great benefit, technically as well as economically, to execute investigations at the level and in the alignment of the future tunnel:
- Horizontal adit, which can be several kilometres long with in-situ testing and convergence measurements on different types of support (including no support). These adits are expensive, but their cost can be paid back by integration in the final project (safety tunnel, access tunnel to critical zones for the construction of the main tubes, drainage tunnel, etc.).
- Directional drilling, when the access for an adit is not existing or not feasible for various reasons. The cost of such drilling is, however, almost as high as that of an adit, and the collected information is, of course, less valuable (scale effect, unvisitable).

4.1. SAFETY

• Safety design
Safety operation is one of the key elements for the design of a long tunnel. Designing a tunnel for safety has an impact on the design of equipment, ventilation and infrastructure (type section, cross-passage, emergency exits …). It also has an impact on the mode of intervention of the rescue services, and on the rolling stock that can be used in operations (for railways tunnel). Thus a holistic approach is required. Following the progress of a project, from the different design phases to the construction and operation, an optimal level of safety must be aimed at each stage, in addition to considering the costs.



Ferden Rescue Station - Lötschberg Base Tunnel

Safety issues during construction and operation are different concept. Safety issues during construction are tightly linked to the construction methods. A specialist of safety during work should be involved in the final design.
Synergy could be find between both issues, for example early building of auxiliary infrastructure, needed for operation, could improve the safety level during construction.

• Safety management group
A competent and responsible group for safety management should be created implementing national authorities, the owner, the designer, and in some cases, operators in order to validate safety levels in operation.

During construction the contractor should be involved in the safety management group.
The safety management group will utilise the following instruments: safety organization, safety philosophy and objectives and associated measures, and the safety report.

- Safety organization
The organization is applied at each stage that is identified by the studies, the construction and the operation. It is effected at the upper hierarchical level. The tasks and responsibilities are defined and clearly assigned to each office involved. The safety organization regularly checks the execution of the safety philosophy, the safety measures and the safety report.

- Safety philosophy and objectives:
Accidents and fires in tunnels, which can lead to injuries to individuals or damages to the environment and to the work, should be avoided as far as is possible.
In case of accidents or fires, a mitigation of the risks has to be foreseen and implemented. Special arrangements must be found to allow for the evacuation of people (workers and users) by their own means, for the retaining of dangerous substances, and for the efficient engagement of the rescue crew (firemen, police, medical assistance).
Especially in long tunnels, the safety management must constantly follow the technical innovations and adapt the systems for reducing the risks for the individuals and for the environment. The required measures should be economically bearable.
The acceptable risk for individuals and the environment shall be estimated through quantified objectives or risk scenarios. Additional safety measures are necessary when the risks cannot be accepted, using a probability of occurrence-loss magnitude diagram.
The "Guidelines for tunnelling risk assessment", reported by the ITA Working group Nr. 2 (TUST 2004, p. 217-237) are valid for long and deep tunnels.

4.2. ENVIRONMENT

The sustainable development is the key issue for the environmental and quality management of the project, in early design stages, tendering and contract negotiation, construction and operation.
The risks to the environment include: air, water and soil pollutions; impact on health and safety of people; changes in water resources; and damage to flora and fauna.

• Design phases
For the portals, shafts and adit locations, areas sensitive to nature and landscape protection should be avoided or mitigated.

• Reuse of excavated materials
Wherever possible, priority should be given to reuse of the excavated materials as construction material in order to minimise their environmental impact.

• Construction
The following environmental loads, which are associated with construction, must be kept to an acceptable level with proposed and implemented risk mitigation:
- settlements, slope failure and surface impacts
- acoustic emissions,
- dusts and air pollution,
- vibrations caused by blasting or mechanical excavation,
- site water evacuation and treatment,
- transports (noise, dust)
- drying up of water springs or loss of flow rates of hydro-thermal (cultivated) waters.

• Operation
The disposal in the biosphere (air, water, soil) of non degradable pollutants should be kept at or below a defined and acceptable value.
The temporary drainage effect of a tunnel during construction cannot always be tolerated for the subsequent operational period of the work, in protected groundwater areas particularly. The installation of a waterproof envelope between the temporary support and the final lining can be mandatory, but eventually not suitable in very deep tunnels because of the huge water pressure finally acting on the lining. Alternative techniques, such as annular grouting of the rock mass at some distance around the tunnel section combined with a drain element located behind the waterproof membrane, are then required.

5.1. TECHNICAL APPROACH

The main design and construction issues are interrelated and must be dealt by following a well-structured approach.
Before defining the approach, it is useful to recall and summarize the major characteristics of a long and deep tunnel project:

- The Technical Feasibility Study (TFS), the Preliminary Design (PD), the Final Design (FD), the Tendering, and the Construction are basically decision-problems.
- The decisions, starting right from the first stage, i.e., the problem statement, is not a simple, single-stage, decision-problem, but a complex, multi-stage, decision-problem, i.e., most decisions that the owner or the designer makes lead to other decisions.
- Most decisions must be made under conditions of uncertainty due to the many nondecision variables involved, such as the ground conditions and construction parameters, which are not subject to control by the decision-makers. Therefore, the decisions always involve a certain degree of risk.
- Thus, the long process of implementing a long and deep tunnel is a continuous, decisionmaking process directed towards selecting a chain of best alternatives.

In current tunnelling practice, however, reliance on engineering judgment and a set of design principles is the rule; the use of decision-analysis techniques is rather uncommon. Examples of the background and use of the decision-analysis technique can be found in Einstein et al., 1998a and Einstein et al., 1998b
For new projects of long tunnels at great depth, where the process is very complex and has to be seen in a decision perspective, it is recommended that an innovative approach should be followed to fulfil the project objectives.

- **The proposed approach is both sequential and integrated, with the following key elements:**

1. Review of background information and execution of a site investigation program (see Section 3.2)
2. Statement of the characteristics of the various options through conceptual and preliminary designs
3. Constructability analysis of each design-construction-investment option
4. Comparison of configuration and method options, and
5. Comparison of alignments (including also the Surface Option versus the Tunnel Option).

- **The approach incorporates the following set of decision-aids:**

- using a decision tree (or multi-stage decision tree) to model and analyze the multi-stage decision problem;
- using the multi-criteria decision-making technique to select an alternative; and
- using DAT, a special, purpose-orientated set of Decision Aids in Tunnelling (Einstein et al., 1998a), to effectively account for the uncertainties and quantify the risks associated with a design-construction solution.

With this innovative approach, not only the comparative analysis of the various alternatives at different levels will be well structured and effective, but also a rational, comprehensive, and quantitative basis can be formulated for use by the owner in making more informed designconstruction-investment choices to achieve the goal of the Project.
Details of the key elements of the proposed approach are described in the following subsections.

5.2. STATEMENT OF THE CHARACTERISTICS OF THE VARIOUS OPTIONS THROUGH CONCEPTUAL AND PRELIMINARY DESIGNS

Different levels of options need to be studied:

- Choice between the option of many, short and shallow tunnels and the option of a single, long and deep tunnel
- Alignments
- Tunnel system (a twin-bore Tunnel or a twin-bore plus a third service tunnel)
- Construction methods (see section 6)
- Staged investment: depending on the funding availability and schedule, one may choose to build the twin bores in separate stages. The first-built bore can be initially used for bidirectional traffic or one-way traffic in limited time periods of a day or a week. Of course, in this case, the configuration of the typical section, the safety measures (i.e., the pilot bore to be used as safety egress) and the tunnel ventilation needs will be different.

The characteristics of the various options will serve the needs of both the constructability analysis and the comparison of options.
The characteristics of each option will be defined initially through a careful, conceptual design and later on through a proper preliminary design (PD). The conceptual design will be made on the basis of effective integration of the available, extensive design-experiences with the needs and expectations of the owner, while the PD will be developed with due respect to the design standards defined for the Project.

5.3. CONSTRUCTABILITY ANALYSIS OF EACH DESIGN-CONSTRUCTION-INVESTMENT OPTION

The constructability of a given option can be evaluated on the basis of the following criteria:

- geological and geomechanical conditions,
- hydrogeological conditions,
- existence of particular environmental constraints and interference with existing structures, as well as availability of borrow areas and muck disposal areas,
- stability of the tunnel face and, eventually, the need for face-support, especially in zones of adverse geologic conditions,
- stability of the pillar between the twin bores, or between the pilot bore and the main tunnel in the case of a twin-bore tunnel plus a third service tunnel, and the need for crossovers and interchanges,
- demand on primary support and final lining of the tunnel cavity,
- construction access requirements,
- construction time and cost as well as the reliability in the cost estimates.

The above list of criteria is generic and would need to be modified to suit the actual conditions of each project corridor.
For situations where only a finite number of alternatives are involved, the problem can be modeled by the approach called “multicriteria decision analysis”. (An example application of multi-criteria analysis can be found in Kalamaras et al., 2000).

Specifically, the multicriteria-scoring model will be used for evaluating the constructability of each option. The technique is briefly described below.
The multicriteria scoring model is a simple procedure in which we score or rate each alternative in a decision-problem based on each criterion. The score for alternative j on criterion i is denoted by Sij.
A weight (denoted by Wi) is assigned to criterion i indicating its relative importance to the decision maker (designer). For each alternative, a weighted average score is then computed as weighted average score for alternative j $=\Sigma W_i S_{ij}$
One can then select the alternative with the largest weighted average score. Two aspects are critical for the application of this technique:
- defining the criteria which are not only common to the given alternatives but also really affect the selection of the best alternative,
- assigning the weights and scores to each criterion in an objective manner.

Both aspects depend heavily on the experience of the Consultant. If the decision maker finds it difficult to objectively determine the criterion scores and weights needed in the multicriteria scoring model, the so-called Analytic Hierarchy Process can be adopted to provide a more structured approach for determining the scores and weights of each criterion.

5.4. COMPARISON OF CONFIGURATION AND METHOD OPTIONS

The multicriteria scoring model can again be used for comparative analysis at the configuration level (which accounts for both the configuration and the construction method).
The suitability of a certain method for a given tunnel configuration can be assessed based on the weighted, average response of the excavation technique to the following major concerns:
- **constructability** of the selected method,
- **flexibility** of the construction method under different conditions (both known and unforeseeable),
- construction **cost** and risk of cost overrun,
- construction **time** and risk of delay,
- the **ease of construction access** and the effect of the excavation scheme on the **access area**,
- **interference** with the environment.

The flexibility of a given configuration, be it a twin-bore tunnel or a twin-bore plus a service tunnel, needs to be assessed in terms of traffic needs, safety requirements and difficulties in foreseeing the ground conditions for tunnelling. The flexibility of the excavation method has to be evaluated on the basis of the possibility to adapt the excavation method and ground support to the variable and unforeseeable conditions or ground behaviors. In this regard, it is true that the conventional methods are generally slow in their response and require a series of simultaneous attacking points, but they can be adjusted to suit the observed ground behaviour. However, it should be noted that the adaptability of the various, conventional, excavati on methods to highly variable ground conditions is also variable. On the other hand, the mechanized methods do offer high degree of adaptability to the ground conditions, a high speed of advance, better working environment, easy for quality control.
The construction cost and time variables are probabilistic in nature. This aspect can be accounted for in performing the cost-time analyses using the specific program DAT (Decision Aids in Tunnelling). DAT is an expert system capable of modeling, in a quantitative way, the process of decision-making for underground excavations under conditions of geological and construction uncertainties.
The interference will be evaluated in terms of infrastructure protection, conservation of aquifers and any archaeological structures, protection and relocation of public utilities, and traffic diversion.

5.5. COMPARISON OF ALIGNMENTS

The comparison of the alternative alignments (and also the comparison between the option of many, short and shallow and that of a long and deep tunnel) is both a typical, Value-Engineering problem and an inherently-complex, multicriteria-based decision-problem. The problem can be effectively dealt with using the following procedure:
1. Represent the problem by properly structuring it into a logical, hierarchic framework.
2. Define the important criteria that are relevant to the section.
3. Evaluate the relative importance of the criteria.
4. Define the preference for the alternative alignments with respect to each criterion.
5. Calculate the global, weighted, average rating for each alternative alignment solution.

In order to assist the analysis, a commercially-available or newly-developed software needs to provide the following additional advantages:
- it can help to effectively sort out complexity,
- it can document, fully and clearly, in digital form, the decisions at all levels,
- it can assist with the subjectivity that is inherent in many decisions since the program can derive priorities from not only tangible information such as data but also intangible information from the decision-maker's experience and intuition, and also
- the program can perform 'what-if' sensitivity analyses.

The important criteria relevant to the alignment selection may include:
1. Constructability,
2. Construction cost (both initial cost and life-cycle cost),
3. Construction duration,
4. Construction scheduling and risk of delay,
5. Environmental impact, and
6. Public opinion (i.e., the preference of the end users of the Project).

Moreover, for railway tunnels, some of the most important criteria are driven by the operational constraints e.g. the characteristics of the traffic, as developed in §7.1

6 >> Tunnel construction

The economic and timely construction of a tunnel project principally involves consideration of:

- the tunnel dimensions and location, site geology and geotechnical characteristics;
- excavation methods for the required ventilation and access shafts, adits, portals, pumpchambers and other ancillary features;
- the support methods for these excavations during construction; and
- user safety and structure maintenance after the tunnel is put in service.

In addition, access to the working sites and their preparation and maintenance may have significant cost impacts. It is, therefore, likely that several alternatives will be examined before any major project is undertaken. Many of these topics are dealt with elsewhere in this report and this section will be limited to consideration of construction methods for excavation and lining with limited discussion of ventilation during construction and haulage.

6.1. TUNNEL EXCAVATION

• Conventional tunnelling

(See ITA report n°2 «General report on conventional tunnelling method»)

In difficult ground, drilling and blasting may always be employed in rock tunnels, and this is generally considered to be the most flexible method for penetrating such ground because it allows the maximum level of access to the working face and employs equipment which can be quickly and readily moved as required. The disadvantages are the danger of handling and using explosives, the need to move men and equipment out of the way before blasting, the need to exhaust fumes and wait in case slow fuses cause a late detonation However, these problems are not unique to long, deep tunnels and are well solvable nowadays. The additional problem with long headings is the potential for prolonged stoppages resulting from the need to halt other traffic while explosives are being moved to the working face. This depends on the safety regulations in effect at the construction location.

The problems associated with poor ground, squeezing and swelling ground, and shear zones are similar in long and short tunnels. However, deep tunnels are more likely to encounter high volumes of high-pressure water and hot water. Squeezing and popping rock are much more likely to be encountered in the excavation. All problems associated with shear zones are likely to be more extreme in deep tunnel, the logistics of transporting spoil and construction materials become more complex in long tunnels.

Measures available to reduce the risks and delays associated with the use of high explosives are: the use of water gel explosives; the construction (if permitted) of an explosives storage vault underground sufficient to contain the amounts of powder and detonators required for the next round; and proper training of all personnel actually or potentially involved in the loading, testing and retreat procedures.

If shear and fault zones or weak rock zones are associated with more than short reaches of squeezing ground, then it is desirable for these reaches to be accessed separately, if possible, so as to allow for the efficient use of specialized labour and equipment without causing overall delay to the project.

• Mechanised tunnelling

(See ITA WG 14 Report 2008)

Despite of the great improvements in this field, no universal tunnel boring machine (TBM) exists today and will not appear tomorrow, in order to drive a tunnel independently of the geological conditions encountered.

In sound rock, tunnel boring machines (TBM) make normally more rapid progress than drill and blast. Options are available which permit the erection of final lining as the excavation progresses, so that faster completion is assured. TBM is also safer when excavating overstressed brittle rock since the fly rock associated with local failures is confined by the face of the shield and by the lining erected under the cover of the tail shield.

One of the major difficulties is that of coping with squeezing ground which may lock the machine in place. A moderate amount of squeezing can be accommodated by using extendable gauge cutters when such ground is encountered but they need some meters to be extended. Success has been had

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using rock anchors installed closely behind the cutterhead, especially for weekend and holiday breaks, major repair time, and the need to stop production for reasons not related to the type of ground being excavated. The assessment of the amount of expected squeezing is difficult, but it is necessary to make a judgement so as to determine the probable effect on construction methods and productivity.
Shear zones in particular create greater problems for the advancing sh ield. Some may be dealt with by slowing the advance rate to keep pace with the more extensive ground support required, especially if one-pass excavation and lining is not employed. Heavy water inflows may be encountered if the faulting has brought the permeable and impermeable rocks into contact in the tunnel zone or if the fault is associated with the development of highly permeable rubble zones. At depth, where a high water table combines with altered quartzitic rocks, which have given rise to sand in the fault zone, even greater difficulty will be experienced by the TBM. Once the sand-bearing water starts flowing, it cannot be stopped by any kind of grouting program. Whereas it is possible in conventional tunnel to install a bulkhead to restore stable conditions, this cannot be done with a TBM, except if the machine is properly designed and manufactured for holding face pressure.
It is, therefore, not recommended to use a TBM of any type if such conditions may be encountered, except when:
- such areas have been recognized in detail prior to the arrival of the TBM;
- the length and the number of such areas are small;
- the tunnelling machine has been equipped to treat this kind of accidents or in case a treatment through another access (gallery, surface) is possible.

At this time, the state of the art for tunnelling in permeable soils beneath the water table will only permit progress under a water head of about 10 bars. It is also necessary to determine the potential sources of recharge. Some volcano-clastic rocks have isolated pockets of water which, when breached, deliver enormous flows for several hours and subside within a day or two. These conditions are rare, but the association of high heads and flows with faulting is common.

• Special Problem Treatment

It will sometimes be appropriate to divide the project into segments constructed by different equipment spreads. However, it is possible to be too enthusiastic in adopting this solution because of the high cost of excavating and maintaining shafts or access drifts, as well as the added costs of installation and operation of the required headframes and hoists required for developing a tunnel from a shaft instead of a portal. Ventilation requirements of the finished tunnel may dictate that some shafts are required anyway; or that they can be used if otherwise needed for construction to reduce permanent ventilation costs.
Considering construction activities alone, it is prudent to locate shafts at significant changes in the location of faces at the tunnel horizon in order to minimize the problems of mixed-face tunnelling or to separate reaches which can be more economically constructed by different methods. In addition, localized problems, such as the sand-bearing fault zone referred to above can be dealt with more safely and efficiently from a surface access than from a tunnel face.
If high volumes of methane and/or hydrogen sulfide are known to be present, it is usually possible to exhaust such gases from a pattern of deep borings designed for the work than it is to rely on increased face ventilation to deal with these noxious gases.
It should also be noted that other gases such as radon and carbon dioxide are sometimes encountered where a fault trap, or impermeable cap rock, lies above uranium or pitchblende deposits or above rocks derived from deposits containing organic material. Shale or limestones are especially likely to be reservoirs of organically derived gases.

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6.2. TUNNEL SUPPORT

As stated in section 3.1, adverse conditions for tunnelling are often related to the great depth, where high existing stresses need large convergences to be partly relaxed before placing the support.

• **Temporary support** in reasonably sound rock may be of the same types as those used in shallow tunnels, i.e., rock bolts with or without mesh or mine straps; shotcrete with or without steel fibre or mesh reinforcement; precast concrete or steel segmented linings; or steel ribs and wood, steel or concrete lagging. The support installation is, however, more complex if the rock displacements should be controlled and monitored.

• **Permanent support** may be the shotcrete lining, but it is not easy to keep clean and does not permit the installation of a waterproof membrane with geotextile backing for permanent drainage systems to reduce hydrostatic loading on the lining. The precastconcrete segmental lining does permit the installation of waterproof membrane in advance of the permanent lining installation. In-situ concrete linings are suitable and most often used in shorter, shallower tunnels. Their disadvantage is that they must generally be installed after the excavation is finished, and this adds substantially to the schedule time and cost.

Grouted, precast-concrete segmental linings with adequately designed gasket have been used in TBM-excavated tunnels. They may be installed independent of the excavation by using a double shield TBM, the second shield moving independent of the excavation module. Such linings can be made substantially watertight, but do not permit the installation of a waterproof membrane, unless a follow-up permanent lining is installed. This type of support has not been used in deep tunnels, but has found favor in subaqueous tunnels. This type of lining generally referred to as one-pass lining, leaves the tunnel completely lined when the excavation is finished. High productivity is common, but it depends completely on the ground being suitable for use of a TBM or earth pressure balance TBM.

6.3. VENTILATION DURING CONSTRUCTION

The provision of adequate ventilation in tunnels is required, regardless of their length or depth. However, long tunnels do have some special problems of maintenance. Ventilation is usually provided by blowing air into the tunnel to a point within about 30-50 meters of the working face. In multiple heading tunnels, this flow needs to be diverted or directed to each of the working areas. Air velocity in the entire length of the tunnel needs to be kept moving at a velocity of about 0.5 m/s and to a maximum of 1.5 m/s. In deep tunnels, the temperature is likely to be high to the point where heat stroke and reduces productivity are associated problems. In such cases, consequent (several MW) refrigeration of the air supply is necessary. High ground temperature shall require special evacuation measures (water and muck). The ventilation air is supplied through ducts, which may have a diameter of up to 1.5-2.0 m or more in very large tunnels. If the support needs to be reinforced later, the need to remove and reinstall the ventilation duct and other utilities, such as telephone, power, pump discharge and compressed air supply result in substantial delay in resumption of operations.

The amount of ventilation is largely determined by the amount of diesel equipment and special ground conditions

(coal, gas). The magnitude of the ventilation requirements could be reduced by the use of conveyor systems for spoil disposal and the provision of electric power for other equipment.
If flammable gas is present in the rock, the electrical equipment and switchgear will have to be of an explosion-proof design. Such equipment requires frequent maintenance to ensure its integrity in the dusty and sometimes oily environment; otherwise it will be subject to loss of its explosion-proof rating. The same applies to in-line fans in the ventilation duct. Appropriate gas measurement sensors should be installed.

6.4. HAULAGE AND TRANSPORTATION EQUIPMENT

In long tunnels the transport of materials is really possible only by conveyor or by rail; but even if conveyors are used, rail haulage is still required for transportation of work crews, explosives, equipment and tools, and permanent materials such as tunnel support, concrete and grout materials. In larger tunnels on short distance, trucks and LHDs (load-haul-dump) may be selected. Trucks are common in mines with large workings excavated from a portal or portals; the access adits are necessarily of sufficient diameter to accommodate bi-directional traffic of large vehicles. In civil works construction, such methods are rarely used today because of the impact on ventilation requirements. Rail haulage is still the norm, but electrically driven conveyors are common all around the world. They also have the advantage that they can transfer directly to vertical conveyors in relatively shallow tunnels.

6.5. REUSE OF EXCAVATED MATERIALS

The concept of reusing the excavated materials is becoming an obligation regarding the environmental regulations because of the high quantity of materials involved. Some aspects of the process of reuse have to be pointed out:

- Study phase: a feasibility study should be done, including both geological information and concreting process – precast elements or in-situ lining – in order to make an operating simulation, and to check the quality of the materials and the production of concrete aggregates and/or embankment materials, relating to the consumption and the placing methods.
- Planning of contributions/supplies and needs.
- National regulations: they have to be taken into account regarding the final deposit of materials or waste materials, used water treatment, etc.
- Processing:
  - Depending on the excavation process – drill and blast or tunnelling machine – and on the handling method, care will have to be taken regarding, if required, the choice of the inside primary crusher in order to keep the maximum size of the materials in accordance with the transportation equipment and the secondary crusher, and to reduce the production of fine elements.
  - Primary screening is of major importance to eliminate fine elements (if necessary) and unsuitable materials like metallic pieces, woods, wires, etc.

  - Secondary crushing/screening/washing equipment for concrete aggregates or embankment materials making is to be designed in the most efficient and flexible way in order to produce the best size and form of materials, and to increase the reuse ratio, related to the geological changes.
  - Temporary and final deposit areas, inside and outside the tunnel, are to be designed in accordance with the tunnelling and operating parameters and the selection/storage requirement.
  - Day to day production follow up procedure is suitable in order to adapt the materials production from the tunnel and the demand.
- Concrete: in case of concrete aggregate making, concrete mix-designs have to be implemented as close as possible to the aggregates production ratios.
- Embankment: in case of reuse of low quality excavated materials, lime/cement/hydraulic binders treatment would have to be considered.
- Contractual aspects: the owner of the tunnel project is also the owner of the produced materials regarding both quality and quantity.

6.6. CONCRETE

- Production: inside batching could be the most convenient way to produce the concrete placed within the central part of the tunnel; the right size of the excavation will have considered regarding the erection of the plant and the storage capacity for the components.
- Temperature: high temperatures have to be managed; it is to be taken into account, for production/transportation/placement and hardening of the concrete.
- Long transport distances lead to a very long time between batching and casting of concrete. Specific studies on compaction of concrete have to be done to solve this problem.

7 >> Special conditions for railway tunnels

7.1. TRAFFIC AND CAPACITY NEEDS

Numerous data deriving from railway function have to be taken into account to define the tunnel.
A great railway tunnel, however exceptional it may be, is an element (among others) of the railway system. It has to satisfy the requests of the rail link design of which it is a part. These requests derive from the kind of traffic, line capacity, route performances, and quality of service.

- The kind of traffic (passengers, classical freight, lorries on the train, containers, dangerous materials, but also traction means) will be one of the elements defining the cross section and the maximal slope.

Eurocity train (Cisaplino), 250 km/h

Intercity train, 200 km/h

Freight train, 100 km/h

Conventional wagonload traffic

Unattended combined traffic

Attended combined traffic

Kind of traffic example - Lötschberg base tunnel

- The route performance (route time from the origin to the destination) will depend on the locomotive power, the train weight, the gradient, the resistance progress in relation with aerodynamic characteristics of the trains, and, in tunnels, with the cross section.
- The line capacity between an origin and a destination (total yearly tonnage, daily number of trains according to the kind of traffic) will depend on route performance of all the trains, but also on the signalling, on the number of tracks or, in case of single track, on overtaking points or the number of sidings. Traction capacity is also a decisive factor. In the case of electric energy, it depends on the supplying power by the general electrical network and by the railway system itself (overhead line, sub-stations). In the case of a thermal energy, it depends on the ventilation rate of flow in tunnels.
- The quality of service (performance, but also reliability and frequency) goes beyond the capacity aspect in requiring a traffic organization to be able to satisfy the customers' requests. It depends on the same factors as those defining the capacity, but with more margin and greater flexibility.

Therefore, a long railway tunnel design requires a process that is identical to the process for any other railway project; the process involves:

- Traffic and capacity needs designation with the following assumptions:
  - kind of traffic,
  - characteristics of the trains (traction means, aerodynamics, length, weight, etc.),
  - origin and destination points (generally beyond the tunnel extremities) and time expected between these points,
  - speed limits,
  - yearly tonnage and daily number of trains according to kind of traffic,
  - quality of service with daily sharing between all the kinds of traffic,
  - traction energy (generally depending on that existing in the network the project connects with),
  - kind of signalling which may depend on the existing network,
  - maintenance requirements.
- Infrastructure diagram showing running tracks, sidings, crossing and overtaking points (in case of single track), tunnels, lengths of all these elements, speed limits, signalling. Often, before drawing such a diagram, it is necessary to have already drawn a first layout on a topographical map to obtain expected speeds and tonnage while respecting the rules (minimum curve radius and maximum slopes). This layout, though indispensable for defining the length of the above-mentioned elements and for testing the performances with mathematical model, will not be reached without a geological approach in order to retain the only corridors compatible with the best possible tunnelling conditions.
- The mathematical tests of each kind of traffic planned with the above-mentioned assumptions, particularly geometrical data (curves and slopes), to define the performances, the energy consumption and, in the case of thermal traction energy, the volume of exhaust fumes.
- The schedule design to know the line capacity and the quality of service. According to the results, proposals can be made about the consistency of the infrastructure, either to increase or to decrease them, with a view to the economy. From these results the signalling, power supplying and ventilation equipment, and also the tunnelling works, will be defined. Obviously, an iterative process allows the achievement of an optimal solution.

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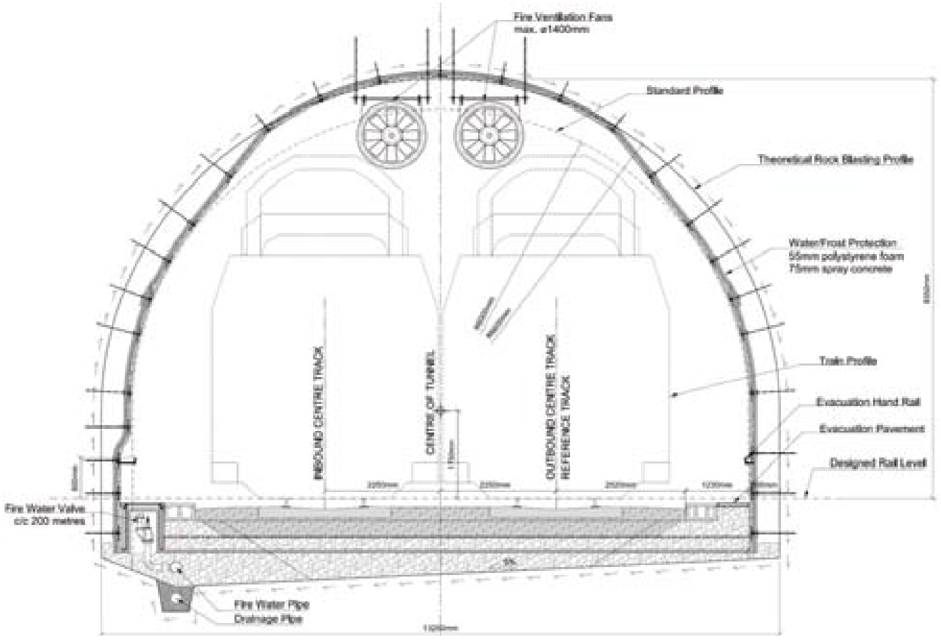
7.2. CONSTRAINTS DRIVEN BY OPERATIONS IN LONG RAILWAY TUNNEL

If any long railway tunnel is, as stated above, only one element among others, it is also a particular element for many reasons.
First, it needs a huge investment requiring special attention to the work definition. But from the functional viewpoint, it is also a particular point because of the confined volume demanding specific running rules in normal or accidental conditions.
Aerodynamics, safety and ventilation studies must be planned rapidly. They may lead to the definition of a new cross section of the tunnel or to the construction of auxiliary infrastructures (Adits, cross-passage ….). In any case, they justify definition of equipment and then the volume needed for their storage for the following two main reasons:

- In normal conditions, a bigger resistance to the progress of the trains affects the route performance and generates greater overheating. High-speed line in a tunnel



ExampleTunnel project Lysaker – Sandvika (N)

requires specific studies to ensure the ear comfort and the eardrum safety because of the pressure wave. The hygienic air renewal has also to be considered. In the case of the thermal traction energy, the evacuation of exhaust fumes has to be taken into account, which might involve a particular system dividing the tunnel into sections to keep a distance between two consecutive trains, allowing sufficient time for air renewal. This could be restrictive in respect of capacity.

- In accidental conditions, for example, if a train is unexpectedly halted, it is necessary to be able to protect passengers; this justifies specific safety studies with different scenarios taking feared events into account. In case of fire, smoke has to be controlled to allow evacuation of passengers and help rescue services.

7.3. SAFETY IN RAILWAY TUNNELS

The safety design always requires a central command including the railway equipment management (signal box and electric traction), as in every railway system for the entire link. Moreover, it also requires the safety equipment management (lighting, sound system, ventilation, smoke evacuation) for the tunnel. The scenarios chosen for passenger protection may involve a particular running with an effect on the signalling design (reversible traffic direction for example) or the electric traction design (particular electric division).
Facilities must also be planned for rescue services and for evacuation and protection of passengers (access galleries, bypasses, refuges, first-aid rooms).
The safety design of a railway tunnel shall take into account the need for provisions for:

- Facilitating the self rescue and evacuation of passengers and train staff.
- Allowing the rescue services to intervene efficiently
  The minimal requirements necessary are:
  - For single-tube tunnel system (with double track), the maximal distance between successive smoke-free exits or safe areas shall be in the order of 1000m (lateral or vertical emergency exit to the surface).
  - For double tube tunnel (with single track) the cross-passages to the other tube shall be provided at least every 500m.
  - Any other system able to provide the same level of safety
- Escape Walkways equipped with Handrail shall be constructed in a single track tunnel on at least one side of the track and in a double-track tunnel on both sides of the tunnel. The width of the walkway shall be a minimum of 0.75 m. The minimal vertical clearance above the walkway shall be 2.25 m. Local constrictions caused by obstacles in the escape area shall be avoided (obstacles shall not reduce the minimal width to less than 0,70m and the length of the obstacle shall not exceed 2m). Handrails shall be placed outside the required minimum clearance of the walkway.

Nowadays, safety requirements for railway tunnels become more and more severe, leading towards a design with two single track tubes, with or without service gallery.
The safety scenario in long tunnels may lead to design tracks for passing trains (loop lines), and crossovers to allow trains to change track.

Sliding door to a crossway

Sliding door to a crossway

Example : Cross-passages of Lötschberg-base Tunnel

7.4. TUNNEL CONNECTIONS TO THE EXISTING NETWORK

The connection points to the existing network are other specific points which may be recognised, for example, because of:

- passing from old track to new track at the time of the putting into service which requires special programming,
- signalling change,
- traction change,
- location to hold the trains (rescue or maintenance trains, commercial trains in the case of single track, siding in the case of incident).

8 >> Special conditions for road tunnels

8.1. SAFETY IN ROAD TUNNELS

Risks have increased in recent years with the ageing of tunnels. Most important tunnels have indeed been built to specification that with time have become outdated: either their equipment no longer corresponds to the state of the art or traffic has significantly increased since their initial opening. Moreover, the main causes of accidents are: incorrect behaviour of road users, inadequate infrastructure and operation, vehicle defects, and problems with load such as chemical reactions.
Among the possible risks, vehicle fires give rise to particular concern because they are not very rare events and their consequences might be far greater underground than in the open, if no appropriate measures were taken. Also, due to the continuous decrease in vehicle pollutant emissions, the ventilation equipment is, in many cases, determined by smoke control considerations in case of fire, not by normal traffic conditions.
New standards have been proposed by PIARC and by the European Commission for Energy and Transport, with similar objectives:

- **Prevention**
  The primary objective is to prevent critical situations which endanger human life, the environment and the tunnel installations.
- **Reduction of possible consequences**
  The second objective is to provide the best pre-requisite for people involved in the incident to rescue themselves, to allow for the immediate intervention of road users to prevent greater damage, to ensure an efficient action of emergency services, to protect the environment and to limit material damage.

8.2. ORGANISATIONAL AND TECHNICAL REQUIREMENTS

Technical inspection bodies. A Technical Inspection Body will be appointed to carry out safety evaluations, tests or inspections. The Administrative Authority itself may perform this function but an organization involved with tunnel management cannot be accredited as an Inspection Body.
Tunnel managers. For each tunnel a single tunnel manager shall be recognized by the Administrative Authority. The tunnel manager may be a public or a private body and is responsible for the operation of the tunnel. For border tunnels, the two Administrative Authorities shall recognize only one and same tunnel manager.
Independent safety officers. For long tunnel, a tunnel manager may be nominated an independent safety officer who will supervise all preventive and safeguards measures to ensure the safety of users and the operation of staff. The safety officer shall be independent on all road tunnel safety issues and not be subject to instructions from an employer in respect of those issues.
Number of tubes. Single-tube tunnels should only be built if long-term forecasts show that the traffic volume within the tunnel will remain moderate; otherwise, twin-tube tunnels should be considered and in this case the option of “staged investment and construction” can be adopted if adequate funding cannot be assured in the short term.
Escape routes. For tunnels with bi-directional traffic the construction of special escape routes or safety galleries is mandatory.
Ventilation. Single tunnels with bi-directional traffic shall have transverse and/or semitransverse ventilation with exhaust possibilities. Longitudinal ventilation pushing smoke in one direction shall be used in these tunnels only when traffic conditions allow uncongested vehicles to drive out of the tunnel.
Emergency exists. If local conditions show that the above-mentioned provisions are insufficient, short perpendicular escape adits to the open or a parallel safety adits with cross connections for self-rescue at intervals of less than 500 meters shall be constructed to allow people to escape on their own. Shelters without an exit leading to escape routes to the open shall not be built.

Distance between drivable cross-passages should be properly defined.
Additional provisions for:
- **Twin-tube tunnels:** in the event of an incident in one tube the other tube is used as the escape and rescue route. Pedestrian cross-connections may link the tubes at maximum intervals of 350 meters. Every third cross-connection shall allow the passage of emergency service vehicles. Propagation of smoke of gases from one tube to the other shall be prevented.
- **Tunnels with a gradient:** as they can increase potential risks, longitudinal gradients above 3 % shall not be permitted.
- **Congested tunnels:** stricter ventilation standards apply to unidirectional congested tunnels.
- **Underwater tunnels:** a risk analysis must be carried out to determine whether partial or total restrictions for the transport of dangerous goods are needed.

Minimum equipment for all tunnels:
- Escape routes: shall be indicated by proper lighting.
- Fire extinguishers: need to be systematically installed in the long tunnels.
- Radio broadcasting equipment: needs to be available in tunnels with special channels for emergency services use. The Tunnel Manager and emergency services shall be able to interrupt radio broadcasting for emergency messages.
- Video monitoring system.
- Safe feeding of high-voltage and low voltage.

8.3. OPERATION

An operation concept is required for each tunnel. An example of the management of the operation and safety systems is given in the following table, valid for an uni-directional traffic, extracted from the new Swiss SIA code for road tunnels.

Supervisory system (triggered by)	**Fire detection system in tunnel**		**Fire detection system in buildings**	**Emergency telephones**	**Automatic incidents detection (image processing)**	**Centralized traffic management center (manual operation)**	**Centralized operation center (manual operation)**
Operating system (action)	**Fire alarm**	**Fire extinguishers removal**	**Fire alarm**	**Call**			
Tunnel ventilation	Set automatically to “Fire Mode”	Set automatically to “Fire Mode”	---	---	---	Tunnel operation mode ▫ fire ▫ accident ▫ maintenance (according to manual selection)	All the operation modes (according to manual selection)
Centralized traffic management center (road police)	Alarm from centralized traffic management center	Alarm from centralized traffic management center	Alarm from centralized traffic management center	Answer to call	Alarm from centralized traffic management center	---	---
Fire detection center	Alarm from fire brigade center	Alarm from fire brigade center	Alarm from fire brigade center	---	---	---	---
Traffic monitoring CCTV	Several cameras switched ON	Several cameras switched ON	---	Several cameras switched ON	Several cameras switched ON	Normal operation	Normal operation
Tunnel lighting system			---	---	---	Normal operation	Normal operation
• longitudinal lighting	stays in operation	stays in operation					
• pedestrian lighting	stays in operation	stays in operation					
• emergency lighting in case of fire	switched on	switched on					
Traffic management system	Tube under fire: closed (red lights at portal) Tube without fire: warning (flashing lights at portal)	Tube with fire extinguishers removed: closed (red lights at portal) Tube without fire extinguishers removed: warning (flashing lights at portal)	Road lanes closed (red lights at portal) ---	Tube with origin of call: warning (flashing lights at portal) Tube without origin of call: normal operation	Offender spotted: tube closed (red lights at portal) Stopped vehicle spotted: warning (flashing lights at portal)	Normal operation	Normal operation
Building ventilation	---	---	Fire dampers closed	---	---	---	---

9 >> Special conditions for hydraulic tunnels

9.1. DESIGN FOR INTERNAL WATER PRESSURE

• General
Hydraulic tunnels are generally one element of the whole water conveyance system and as such have to fulfil some particular design requirements. The main design considerations regarding internal water pressure are shortly listed hereafter:

• Rock Susceptibility to Erosion and Deterioration
One of the first questions to be posed is the stability of rock in contact with water, i.e. its susceptibility to erosion and deterioration. Rocks containing soluble materials or a high amount of clay, especially if they have swelling characteristics, are prone to erosion and deterioration, mainly along weathered seams and faults. This process can lead to a loosening of the rock around the tunnel and therefore to a reduction of its strength and finally to a loss of the bearing capacity with consequent collapses.
Such rocks have generally to be concrete or shotcrete lined in order to avoid the disintegration process and to maintain the long term stability of the tunnel.

• Location of Natural Ground Water Level
The elevation of the natural ground water table plays a major role for the design of a hydraulic tunnel. A water table located above the internal water pressure line is desirable for the plant operation because it prevents any leakage from the Headrace Tunnel and hence no special lining requirements regarding water tightness have to be stipulated for this case.
On the other hand, if the natural ground water table lies below the internal water pressure line, leakage from pressurized tunnel will occur, depending on the permeability of the liner and bedrock as well as on the prevailing internal pressure conditions.

• In-situ Rock Stress
The knowledge of in-situ stress is fundamental for the design and construction of pressurized tunnels. Sufficiently high stresses are required in the surrounding rock mass in order to avoid hydrojacking.
Hydraulic jacking will develop when the hydraulic pressure within a joint or bedding plane exceeds the normal stress acting upon the plane. If this condition cannot be excluded, a lining has to be designed to control the water losses.
A concrete or shotcrete lined tunnel is seldom watertight. The internal water pressure propagates through cracks in the lining into the adjacent fractured rock mass. If this water pressure is higher than the minor in situ rock stress, the existing rock discontinuities may progressively open and the permeability can increase by several orders of magnitude.
In the preliminary design phase, rules of thumb related to the overburden, are used to judge the adequacy of the prevailing primary stress conditions. However, these have to be checked during the construction by means of hydrojacking or hydrofracturing tests.

• Rock Permeability
A low rock-mass permeability in stretches not prone to hydrojacking limits the leakage rate of a headrace tunnel effectively, especially for tunnels without reinforcement.
With the rock permeability increasing, the sealing function is more and more transferred to the tunnel lining. However, a plain concrete lining can fulfil the sealing requirements only if the strains are small enough, that no longitudinal cracking occurs. Also reinforced concrete lining, even with a heavy reinforcement, cannot be considered as impermeable, since it cracks due to shrinkage. Therefore, if high sealing properties are required from a tunnel lining, special constructive measures, such as steel linings, steel membranes, grouted membranes or prestressed concrete linings are required.

• Deformation Modulus of Rock
A high rock deformation modulus means a high rock participation in the load sharing between lining and rock, thus, if the continuity is reliable, it decreases the liner strain, stresses and permeability. It plays a role in border line cases regarding ground water table and permeability and may have, in such cases, an influence on the required reinforcement content.

• Internal Pressure
Outward leakage problems can be avoided in hydraulic tunnels if the natural head of the ground water table is higher than the internal water pressure. If this is not the case, then adequate confinement must be ensured.
If these conditions can not be fulfilled by a reasonable tunnel alignment, adequate lining measures are required to avoid leakage (reinforced shotcrete / concrete lining, consolidation grouting, grouted membrane or even steel lining).

9.2. LINING CONCEPT

While unlined / shotcrete lined tunnels have obvious important economical and construction time advantages compared to conventional cast-in place concrete linings, a decision must be made on a case specific basis, whether or not a lining is necessary. It must be realized that in many ground conditions there may be disadvantages of such a design, which may necessitate greater maintenance requirements, and hence consideration should be given to full lining implementation.

9.3. CROSS SECTION

The cross section shall fulfil the following requirements:

- The tunnel size shall be optimized regarding hydraulic friction losses using conventional methods
- The friction loss coefficients shall be adapted to the quality of the effective excavation works and the type of lining (steel, concrete, shotcrete).
- If necessary to minimize plastified zones around the excavation and to enable reinforcement against internal water pressure, the shape shall be as close to a circle as possible
- The horizontal invert shall be as wide as practical. It shall, as a rule, be concrete lined for improved trafficability, for prevention of excessive rock loosening/removal due to heavy traffic movement during construction and as an erosion protection during filling and emptying (for unlined tunnels).

9.4. SPECIAL MEASURES TO REDUCE LEAKAGE

• General

The lining system of hydraulic tunnels is generally not fully watertight and hence the interaction with the ground water table requires particular considerations. Special sealing measures are required for the following cases:

- Leakage losses should be economically evaluated and should be reduced by additional sealing measures
- Leakage losses may trigger instability of nearby slopes
- Large scale drainage may be environmentally unacceptable

For such cases, emphasize has to be given to reduce seepage losses and one of the following possibilities may be envisaged:

• Consolidation Grouting

High permeability rock surrounding the tunnel can be treated by consolidation grouting carried out from the tunnel. However, the rock must be groutable and the minimum permeability achievable with conventional grouting is in the order of magnitude of k=10-5 cm/s.

• Heavy Reinforcement

Concrete and shotcrete linings can be reinforced to efficiently reduce the width of cracks developing after loading (first filling). A practically watertight lining is achieved if the crack width is limited to 0.1 mm. Such cracks are generally fully clogged by silt particles after a relatively short time of operation.

• Grouted Membrane

A membrane of 2.5-3.0 mm thickness can provide full watertightness if carefully applied. The annulus behind the membrane has to be grouted and an inner ring of reinforced concrete is required to support the membrane in case of revision (emptying) of the tunnel.

• Steel Lining

Steel lining is the most effective but by far the most expensive sealing measures. It is generally applied in the tunnel portal area as interface between penstock and tunnel, near gates and valves and in areas with insufficient rock confinement. A special application is the crossing of potentially active faults where relative displacements of several decimetres during an earthquake are expected. Such systems are provided with hinges in short distance and mounted on individual supports.

9.5. ACCESS AND DEWATERING FACILITIES

Hydraulic tunnels require adequate access possibilities for maintenance. Depending on the tunnel diameter and length, access shall be possible with or without vehicle. For tunnel stretches longer than 5-7 km, a vehicle should be available for inspection and small maintenance activities. For cleaning the rock trap, a near-by access for vehicles should be provided whenever possible. Access possibilities may be provided by the Safety Valve at the downstream end of the headrace tunnel and/or by a roll-out section on the top end of the penstock/inclined pressure shaft. Drainage of hydraulic tunnels is possible either through the turbine, a by-pass pipe or a rollout section. A particular drainage concept is also required for the rock trap. Dewatering by gravity is sometimes possible through separate pipes located on a lower elevation. However, in many cases, dewatering of the rock trap is performed by mobile pumps installed only for the duration of maintenance.

9.6. CONSTRUCTION

Excavation methods and temporary support are basically the same as for other tunnel types. Some particular developments are mentioned hereafter:

• TBM-Excavation with Precast Segment Lining

For long low pressure headrace tunnels with relatively high external ground water pressure, a recent tendency to the excavation with TBM and contemporary installation of pre-cast segments (mostly honey-comb) as final lining can be observed. The great advantage of this system lies in time-saving. Soon after the TBM's breakthrough, the lining works are also completed.

• Temporary Construction Adits

Hydraulic tunnels, particularly headrace tunnels, are often confined on both sides by important structures which have to be built at the same time (intake structure upstream, valve and surge chamber downstream). In order to avoid hindrances and frictions between the tunnel and outdoor structures, separate construction adits are mostly required.

All temporary adits leading to the water ways will have to be plugged at the end of the construction period, mostly using mass concrete. According to the general concept and the headrace tunnel diameter, some will be equipped with bulkhead doors to provide maintenance access for vehicles, others with manholes or dewatering facilities only, larger ones incorporating a short adit for grouting.

Plugs should be designed such that their length satisfies criteria for acceptable shear strength and hydraulic gradients around the plug.

9.7. OPERATION AND MAINTENANCE

• General

The most critical operation phases for a hydraulic tunnel are filling (particular first filling) and emptying the tunnel. During tunnel excavation, the ground water level in the rock mass is generally lowered down because the tunnel drive acts as a drainage gallery. The degree of ground water level lowering depends on the rock permeability and water replenishment conditions.
During filling and emptying procedures, the water pressure conditions in the vicinity of the tunnel are changed fundamentally and this has to be considered when the filling and emptying rates are defined.

• First Filling

The filling of the tunnels is required to be carried out in such a way that several days are provided for gradual adjustments of ground water pressures and transferring of internal pressures to the rock around the lining. Thus, filling rates / pressure increases of about 1 m/hr or even less are generally foreseen.
The possibility of using higher filling rates require to be decided considering the actual geological conditions, the extent of steel lined or concrete lined sections and tunnel gradients.
To check the adequacy of the filling flow rate, the water volumes required for the restoration of the mountain water table (filling of voids, drained by the tunnelling activities) may be roughly estimated.
The water levels in the tunnel shall be controlled with the pressure monitoring instrument often installed for the surge shaft or the pressure gauge at the powerhouse.
After filling of the tunnel, the net water outflow or inflow are measured. Visual inspection of the plugs shall be made and potential leakage flows estimated. Potential water inflows in existing access galleries shall be monitored before and after tunnel filling.
Critical slopes, which could be affected by the tunnel filling shall be inspected for possible new springs, especially in the downstream portal area and along the penstock or pressure shaft alignment.

• Emptying of Tunnel

The emptying flow rate should even be smaller than the filling rate as sufficient time shall be provided for the reduction of excess pore water pressure near the tunnel excavation boundary.
The routine inspection after emptying of the tunnel shall be focussed on the following points:
- General state of the tunnel by visual inspection, photos
- State of the lining: surface, detection of cracks, fissures
- Water inflows, measurement or estimate of quantity and pressure (inflow without pressure or length of potential water jets)
- Detection and removal of loose rock pieces
- Volume estimate and removal of material in the rock traps, grain size distribution
- Significant deformations

• Maintenance Works

Water conveyance tunnels generally are emptied and inspected after first filling and prior to full commissioning, after the first year of operation, and, later on, every 3-7 years. In some cases, unlined tunnels have not been emptied after commissioning, since the emptying procedure presents higher risk conditions than operation.
Vehicle access to the rock trap, for tunnel inspection and for the removal of the accumulated material in the rock traps, shall be provided. Whenever possible, the passage of vehicles over the rock traps shall be avoided.

10 >> Special conditions for subsea tunnels

10.1. GROUND CONDITIONS

Subsea tunnels are quite special in several ways. Concerning engineering geology and rock engineering, the following factors are the most important.
Most of the project area is covered by water. Hence, special investigation techniques need to be applied, and interpretation of the investigation results is more uncertain than for most other projects.
The locations of fjords and straits are often defined by major faults or weakness zones in the bedrock. Also in generally good quality rock conditions, the deepest part of the fjord, and hence the most critical part of the tunnel often coincides with weak zones or faults, which may cause difficult excavation conditions.
The potential of water inflow is indefinite, and all water leakage has to be pumped out of the tunnel due to its geometry. The consequences of cave-in or severe water ingress in a subsea tunnel may be disastrous. Stability problems due to major weakness zones represent a threat to hard rock subsea tunnel projects. In some cases, severe instability has occurred. In the majority of such cases, the problem has been caused by faulted rock carrying clay minerals and water leakage of relatively high pressure.

A typical weak zone consists of heavily crushed and/or altered rock. Gouge material of swelling type (smectite) is often found in such zones. Swelling pressures of around 1 MPa is common, and in extreme cases swelling pressure of more than 2 MPa has been experienced. The particularly high activity of smectite in subsea tunnels reflects the ability of the clay mineral to absorb Na+ from sea water. Major water inflows have been found relatively rarely to be directly connected to the major weakness zones, probably mainly due to the high content of low permeability gouge of such zones. Distinct, continuous single joints apparently are more important. The magnitudes and orientations of rock stresses definitely have influence on water inflow. The effect is, however, complicated by factors like anisotropy and channelling.

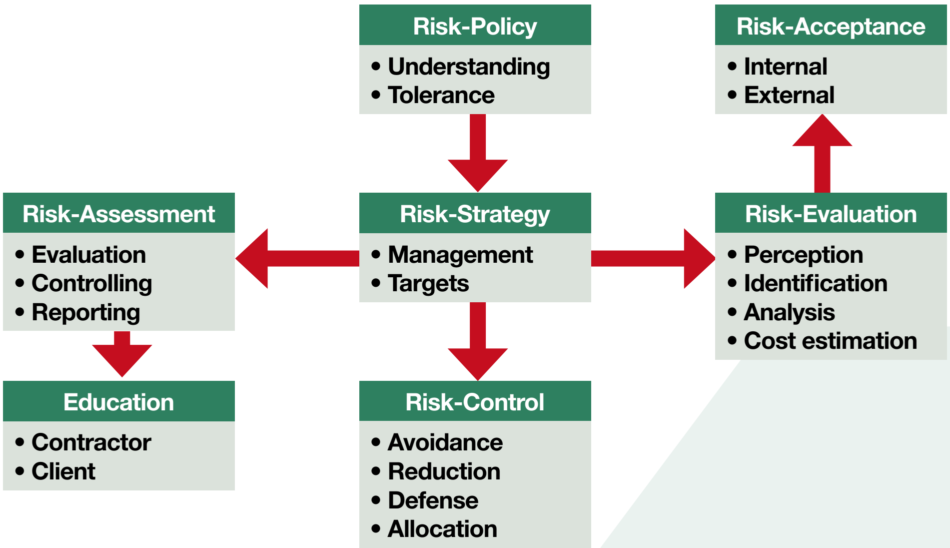
10.2. SAFETY MEASURES DURING CONSTRUCTION

The special challenges of subsea tunnelling require thorough planning and execution of the excavation works. The following important safety measures are standard today in Norwegian subsea conventional tunnelling:

- Systematic long exploratory drill holes ahead of the tunnel working face. In addition, longer exploratory core drill holes where possible poor quality rock masses can be expected.
- High pressure pre-grouting ahead of the tunnel face if water bearing zones, and/ or poor rock mass qualities have been detected in the exploratory holes.
- A high pumping capacity for de-watering the tunnel in case of unforeseen water ingress.

10.3. OTHER PROBLEMS

The saline character of leakage water represents considerable problems for tunnelling equipment and rock support materials. Shotcrete is broken down by seepage in salt water. Poor quality shotcrete is much more susceptible than high quality shotcrete. Consequently, stringent rules have been made for the use of shotcrete in tunnels. So far, corrosion has not resulted in any great problems for subsea tunnels. However, electrical equipment, pumps and piping have had to be replaced in several tunnels because of corrosion. Attention must be paid to the choice of corrosion resistant materials. Damage to aluminium linings by salt water has been registered in some tunnels. The corrosion damage to the aluminium linings due to seawater is of such a scale that the linings must be replaced.
The most extraordinary problem in subsea tunnels is algae. This phenomenon exists in a number of tunnels. There appears to be no connection between type of rock and the presence of algae. Experiences would tend to suggest that algae or microorganism population expands to a certain level before collapsing and starting all over again. Seawater leakages on the asphalt surface make the asphalt quite slippery, possibly because of the algae.



11.1. INTRODUCTION

The design and construction of long and deep tunnels, as well as the tunnels located in urban areas, are often associated with the risks arising from the inadequacy of geotechnical information, a wrong choice of construction methodology, and a potential accident during construction
A certain degree of uncertainty and, therefore, the resulting level of risk, are not completely avoidable regardless of the experience, the time, and the costs incurred.
However, most risks can be managed through the use of a Risk Management Plan, RMP, which aims to identify and quantify the risk or potential problem, select and implement the measures for mitigating or controlling the risk, and indicate if there is a residual risk which would need to be shared among the Parties involved in the project.
The following guidelines for developing a RMP are in the ITA-WG 2 Risk management Guidelines (TUST 2004, p. 217-237).

Definitions

A project has events or hazards which may give rise to the elements of uncertainty.
Each event is associated with a probability of occurrence, P, and impact, I, in terms of safety, time, and cost. The risk, R, associated with an event is generally defined in the literature as a product of the probability and the impact: R = PxI.
For each risk, it is necessary to determine the level of acceptance which allows to define if the risk can be assumed, or minimized, using appropriate counter measures for reducing the probability or impact of the various negative factors.
The residual risk is defined as the risk that remains after implementation of the actions for mitigation. The residual risk should be evaluated for its acceptability.

Types of risk

The types of risks that may be encountered in underground works are:

- geologic risk, connected with the sufficiency of information obtained through the planned investigations;
- design risk, especially connected with the difficulty of adapting the design to the encountered geomechanical conditions, poor construction, experience of the designer, and contractual constraints;
- construction risk, connected with the choice of an inappropriate or insufficiently industrialized construction technique, occurrence of instability, experience of the contractor, and the contractual constraints;
- financial risk, connected with the social and political constraints, unclear assumption of responsibility, litigation, and security (this risk is not specifically addressed in this article).

11.2. RISK MANAGEMENT PLAN (RMP)

• Parties and contributors

The Parties directly involved in tunnelling projects, as in general in all the construction projects, with specific roles and responsibilities are:
- the Owner,
- the Designer,
- the Contractor,
- the Engineer.
The needs and objectives of the above parties may be different or in conflict. However, the Parties shall directly plan, design, construct and manage the infrastructure whose exploitation may condition also other subjects (the population) and impact on the environment.
The evaluation of consequences of the realization of long and deep tunnels shall be taken into account, in all the phases of the process, the needs and expectations of other parties, that are not directly involved.
The adoption of the RMP is in the primary interest of the Owner, who shall assume the leadership in managing it, and it should be the responsibility of the Owner to adequately take into consideration the point of view, needs and objectives of all the other parties, directly or indirectly involved, and of the final users (particularly for road and rail tunnels).

• Time scale

The time span between the decision to build a long and deep tunnel and to bring the tunnel into operation is usually several years, often up to 10 or 15 years. In this time interval, modifications may occur, that change the project situation, in terms of requirements, processes and impacts. As an example, the problems of safety during operation of long road tunnels have become extremely important in the last ten years.
Regarding the design and construction activities, it is expected that the modifications are – with time – going in a positive direction: research studies, feed-back from experience, and innovations in construction technologies contribute to general improvement. Other aspects may change in different direction, for

example political and economic situation that may negatively influence the project or some of its stages.
In the RMP all the parties involved shall do their best to assess the key aspects taking into account the time scale factor.

• Risk identification
Risk identification is the central issue and starting point of a RMP.
Typical variables associated with a risk-inducing hazard are:
- general conditions (political, economical, financial and social);
- environmental conditions;
- skills of available resources (of all the Parties involved);
- the extent of site investigation;
- flexibility of design and construction method to diverse ground conditions;

General conditions are often related to politics and social constraints, unclear assumption of responsibility in multinational projects, inadequacy or incompleteness of the general feasibility studies, that may lead to weakness in the definition of the scope of work and may constitute reason for disputes and claims. These variables are difficult to quantify, but can assume significant proportions in the development of big tunnelling projects.
The extent of the site investigation contributes to the risk potential if it has failed in the identification of hazards and in the definition or limitation of their uncertainties.
Regarding the design phase, risk is usually linked to low structural reliability, but several other sources of risk may be identified, for example, in the lack of adaptability; in the introduction of novel solutions, for which only a limited experience is available; in the inadequate design in terms of safety and ordinary maintenance; and in the weak assurance of constructability of the proposed design solutions.
In the construction phase, risk is mainly associated with wrong estimates of construction time and cost, with selection of inadequate construction method and equipment, with inappropriate type of contract in terms of risk sharing, and with optimistic evaluation of advance rates.
Risk identification is not restricted to the phases of planning, design and construction; it also involves the entire operation of the structure to be built; therefore, it should be recognized as a continual process that should be managed by the Owner with appropriate procedures.
The process of risk identification requires the creation of a team of specialists, the continual collection of all the available data, the availability of reference models for estimating the variations of the actual conditions, and the planning of common work sessions among the Parties to analyzes the extent, likelihood and impact of the various hazards.

• Risk quantification
In the field of tunnelling, risk quantification is based on a combination of objective and judgmental (experts' opinion) approaches. This is true for quantifying both components of risk, the probability of occurrence of a problem (or hazard) and the resulting impacts (loss or damages).
These two factors may be qualitatively classified by assigning the following levels (or scales):
- **Probability of occurrence (of the problem):**
  - Very likely
  - Likely
  - Occasional
  - Unlikely
  - Very unlikely
- **Impacts:**
  - Very high
  - High
  - Medium
  - Low
  - Very low
- **The combination of probability and impacts give the scale of the risk:**
  - negligible
  - acceptable
  - not acceptable

The above levels may be translated into quantitative weights to perform a quantitative risk assessment. This second approach requires to take into account uncertainty, i.e. to define the possible variation of the elements under study (minimum, maximum, and most likely value) by assigning a statistical distribution.
Judgmental quantification becomes necessary when the nature and extent of the data are not susceptible to statistical manipulation or when a large set of data is available, but the statistical analysis of the data cannot identify the specific problem.

• Development of response to risk
The response to risks (RR) consists of procedures for managing risks both technically and financially.
The technical countermeasures must form an integral part of the overall design. The RR should be updated in the course of the project, as a function of the variation in the risk environment.
Although a RR is technically indispensable for facing risks, the financial implications of dealing with risks require an 'a priori' definition of specific contractual clauses. Most risks can be, by contractual arrangement, assigned either to the Owner, or to the Contractor, or can be shared between them. In general, forcing the maximum assumption of risk to one side (contractor or owner) is likely to result in high project costs.
For example, with regard to ground conditions, the most efficient RR is to adopt risk-sharing approach. Risk sharing should aim at providing an incentive for the timely completion of a project.

• Monitoring of response to risk
The objective of monitoring the response to risk is to determine the extent to which the actual response has reduced the specific risk.
The following considerations should form an important part of monitoring the response to risk:
- monitoring should not be viewed as an obstacle, but accepted as a necessary ingredient of a safer and more economical construction;
- every parameter selected for monitoring should in fact be critical; every procedure should

have a clear and defined purpose;
- a clear and timely communication about the results of monitoring is essential.

12 >> References / Special thanks

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