SAFETY IN LONG SUBSEA RAIL TUNNELS

Timo Salmensaari 2010

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Abstract:

Increasing traffic and emerging interest for fixed ground connections provides possibilities for economically viable tunnel connections. Knowledge in underground construction and tunneling techniques provide great opportunities for constructing tunnels both on land and under the sea. At the moment, there are several tunnel projects are under construction or in a serious planning phase in Europe and Asia.

Tunnels are challenging spaces in terms of safety. Compared to an open space, evacuation possibilities are very limited and rescue personnel needs additional equipments to reach underground locations. Safety issues both in construction and in operational phase are evident factors that influence the possibility and feasibility of a tunnel project.

The main challenges regarding safety in tunneling are evidently different kinds of accidents. In a subsea tunnel the most severe risk scenarios are fire and flooding. Other important factors are reliable operation and handling of aberrant situations. Prevention of potential risks in advance and a rapid response are the key guidelines when planning a safe long tunnel. It is vital to make detailed plans of action to be prepared for emergency situations.

Previous projects have clearly proven the benefits of careful pre-investigations in tunnel construction. Despite the fact that they cannot provide complete information on the study area, they still give a necessary overall picture and reveal potential problems. A good understanding on the surrounding environment is important in order to select the best possible solutions as basis for tunnel planning.

Based on lessons learned from previous projects and the latest Nordic planning standards, this publication concludes methods for constructing a safe long subsea rail tunnel for freight or passenger use.

Preface:

This publication is based on Master's Thesis of Timo Salmensaari 2010. Thesis was written for Aalto University and supervised by Professor of Engineering Geology Jussi Leveinen. Instructor for the project was Ilkka Vähäaho from Geotechnical Department of City of Helsinki. Project was supported by cities of Helsinki and Tallinn. Author wishes to thank all the people involved in project.

Safety in Long Subsea Rail Tunnels

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Definitions:

Active safety - Systems to prevent problems and react to impulses. Eg. tunnel surveillance, fire extinguish systems

Acoustic surveying – A geophysical surveying technique taking advantage of sound waves reflecting from material interfaces

Aerogeophysics – Performing geological surveys airborne, with an aeroplane or a helicopter

Bath effect – Change of sea level in an almost closed system, where weather conditions affect differently around the area. Eg. The Baltic Sea.

Drill 'n' blast - Tunnelling method using explosives to break the rock

Expandable clays - Clays that are characteristically capable to volume changes related to water concentration

Fracture – Local discontinuity of rock mass, causing decreasing rock strength

Fracture zone - Area of fractured poor quality rock, possible problems with water seepage

Fire safety - Combination of measures to prevent fire and react to escalated fire. Eg. fireproof materials, evacuation procedures

Ground penetrating radar (GPR) - Geophysical surveying method using radar pulses and their reflections and refractions

Grouting - Injecting cement in rock mass to reduce water seepage and to increase stability

Hard rock – Igneous or metamorphic rock types. Eg. granites, gneisses

Hydrogeology –groundwater distribution and movement in soil and rocks

Lineament - Characteristic features of individual data. Eg. similar geological structures

Passive safety - Safety measures for preventing problems and reducing their probability without any continuous actions. Eg. Fireproof materials

Magnetic surveying – A geophysical surveying method measuring magnetic properties of soil

Marine geophysics – Geophysical surveys performed on sea

Piston effect – Movement of air in the tunnel as a train moves

Q-index - Engineering geology index for describing rock quality

RQD-index - Engineering geology index for describing rock quality

Scaling – Securing working area by removing loose rocks

Seepage - Water inflow to tunnel through tunnel walls

Seismic surveying – A geophysical surveying technique

Shotcrete – Concrete shot on tunnel ceilings to reinforce the tunnel

Single tube - see Tube

Soft rock – Sedimentary rock types, Eg. sandstone, limestone.

Spalling - Mechanism of rock or concrete weathering occurs at the surface of a rock when there are large shear stresses under the surface.

TBM - Tunnel Boring Method, a method for continuous tunnel drilling, commonly used in soft rock environment. Drills are size of a tunnel diameter.

Tube - Tunnel, a term used to describe tunnel layout. Eg. Twin tube - two parallel tunnels

Twin tube - see Tube

Ventilation shaft – A shaft for transporting air in and out of tunnel.

Water mist systems – Sprinkler extinguishing systems, which use high pressure to produce water mist. Effective in cooling down fires.

Wire mesh – Iron grid used to reinforce tunnel ceilings in poor rock quality.

1 Introduction

1.1 Emerging interest in long tunnels

Modern tunnelling technologies allow construction of longer and still economically viable tunnels. Safety issues in both construction and operational phase are evident factors that influence the possibility and feasibility of a tunnel project. Tunnels exceeding the length of five kilometres can be considered long, and tunnels longer than 50 km have been constructed for subsea rail traffic. Several longer rail tunnels are currently under construction and many others are planned. Main challenges for tunnel safety are evidently different kinds of accidents. Additionally, reliable operation and handling of aberrant situations are important issues concerning safety in long rail tunnels.

Another interesting topic is risk management in tunnel building as financial risks are relatively huge in capital intensive infrastructure construction projects. In order to deal with the risk management issue, the following questions need attention in order to ensure that a project becomes a successful one.

- How to prepare to deal with the unexpected problems and what can be done to prevent them from realization?
- How detailed investigations are needed in forehand and what are their key benefits and weaknesses?
- What can be learnt from previous projects?

This thesis will provide basic background information about rail tunnelling and a more focused insight to safety in long rail tunnels. The study focuses on Nordic hard rock conditions, but the basic principles are similar globally.

1.2 Tunnel safety in general

The fact that tunnels are underground brings some additional limitations for movement and rescue, and also more factors of uncertainty in contrast to open space. During the construction phase safety refers to work safety for tunnel constructors against fire, cave-ins or other hazards. In addition, unexpected geological conditions faced during construction may develop issues of safety for human lives, risks for machinery, and project feasibility in financial aspect.

Considering a subsea tunnel the risk for massive water inflow would be catastrophic, and can not be tolerated.

During operational phase safety relates mainly to evacuation and rescue possibilities for tunnel users in different kinds of emergency situations. As tunnels are closed spaces, fire is one of the most severe threats in a tunnel. Rapid spread of smoke will dramatically reduce rescue possibilities and fires have a tendency to develop violently. Therefore, safety issues need to be carefully surveyed and actions in different scenarios planned in advance to be ready to act if something goes wrong.

1.3 Geological outline of Finland and surroundings

Characteristically Finnish bedrock is old and hard covered by a thin layer of sediments. Geological conditions in Finland are stable, and the combination provides great opportunities for underground construction. Strength of rock allows constructing large underground spaces with relatively thin rock cover. Typical rock types over the long geologic history of Finnish Precambrian soil are different granitoids and gneiss. However, tectonic activities have caused various joint and fracture zones, which are a challenge to rock engineering. Geological map of Fennoscandian Shield is shown in ILLUSTRATION 1.1. [The Fourth Wave of Rock Construction, 1997]

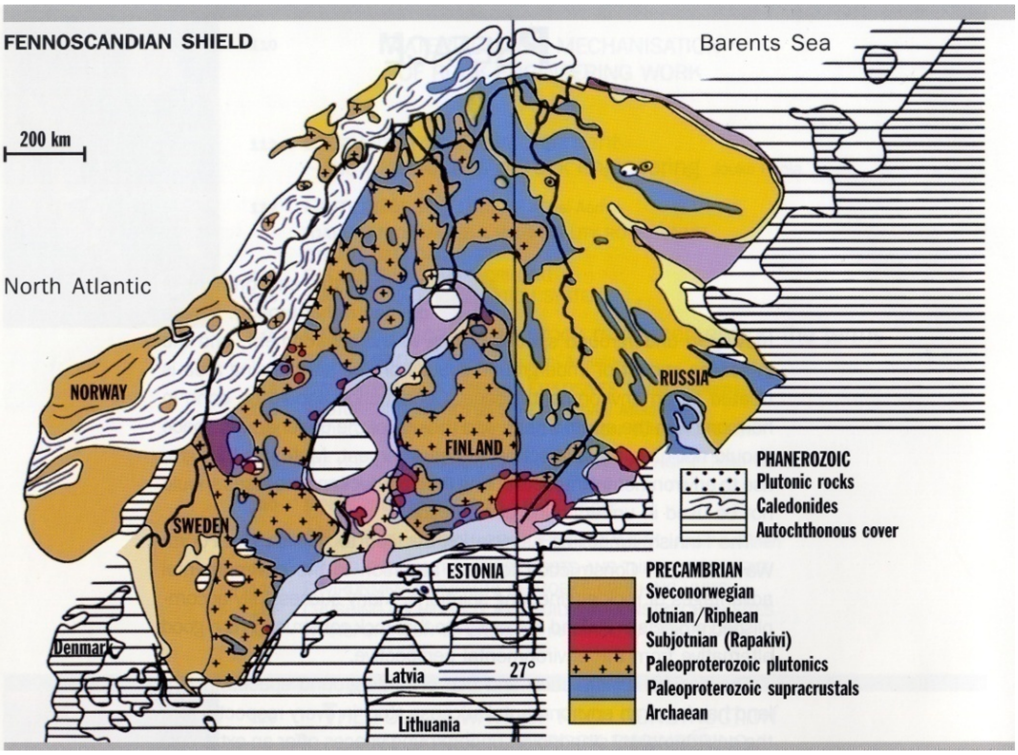


ILLUSTRATION 1.1. Geological map on Fennoscandian Shield [Fourth Wave of Rock Construction,1997]

Compared to its southern neighbour Estonia, Finland lacks almost completely sedimentary rocks as a result of erosion during ice age. Coarse geological map in surroundings of Helsinki and Tallin is shown in ILLUSTRATION 1.2. The depth where bedrock is found descents gradually under the Gulf of Finland. At the Estonian side near Tallinn bedrock is found at the depth of 200 meters as seen in ILLUSTRATION 1.3. [Koistinen, T (ed.); 1994]. A more detailed version is found in Annex 1.

ILLUSTRATION 1.2. Geological map in surroundings of Helsinki and Tallinn [Source: Koistinen, T.(editor), 1994. Precambrian basement of the Gulf of Finland and surrounding area, 1:1 mill. Geological Survey of Finland, Espoo]

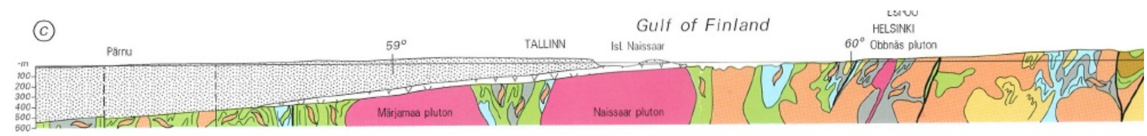


ILLUSTRATION 1.3. Geological cross section in surroundings of Helsinki and Tallinn [Source: Koistinen, T.(editor), 1994. Precambrian basement of the Gulf of Finland and surrounding area, 1:1 mill. Geological Survey of Finland, Espoo]

1.4 Helsinki – Tallinn vision and similar visionary projects

Helsinki and Tallinn are two capital cities in EU Shengen-area separated only by a sea and a distance of 90 km. The cooperation between the cities has been increasing rapidly during the last decade in multiple areas. Business and leisure travel between the cities is vivid. Currently, the traffic is carried out mainly by ferries, but in long term visions a fixed rail connection is visioned. A rail connection through a tunnel would not only ease the movement of labour and business travellers, but also provide possibilities for further cooperation. Tunnel would as well serve as a part of a direct rail connection from Helsinki to Central Europe. Also a international railway connection from St. Petersburg via Baltic countries could be routed through Helsinki and Tallinn.

Different routes for tunnel and preliminary plans have already been studied and one interesting possibility brought forward by Martti Kalliala, is construction of artificial islands for shafts and tunnel ventilation. Additionally, these islands could provide wealth, accommodation and leisure activities for habitants. The amount of excavated rock according to Kalliala's studies is 16 000 000 cubic metres stone, which could be used as base for the artificial island. [Kalliala, M; 2008]

Similar projects are visioned at Gibraltar to connect Europe to Africa with a rail link, and in Bosphorus strait to connect Europe and Asia. Some further visions are to construct a link under Beringer strait from Russia to Alaska, a tunnel from Taiwan to China and an Andes Base tunnel between Argentina and Chile. All projects are technically possible but challenging, and mainly financial realities have kept them in visionary phase.

2 Tunnels around the Globe

2.1 Long rail and road tunnels around the world

Longer rail and road tunnels are found around the world. Perhaps the most important is Japanese Seikan rail tunnel opened 1988 still being world's longest rail tunnel with 53,85 km and operating high speed trains. During construction of Seikan tunnel four water inflow accidents took place severely detaining construction and caused financial losses and death of four humans. [Eskelsen S.D et al; 2004; pp 217-223]

Tunnel construction has been intensive in Asia recent years. North East MRT Line in Singapore operates fully automatic 20km rail tunnel in Singapore since 2002 and Wushaoling in China is a 21km rail tunnel opened in 2006. China is actively constructing underground passages especially for vehicle traffic and already 4300km of railway tunnels are planned only in China, and many projects of different scale are constantly under construction in Asia. [Jinxiu Y.; WTC2009 pp. 18]

2.2 Long European rail and road tunnels

Perhaps the most famous tunnel in the world is the 50 km long Channel Tunnel opened for traffic in 1994. It connects United Kingdom to France with two tubes and a service tunnel. Channel tunnel has suffered from several operational interrupts and financial disappointments after larger tunnel fires in 1996 and 2008 in addition to other less severe difficulties. A large effort has been put on in considering safety in Channel Tunnel already before opening the tunnel, and even more so after the accidents to restore the confidence for safe operation.

The Alps have been a natural place for tunnel construction. The first really long rail tunnel with 15km is the Gotthard Rail tunnel in Switzerland. Opened in 1882, it is one of the oldest rail tunnels still in use. In terms of road tunnels, the Gotthard Road Tunnel should not be forgotten as it is the world's longest road tunnel with 24,5km since 1980. Another interesting rail tunnel project is the Gotthard Base tunnel totalling 57,1km when completed in 2018 according to the current construction schedule. Profile of Gotthard Base tunnel is shown in ILLUSTRATION 2.1. Tunnel life cycle can be extended with maintenance and several old tunnels are still in operation in Switzerland. One latest recent long tunnel constructions is the Spanish Guadarrama Tunnel (28,4km) near Madrid, which was opened in 2007.

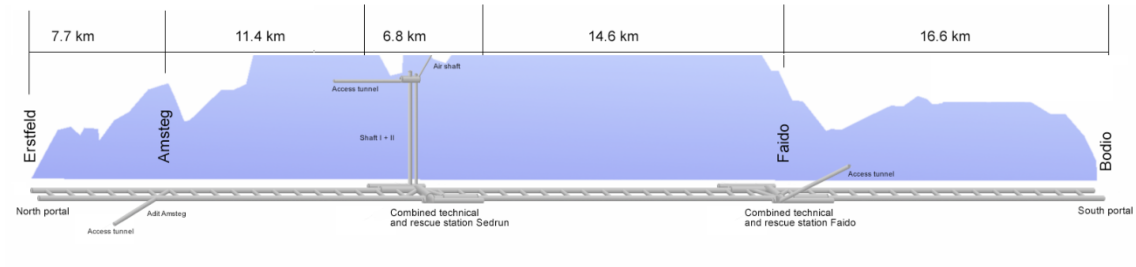


ILLUSTRATION 2.1. Profile of Gotthard Base tunnel [Source: Gotthard Base tunnel site, http://www.alptransit.ch, referred March 2010]

2.3 Nordic rail and road tunnels

Norway has a favourable geology and social structure for tunnelling and therefore several tunnels have been constucted. Some longer tunnels are Finse rail tunnel, 10,3km opened in 1993, Lieråsen (10,7km) and Romerike (14,6km) opened in 1973 and 1999, respectively. The metro systems in Stockholm and Oslo are also partly in tunnels in central areas of the cities. The world's first subsea tunnel, 7km Severn railway tunnel was opened in Norway in 1886.

Numerous tunnels for road traffic are constructed in Norway throughout 20th century. Eiksund Undersea Tunnel with 7,8km is the longest subsea road tunnel in the world. The tunnels in Norway vary in length and their user volumes are relatively low. Some of the tunnels are really long such as the Lærdal Tunnel (24,5km) succeeding Gotthard Road Tunnel as the second longest road tunnel in the world by only a few dozen meters.

In Norway the geological conditions are often similar to Finnish hard rock concerning tunnel construction. However, southern areas in Norway and Sweden have softer rocks and more fractured rocks. Norwegians have been active in developing tunnel safety especially in the area of fire safety.

Combining a tunnel and a bridge is one solution to create new routes. Examples of combined solutions are the Great Belt tunnel in Denmark, a subsea rail tunnel of approximately 8 km, and the 4 km Drogden Tunnel in Öresund immersed combined road&rail tunnel connecting Sweden to Denmark

A good example of the necessity of careful pre-investigations for tunnel projectis is a still ongoing construction project of 10,5km called Hallandsås tunnel in Skåne, Sweden scheduled for commission in 2011.

2.4 Tunnels in Finland

Finnish geology is favourable for tunnels, as solid bedrock is typically found near surface. However, the landscape is quite flat and therefore tunnels are not normally needed on traffic routes. The hiding underground of service traffic and other services such as sewering, district heating, telecommunications is seen as an attractive solution. Thereby, for example Helsinki is full of tunnels for various purposes. In most cases one tunnel can serve for different purposes, which lowers the costs of construction and maintenance. Also water supply for capital area is served by a tunnel called Päijännetunneli. The fresh water tunnel, opened in 1982, totals the length of 120km and was renovated in 2001 and 2008. The first traffic tunnel in Finland was built already in the end of the 19th century for railway use, and later over 40 tunnels are built solely for railway operation. Recently longer tunnels have been excavated also for road traffic.

2.4.1 Rail tunnels in Finland

The longest rail tunnel (13,5km) in Finland is located in Vuosaari serving rail traffic to the port of Helsinki. The new tunnel is a single track, which makes it interesting as most tunnels built nowadays are twin tubes. It is only used for freight traffic and not for passengers. The new tunnel has faced some operational problems related to the climate inside the tunnel. Relative air humidity in tunnel increases on cold weather and moist causes problems to electrical locomotives. Problems are however solved with workaround solutions.

Most of the tunnels in the railroad network of Finland are on routes Helsinki-Turku and Jämsä-Jyväskylä. Most of these tunnels, which are still in operation, were built during the 1960s and 1970s. A common problem for these tunnels is a pressure attack to thermal insulation in tunnels, which is mainly a consequence of a tight cross profile and lack of mechanical protection layer on the insulation. Pressure attack is more violent as operation speed in tunnels has increased. The oldest tunnel in Finland, already decommissioned original Pohjankuru tunnel, was taken in operation already in 1899.

2.4.2 Road tunnels in Finland

During the last decade some road tunnel projects have been completed in southern Finland as parts of other infrastructure improvements. These tunnels are the Hiidenkallio tunnel in Espoo as part of Ring II, the Vuosaari tunnel as part of Vuoli project in the new port of Helsinki and tunnels in E18 motorway. The Karnainen tunnel (2,2km) along E18 motorway is the longest road tunnel in Finland.

These new road tunnels have faced some teething problems concerning especially tunnel security systems, which have brought up questions concerning the maturity of the used technology and the tunnel safety design. Just after opening, operational interrupts and problems with tunnel surveillance systems at E18 and Vuoli were so common that they were made fun of in the media. Time and experience have developed the systems less fragile for different types of operating conditions.

2.4.3 Ring Rail Link project, Helsinki metro and Länsimetro expansion

During 2010 two interesting projects are under construction in greater Helsinki area. The Ring Rail Link connects Helsinki Airport to rail network. Tunnel construction started 2009 and operation is started in 2014 according to project stakeholders. Total length of new rail track is 18km, of which about 8km in tunnel. Two underground stations will be taken in operation at first phase and another two will be left as options for later needs. Map on Ring Rail Link is shown on ILLUSTRATION 2.2. [Ring Rail Link: http://www.keharata.fi referred March 2010]

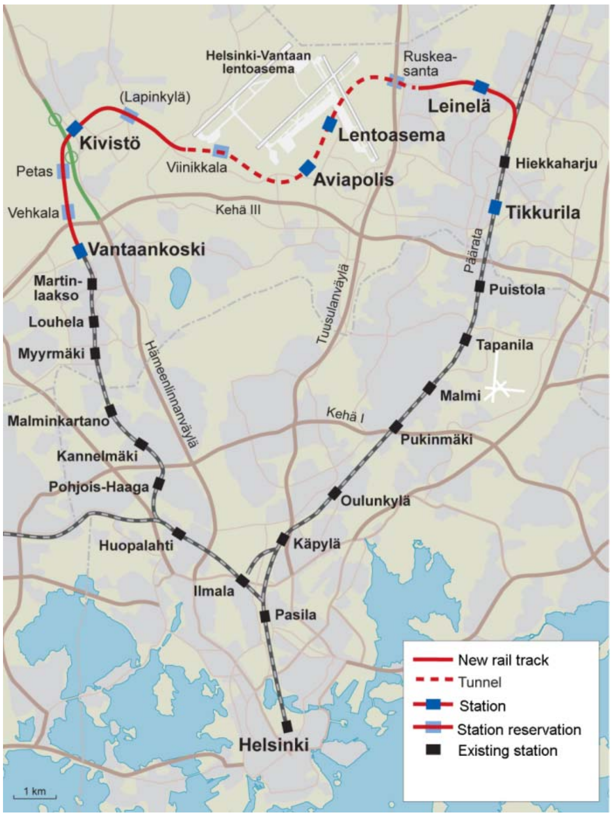


ILLUSTRATION 2.2. Map on Ring Rail Link (Source: Ring Rail Link site http://www.keharata.fi referred March 2010)

Helsinki subway was taken in operation in 1982 and will be extended to Espoo in the near future. At the moment the Helsinki subway totals 21,1 km and has 17 stations. It operates underground for 4,9 km in the central area, but has been constructed above the ground in the outskirts of the city. In the year 2009 construction project called Länsimetro has begun to extend metro to Espoo with a 13,5 km line, 8 new stations. Second phase of project is to further extend the line towards west. The first phase of Länsimetro will be constructed fully underground. Tunnel safety and especially fire safety were considered when constructing the subway and improvements are currently under discussion again while planning the western extension and possible automation of the system. A metro system differs from a long rail tunnel as stations are closer to each other and the maximum depth is much lower than in a subsea tunnel. Route of Länsimetro is shown in ILLUSTRATION 2.3 and depth from surface can be seen in ILLUSTRATION 2.4. [Länsimetro site http://www.lansimetro.fi, referred March 2010]

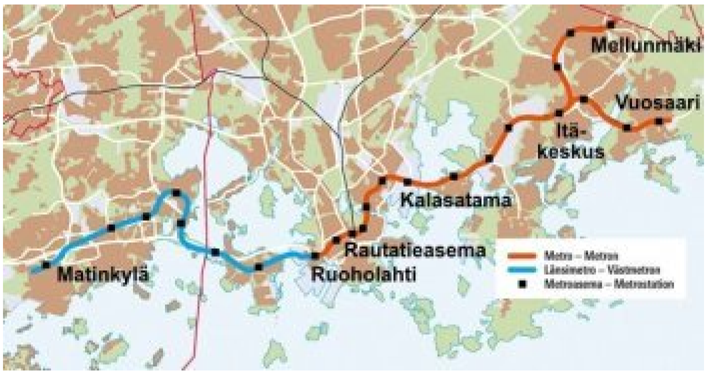


ILLUSTRATION 2.3. Länsimetro expansion on map [Source: Länsimetro site http://www.lansimetro.fi referred March 2010]

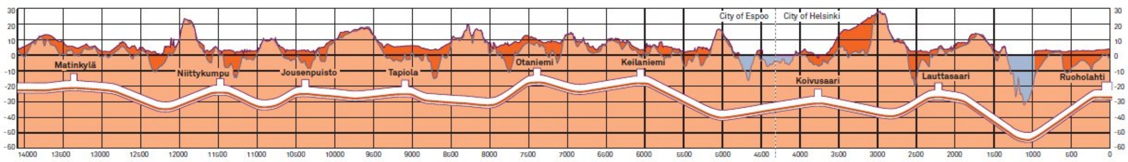


ILLUSTRATION 2.4. Länsimetro tunnel profile [Source: Länsimetro site http://www.lansimetro.fi re - ferred March 2010]

3 Challenges and problems faced on previous projects

Tunnel projects are large construction projects where location underground adds an additional factor of uncertainty. These types of projects commonly attract public interest and the encountered problems get easily attention in the media. Despite of the fact that most tunnel projects are completed according to the schedule and the budget without major drawbacks, some projects have faced serious problems. These challenges are occasionally brought up when debating the feasibility of tunnel alternatives. Careful planning and pre-investigations are keys for a successful project. Some problems are difficult to recognize in advance and as tunnel systems develop more and more complex careful testing becomes important.

3.1 Operational challenges

In Finland recent teething problems in tunnel security and signalling systems have caused operation breaks. Surveillance systems have detected nonexistent threats and stopped the traffic. These issues have not been a question of safety but because of the interruptions in traffic, tunnel projects are seen in bad light. Problems have been eventually solved with additional testing and adjustments. The Channel Tunnel has also suffered for weather issues and technical difficulties caused by icy winter conditions. Tunnel operation should tolerate normal weather condition without a risk of an operational interruption. Individual sensor failure should be tolerated in operation without significantly reducing safety margins.

Typical operational problems include:

- Fire
- Equipment failures
- Problems in control and safety systems

3.2 Construction time challenges

Problems in the construction phase are often faced suddenly and unexpected. However, previous projects show that encountered problems can be solved. For instance problems with machinery, geology and building techniques caused problems and delay in the construction of Japanese Seikan Tunnel. With enough effort, the problems got solved and the tunnel is heavily trafficked. In Finland, there were problems during the construction of Helsinki metro system. A known fracture zone at Kluuvi caused extensive trouble for constructors, but solutions for sufficient reinforcements were found and metro track was finished. Therefore, construction problems are possible to solve with enough effort, but foreseeing problems is important in order to keep costs in the budgeted range.

In the Nordic Countries most severe tunnel construction problems were faced recently at Hallandsås tunnel where unexpected geological conditions and other problems have delayed the project by years. Earlier, tunnel cave-in and flooding challenged the construction of the Great Belt tunnel. The accidents affected heavily the construction budgets and schedules. Machinery was destroyed in flooding and an alternative route needed to be taken to bypass flooded area.

Construction challenges are usually related to unforeseen geological situations, typically problems are caused by:

- Water inflow (causes delay, in extreme cases even cave-in)
- Slow progress (causes financial problems)

Excavation process is naturally slowed down in poor rock quality zones where additional support is needed. High water inflow is usually encountered at fracture zones, where ground water flows more easily. Especially horizontal fractures can be tricky to detect in advance but are capable of causing a lot of seepage.

Compared to city tunnelling, also advantages of surrounding environment can be seen in construction of a subsea tunnel. As most of the work takes place in uninhabited areas, construction work is less limited by restrictions in the levels of noise, vibration and particle emissions.

4 Environmental uncertainties and significance of pre-investigations

Environmental uncertainties are always a challenge to underground construction. Despite extensive pre-investigations the underground conditions can never be entirely predicted. Yet, careful pre-investigations are a key to a successful project. Many different factors influence the selection of the optimal route in terms of operation, construction and financing of the project. It is crucial to notice that the best option for tunnelling is not necessarily the shortest distance between a tunnel's endpoints.

4.1 Climate change and elevation of sea level

The sea level is not constant, but fluctuates continuously according to prevailing weather conditions. Typically in the Baltic Sea region the yearly levels of elevation are from +120cm to -50cm compared to the long term average level [Lehtimaa, R; 1997]. Special weather conditions such as storms and bath effect may raise sea level temporarily by another meter. Additionally, waves cause rise of effective water level. As water inflow to a tunnel would be catastrophic, conservative safety margins should be applied. In Helsinki, a minimum safety margin of +2,6m (+2,3m sea elevation plus 0,3m of wave effect) is applied in construction of tunnel entrances. [Valkeapää, R. et al; 2008]

Construction of artificial islands is a potential option for ventilation of tunnels. However, by doing so the risk of high waves is more probable and additional safety margins should be considered separately for each case. In addition, a possibility to temporarily close ventilation shafts should be considered in locations where a risk for water inflow is possible.

Climate change has also a possible effect on sea level in the form of greater fluctuations and even a permanent rise of sea level. When considering new projects, tunnel entrances and shafts should be constructed bearing in mind the necessary safety margins for potential floods in the future. Nevertheless, changes in sea level are slow and do not happen unexpectedly. Safety margins ought to be planned greater than the current regulations require, in order ensuring safe operation beyond the planned tunnel life cycle. [Instanes, A.; SC2009 pp. 23-24]

4.2 Expandable clays

Some clays are prone to large volume changes that are directly related to changes in water content. Hydration can cause a variation of volume in a clay particle by as much as 75%, which may affect the stability of an underground space. Especially in fracture zones hydro-geological properties change in joint fillings and expansion takes place causing more fracturing. According to Avrami (2008) sedimentary rocks are probable environments for expanding clays. Some clay minerals, especially smectite, are capable to incorporate water molecules and charged cations in their structure. This changes the dimension of a clay particle. The extent of cation exchange capacity depends on chemical properties of clay. It can be measured in laboratory tests, but also indicative field tests may be carried out in situ. [Olis, A; 1990 & Avrami, E. et al; 2008] [Carlsson, L.; 2004]

In Norway, expanding clays are found widely. In Finland the subject has not yet been studied to large extent but they have been encountered in joint fillings [Ilkka Vähäaho, 2009]. As there is a great diversity of clay types in Estonia, the probability of existence for expanding clays is relevant. The expansion in terms of underground space construction is not a problem as long as hydration levels stay unchanged. Nonetheless, continuous changes in hydrological properties are a risk to rock mass stability as shrinking and expansion of clays may broaden fractures in rock. Risks can be minimized by avoiding areas where expanding clays are found, and by maintaining stable hydrological conditions. [Righi, D. et al; 2001] [Gillot, F. et al; 2001]

4.3 Geological risk

Geological weakness zones augment the challenge to tunnel construction and increase costs. Tectonically Finland is a rather stable area, but small scale tectonic movements may occur locally and cause stability challenges for an underground space. Fracture zones generally refer to poor rock quality, which may significantly delay a construction process as additional rock support is needed. These kinds of fracture zones are known to exist in Estonia and Finland, but predictably exist under the Gulf of Finland as well.

At the Estonian side, possible existence of post-glacial fracture zones should be taken in to account when gathering background information for underground space construction. Additionally, hydrogeological properties of the area should be studied to be able predict water seepage. Special attention should be addressed to study presence of horizontal fractures, as groundwater flow through them can be significant. [Niini, H.; 1983]

4.4 Geophysical methods of pre-investigations

4.4.1 Basics of geophysical surveys

Applied geophysics is an approach to investigate earth soil indirectly, taking advantage of different properties of soil. Different kinds of changes in measured properties, anomalies, are studied with mathematical methods and human interpretation to build a model of geological properties. Anomalies in sound velocity, gravity, magnetic field and electro-magnetic response can be surveyed and interpretations drawn from collected data. Usually more than one property is surveyed to gather more information. Models are refined and adjusted with drilling data at later stages. Surveys can be done on foot, by vehicles, airborne with helicopters or an aeroplane or with satellites. Detailed information of different geophysical methods is found in literature.

At early stages of a project, geological investigations rely mainly on seismic measurements. Potential weakness zones are determined by low acoustic velocity measurements. More precise investigations and drilling may be conducted on these locations. Some methods of marine geophysics are shown in ILLUSTRATION 4.1.

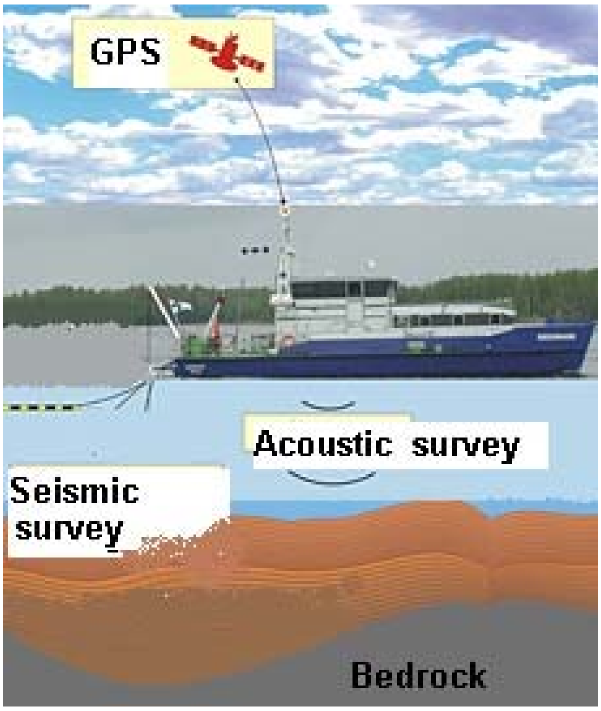


ILLUSTRATION 4.1. Marine geophysical surveys [Modified from: http://www.gtk.fi/merigeologia]

Commonly used geophysical methods include: [Pennington, T.; SC2009 pp.430]

- Seismic reflection and refraction surveying for mapping bedrock structure
- Acoustic profiling for detailed mapping of bottom surface and lithology
- Magnetic surveying for large scale geological mapping
- Ground penetrating radar (GPR) for mapping near surface properties
- Core drilling to bind geophysical interpretations to reality

4.4.2 Potential approach to carry out pre-investigations

A potential approach on pre-investigations could include following steps:

1) Gathering previous data on study area and deciding necessary supplementary surveys
2) Aerogeophysical surveys and data interpretation on wide area of potential tunnel routes in order to find possible fracture and weakness zones.
3) Selecting alternative tunnel linings based on information from aerogeophysical surveys.
4) Additional seismic surveys on selected tunnel routes to refine and revise earlier investigations and interpretations
5) Choosing locations for core drillings
6) Core drillings on selected spots to further verify and update information on possible tunnel routes
7) Selecting and adjusting actual tunnel lining
8) Systematic drillings on selected tunnel route to gather information for specifying rock conditions through whole tunnel line.
9) Constant update and comparison with modelled geology and actual subsurface survey results

A general map on area's geological conditions can be drawn at early stage after first surveys and updated throughout the investigations. A more detailed zone map is drawn after all investigations are completed for basis of tendering. Identification of weakness zones and their alignment is one important property. Rock quality and constructability analysis should be conducted on tunnel route in order to provide necessary basis for further studies in feasibility analysis. Alternative tunnel routes studied for Päijännetunneli are presented in ILLUSTRATION 4.2. [Niini, H.;2000]

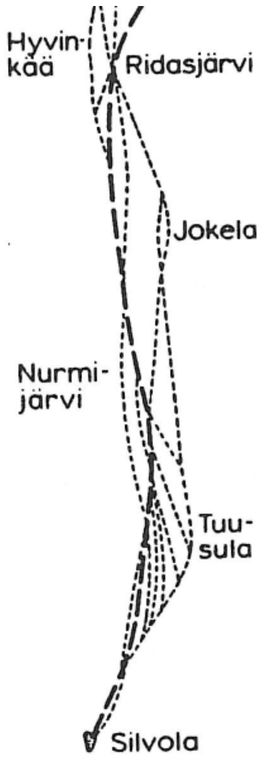


ILLUSTRATION 4.2. Alternative tunnel linings for Päijännetunneli [Source: Niini H. et al; 1971]

Weakness zones where rock quality is poor and a lot fractures are found are the areas where stability problems are most likely faced. Tunnelling costs are significantly higher when passing a weakness zone. Therefore, weakness zones and their alignment are important to identify in advance. Tunnel route can be selected to cross weakness zone in steep angle in order to minimize the necessity to construct tunnel in poor rock. Tunnel length is a less important parameter compared to ease of tunnelling in good rock conditions. Crossing weakness zones in steep angles is presented in ILLUSTRATION 4.3 and correlation of low velocity zones and weakness zones in Fryøa Tunnel is shown in ILLUSTRATION 4.4

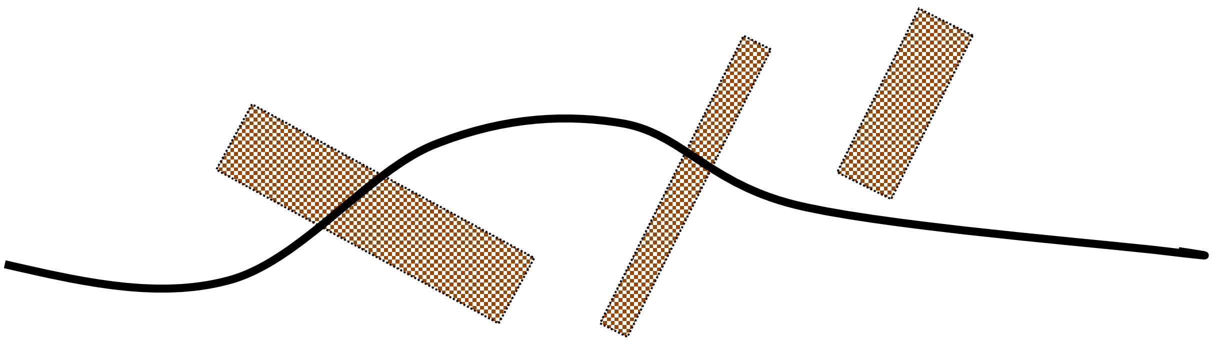


ILLUSTRATION 4.3. Choosing tunnel lining to pass weakness zones in steep angle to minimize tunnelling in poor rock conditions

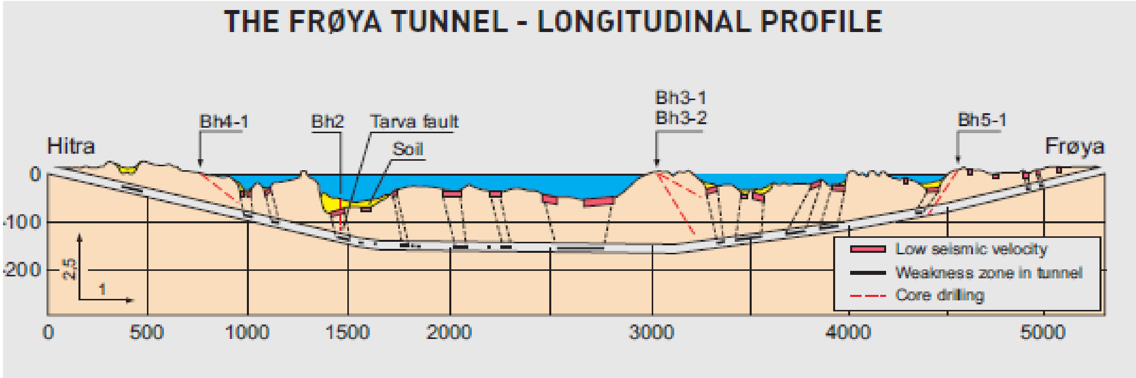


ILLUSTRATION 4.4. Correlation of low velocity zones andweaknesszones in Frøya tunnel longitudinal profile. [Source: Norwegian tunneling society, publication n. 18 "Subsea tunnels"; 2009)]

Additionally, rock support should be carefully planned on these zones to avoid problems during construction. However, precise support methods are typically decided in situ according to encountered rock conditions and to information gathered from probe drillings. Most severe risk for cave-in occurs in areas where water seepage is high. In these weakness zones additional support and grouting is needed. [Nielsen B. et al; SC2009 pp. 38-39]

The result from pre-investigations is a constructability map, which is updated constantly as new results from surveys refine interpretations. Detailed results from pre-investigations are crucial for later feasibility studies.

4.4.3 Lineament interpretation

An integrated approach with lineament interpretation combining geophysical and topographical data is a promising approach according to studies on Olkiluoto area. The geophysical data including magnetic, electromagnetic, seismic, and acoustic data from aerogeophysical, ground, and marine surveys is combined with topographic data and a detailed digital elevation model elevation contours. At Olkiluoto area the interpretations were done in four stages:

1) Interpolating raw data to regular grids and post processing using frequency-domain filtering and compiling several sunshaded colormaps from the processed data.
2) Identifying and digitalizing lineaments from each method-specific data set
3) Comprising the coordination of those method-specific lineaments that describe the same linear feature.
4) Linking coordinated lineaments describing the same linear feature into a single lineament.

Integrated interpretation can present complex data visually, helping to group similar characteristic properties and allowing more detailed interpretation done easier. [Korhonen, K. et al, 2005]

4.5 Significance of pre-investigations

Pre-investigations have proven their necessity in many projects. Their costs are paid back easily when costly problems are avoided. Good understanding of the geology in a target area enables the selection of the best possible tunnel route. It is by far the most important decision concerning the economy of a tunnel project.

In subsea projects geological information is typically even more limited than in traditional tunnel projects. Drilling is more costly than in inland appliances as drilling needs to be done from a ship or from an offshore platform. Costs for pre-investigations are typically around 3-7% of the total construction costs [Nielsen B. et al; SC2009 pp. 38-39]. Even careful pre-investigations may fail to provide information on the nature of weakness zones, which needs to be taken in consideration during construction. Understanding of geological properties is important as rock support costs are directly related to the quality of rock mass. [Panthi, K.K.; SC2009 pp. 421] Three geological uncertainty aspects for rock mass are:

i. rock mass quality
ii. groundwater inflow through rock mass
iii. rock stress.

In a subsea tunnel, rock stress is seldom a significant factor. Rock stress is moderate compared to heavy stress encountered in mountainous areas and great depths. High rock stress causes tunnel deformation and additional support is required. Methods for characterising rock mass quality are: rock quality designation (RQD value) and derived rock quality index (Q index). Typically a tunnel path is divided in sections according to describing value of rock quality. In later phases, the same information is needed in tendering. [Panthi K.K; SC2009 pp. 421]

Fogarasi & Flatley also point out also the significance of carefully interpreting collected data, and building a complete picture on construction site in question. Construction plans need to be updated during the progress of the project and when new data is collected. [Fogarasi I. et al; WTC2009, pp 15-17]

4.6 Effects to surrounding environment

Tunnels have limited effect on surrounding environment but may have impact to groundwater flow. Use of chemicals during construction needs to be controlled in order to avoid emissions to groundwater. However, in subsea constructions outside water pressure is likely to prevent any emissions from spreading to groundwater. Nonetheless, hydrogeology around the construction site need an own survey and must be dealt in the Environmental Impact Assessment process. [Jinxiu Y. & Shoujie Y; WTC2009 pp. 18-22]

Most notable environmental changes take place if artificial islands are built to sea for shafts. Impact on landscape depend the architecture of these islands and implemented functions. All environmental effects are taken in account during Environmental Impact Assessment process.

5 Construction methods and work safety

Standards respond slowly to new development but in new projects also innovative solutions are needed to achieve the best possible result. Unconventional projects also need unconventional innovations and safety solutions need to be thought specifically for each individual project concerning its properties and risk scenarios

5.1 Construction practices

5.1.1 Excavation methods

In hard rock conditions drill&blast excavation method is proven itself an efficient technique considering time, energy usage, flexibility and financial aspects. In Norwegian subsea tunnel projects probe drilling and pre-grouting has proven to be working construction method [Nielsen B et al; SC2009 pp. 35]. In softer soil especially when considering longer tunnels Tunnel Boring Method (TBM) is widely used. Drill&blast method is considered more flexible in changing rock conditions, but continuous process in TBM allow speeding up the progress and even greater excavation speeds in solid rock can be achieved. However, latest experience from TBM in Nordic hard rock conditions from Hallandsås project in Sweden is not very encouraging. Project was driven in to problems as rock quality was not what it was expected based on pre-investigations.. Selection of the excavation method is very important question in a project considering financing of the project. Tunnel cross-sections strongly depend on excavation method, and typical alternatives are a horseshoe shape with drill and blast method and a circular profile with TBM. One tunnel boring drill is presented in ILLUSTRATION 5.1.

ILLUSTRATION 5.1. One tunnel boring drill [Source: http://www.niagarafrontier.com, referred January 2010]

The drill&blast excavation cycle starts with pregrouting and rock bolting when necessary, followed by drilling a grid of holes in rock mass. Holes are filled with explosives and fired. After explosion fumes are ventilated away from working area blasted rocks are hauled away. After securing the working area the cycle is restarted. Securing the working area means scaling and in poor rock mass possibly also some bolting and shotcreating. Drill and blast cycle is illustrated in ILLUSTRATION 5.2.

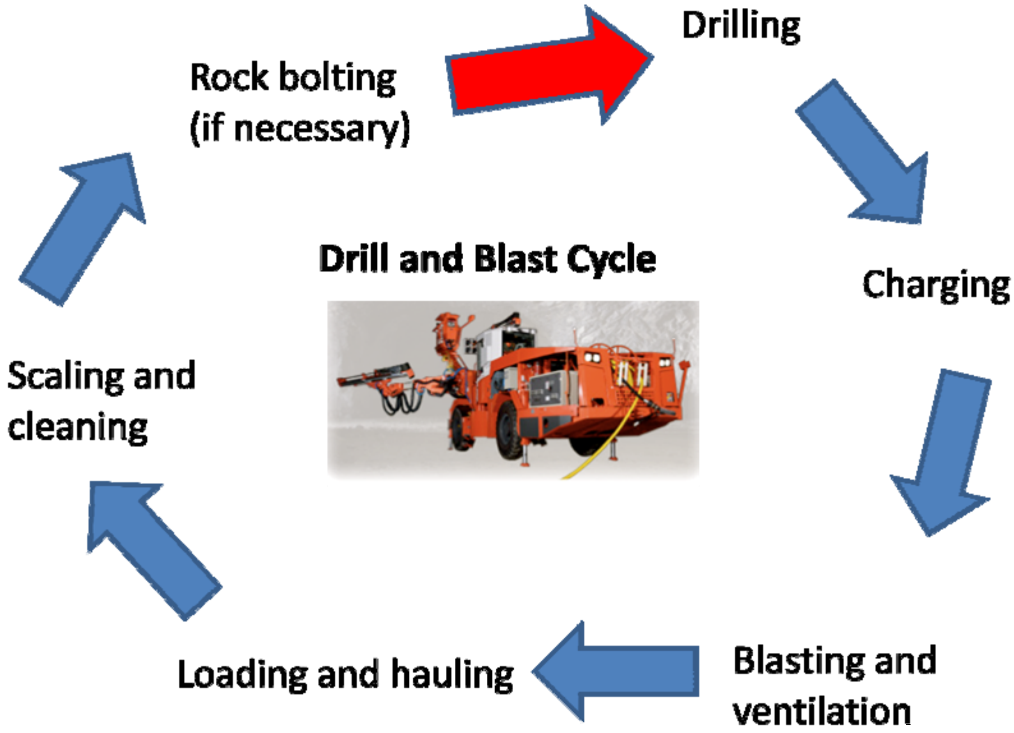


ILLUSTRATION 5.2. Drill and Blast cycle

In a TBM method excavation is carried out continuously by the TBM which is capable of performing all necessary steps from excavation to rock support and reinforcement. The significant difference between the methods is how the excavation is carried out. In a TBM method the rock is excavated by scraping with a rotating drill, the drill and blast methods takes advantage of explosives to break the rock. Small diameter (< 1 meter in hard rock) shafts can be excavated by raise drifting method by with a special pneumatic drill with a similar method to TBM but less complicated. In larger shafts drill&blast method is usually more cost-effective

Which excavation method to use is a big question concerning tunnel design and is financially weighty as well. More investigations could be carried out on efficiency of full profile tunnelling in mixed rock conditions.

5.1.2 Grouting and rock support

Grouting and rock support are needed to control tunnel water inflow and rock stability. Methods are chosen by observed rock mass quality. Systematic pre-grouting is a common practice and helps as well to predict water leakage in working area. When water leakage is considered too high additional grouting is applied. Grouting can be done afterwards if water inflow is too high. However, planned pre-grouting is always easier method to control water seepage.

Additional method to increase rock mass stability around the tunnel is bolting. Problematic areas where stability problems are expected are covered by spot bolting, or systematic radial bolting. Also vertical umbrella bolting may be used to stabilize tunnel. More stability is archived with wire mesh reinforced shotcrete or even concrete elements in extreme cases. See ILLUSTRATION 5.7 on rock support in CHAPTER 5.3.

5.1.3 Tunnel options

Different safety standards are needed for different types of tunnels. Naturally a tunnel designed only for freight traffic needs less strict evacuation standards than a tunnel in passenger traffic. Also emergency guidance systems may be reduced in contrast to tunnels in passenger traffic. As all long tunnels are unique projects real risks and safety assessments need to be carried out individually for every project.

Safety solutions should always be considered after a careful risk analysis. According to current Finnish railway regulations, parallel tunnels for passenger traffic are required to be interconnected every 500m [RATO18; 2008]. The same practice is required in EU directives as well. In a single tunnel solution for freight traffic emergency evacuation chambers must be placed in reachable intervals. However, this means additional safety training for tunnel users and necessity to carry along an evacuation gear for reaching a safe in a case of an emergency. This method is also not in favour of rescue authorities, as their working possibilities are considerably limited. The evacuation chambers need to provide communication means and protection as long as it takes for a rescue team to respond after catastrophe. In a case of fire this most likely includes actual burning phase and some smoke ventilation - hours at least in any case. This however acceptable concerning the users, who would be trapped in the case of an emergency in the tunnel until situation is under control. In prolonged tunnel fire evacuation possibilities can be very limited. To ensure sufficient evacuation possibilities in passenger traffic even a single tube solution in reality requires parallel tunnel aside as spacious enough safe havens would not be feasible. Rock mass around the tunnel is good isolation against heat spread, and a parallel tunnel is an obvious evacuation area. However, ventilation needs to prevent smoke from leaking to the evacuation area. Passageways between tunnels are isolated with fire proof doors and air pressure is used to prevent spreading of smoke from tunnel to another.

Twin tube has several advantages compared to a dual track tunnels:

1) Increased safety in emergency situations
2) No collision risk and reduced impact in a rare case of derailment
3) Better access to scene in an emergency situation
4) increased passenger comfort by no pressure waves whilst trains pass by
5) increased safety during construction
6) Maintenance may take place while another tunnel is still operative

Constructing a twin tube is in most cases a good option considering work scheduling and work safety. Drill&blast work sequence allows construction to take place in two separate tunnel ends quite naturally. In single tube rail tunnels with favourable rock conditions taking advance of TBM could allow feasible one tube projects as well, but a twin tube tunnel has serious advantage in safety issues.

A third tunnel serving as a service tunnel eases maintenance of tunnels as different parts of tunnel are reachable without causing unnecessary interference to tunnel traffic. Service tunnel also serves as safe haven and provides rescue authorities direct access to tunnels without a need to avoid traffic in other tunnel. According to Scatzmann A. et al, a twin tube with a safety gallery or service tunnel is most suitable solution for long rail tunnels even though costs are slightly higher than in a solution without a service tunnel. [Schatzmann A. et al; 2001] Rescue operations are discussed in detain later in CHAPTER 6. ILLUSTRATION 5.3 shows a evacuation procedure in a tunnel with and without a service tunnel, and ILLUSTRATION 5.4 is a sketch of twin tube tunnel with and without a service tunnel.

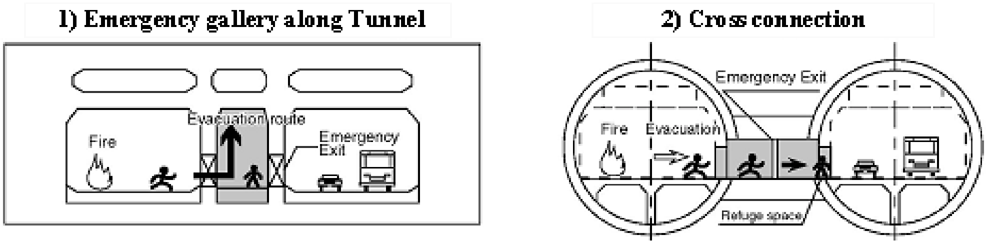


ILLUSTRATION 5.3. Evacuation via an emergency gallery or service tunnel vs. evacuation via cross passage [Source: H. Mashimo, 2010]

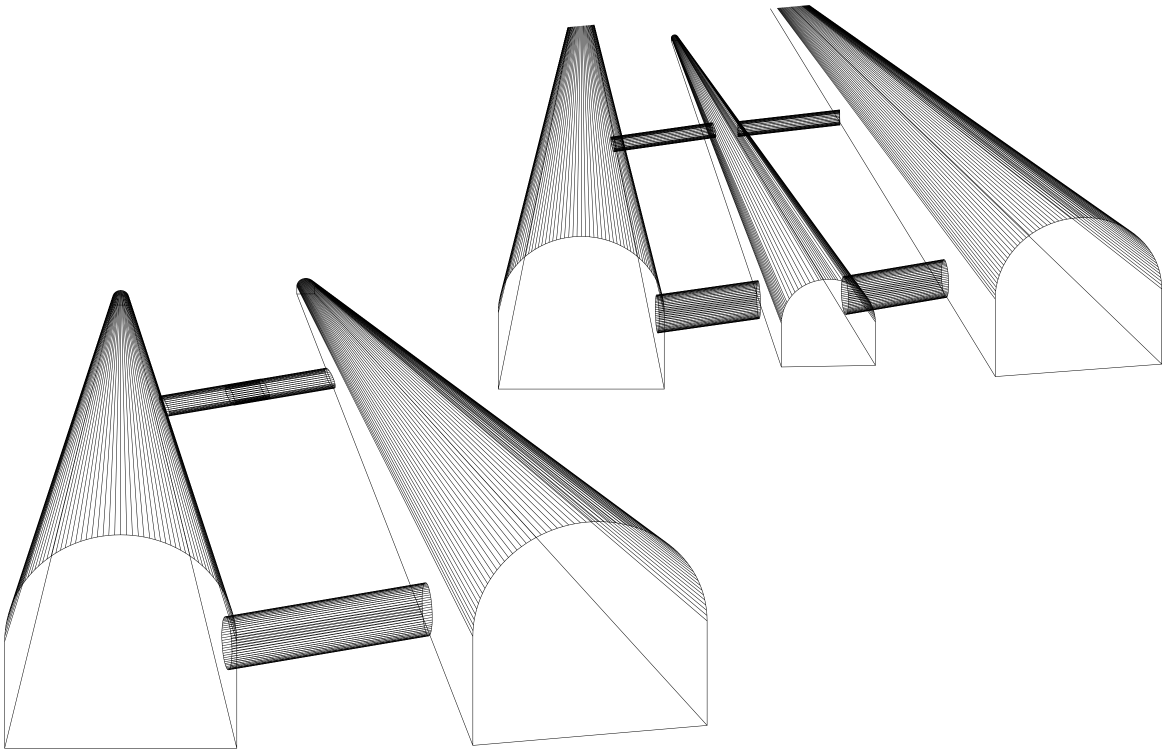


ILLUSTRATION 5.4. Twin tube tunnel with and without a service tunnel.
Tubes are interconnected with smaller tunnels to make cross passage possible.

In metro systems exist normally also a possibility to change tracks or bypass other trains in the tunnel. Option is implemented in the Channel Tunnel and in the Gotthard Base Tunnel. However, it is debated if additional complexity is necessary, as changing tracks in reality has advantage in vary rare situations. In a case of accident all traffic is usually shut down and partial use of a tunnel provides only little advantage. Concerning maintenance operations changing tracks could provide some advantage.

Most traffic tunnels nowadays are twin tubes, but necessity for this need to be calculated by designed tunnel capacity. Separate service tunnel adds more flexibility to maintenance of a tunnel and for rescue operation. Twin tunnel also more than doubles traffic capacity especially if safety solutions and regulations allow more than one train in a tunnel at time. Considering about the need for a service tunnel, special attention should be taken to flexibility in tunnel maintenance and additional usage for the service tunnel. Electricity-, water- and communication cables and pipes could be placed in a service tunnel as well, of course bearing in mind the limitations of safety functions of a tunnel.

5.1.4 Ventilation and shafts

Shafts are need for tunnel ventilation and can also be used for maintenance personnel or passengers to access the tunnel. Shafts are needed for intermediate stations and also possible emergency stations are suggested to be positioned near shafts to maximize possibility for evacuation and ventilation. Pressure management and overall aerodynamic design is subject of a further study. Constructing shafts to sea needs to take advantage of existing islands or artificial islands.

5.1.5 Evacuation possibilities and tunnel instrumentation

Rescue corridors are needed to evacuate passengers from a stopped train. Finnish regulations for railway tunnels require a rescue corridor at least 0,75m wide and 2,25m in height on both sides of the tunnel. In Länsimetro project 1,6m rescue corridor is placed on other side of tunnel. Actual dimensions need to be calculated by passenger capacity of the train individually in each project. Sufficient tunnel lightning is needed to provide sufficient evacuation possibilities to safety.

Selecting and installing a fire extinguishing system to whole tunnel is also an issue worth of debating, as constructing and maintaining such system is a huge project as itself. Again, decisions need to be made individually in every individual tunnel project. Fire extinguishing systems are discussed with more detail in CHAPTER 6.3.

5.1.6 Tunnel Capacity

In a 100km tunnel a train travelling at speed of 150km/h would take 40 minutes which in reality would mean one hourly train. By dividing tunnel to sections two trains could occupy the tunnel simultaneously which would increase possible capacity. General practice should be that a train has clearance to next emergency station / smoke exhaust shaft in both directions, before and after the train. This should allow the following train to stop and evacuate in a case the forward train encounters problems. Principle of simultaneous trains and security clearance in a tunnel is presented in ILLUSTRATION 5.5.

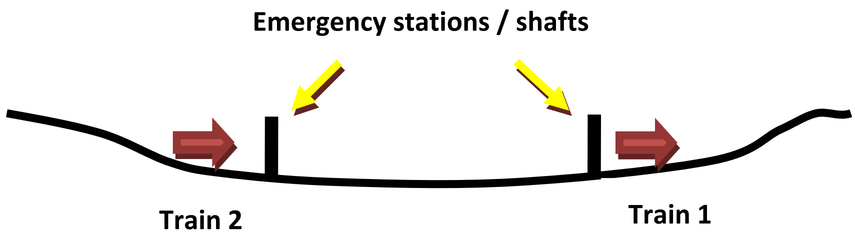


ILLUSTRATION 5.5. Simultaneous trains in a tunnel

Ventilation shafts are needed mainly for smoke exhaust purposes, but are used to provide fresh air to tunnels. Piston effect of a moving train circulates air in a tunnel, but additional ventilation may be used in addition. Train moving in a tunnel pushes air out of the tunnel ahead it and sucks fresh air from shafts behind the train thereby circulating the air in a tunnel.

Underground stations are needed to be built for two purposes: for emergency stations or as passenger terminals. In Helsinki-Tallinn vision an artificial island could be built along tunnel route and traffic carried out through the tunnel. Naturally safety requirements differ greatly by the use of a station. Passenger station is in constant use by people, and has high standards for safety, especially fire safety and evacuation. Also a direct connection to surface is needed. In the other hand an emergency station needs only to provide a place to unload the train and get passengers safe.

5.2 Rock cover

Depth of the rock cover is one of important decisions when planning a tunnel as the cover must be sufficient but overly thick cover increases tunnel length and overall cost during the whole lifetime of a tunnel. [Norwegian tunneling society, publication n. 18 "Subsea tunnels"; 2009] In longer tunnels effect is slightly smaller respectively but rail tunnels are more sensitive to elevation, as maximum gradient is much lower than in road tunnels. Normal gradients in rail tunnels are around 2%, when road tunnels ascent even 5-8%. Low ascent makes tunnel depth a critical issue in rail tunnels. In Länsimetro gradients up to 3,5% are accepted. Alignment of a subsea tunnel is presented in ILLUSTRATION 5.6. Greater ascents may be archived by additional technical solutions such using rubber wheels. Passenger comfort still needs to be considered. A small gradient is needed in a tunnel to ensure desired water flow to ground water pumping stations. [Länsimetron Hankesunnitelma, 2008]

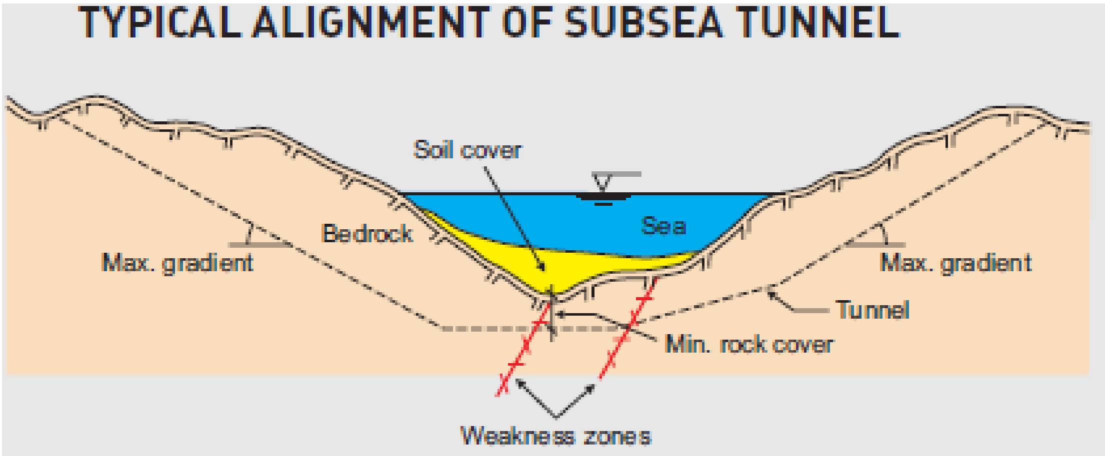


ILLUSTRATION 5.6. Typical alignment of a subsea tunnel [Adapted from: Norwegian tunneling society, publication n. 18 "Subsea tunnels"; 2009]

Typical minimum rock cover in Norwegian subsea projects has been 50m but in favorable conditions also 20m rock cover is accepted. This means more precisely good rock conditions and shallow waters [B. Nielsen; SC2009 pp. 40-41]. Short and shallow water tunnels are constructed typically with one diameter minimum rock cover on top [Ingerslev, L.C.F.; SC2009]. In Finnish Länsimetro project minimum accepted rock cover under sea is 7 metres and 5 metres below land.[Länsimetron Hankesunnitelma, 2008] Difference between Finnish and Norwegian margins reflects also depth of tunnels, as typical subsea tunnels in Norway dive to depths around 200m where Länsimetro does not go deeper than 50m below sea level. Main factor in demanding thicker rock cover is water pressure which increases along with depth. Key factors for considering rock cover are:

- margin for reaction time in case of fallout
- margin for unexpected variation in rock quality

5.3 Adapting to rock quality, rock support and reinforcement

Difficult areas are possible to excavate by freezing the ground but the method is slow and therefore costly. When problematic areas can be handled by conventional grouting tunnelling works can proceed significantly faster.

Rock support methods are bolting and reinforced shotcrete which methods are usually applied together. In good rock conditions spot bolting is usually enough when in poorer rock conditions systematic bolting is usually needed. Shotcreting also improves tunnel resistance to fire. Typical bolting in Norvegian subsea tunnels has been 1.5 to 7 bolts per tunnel meter. Amount of sprayed concrete has increased in recent projects and is around 2m3 per tunnel meter. Grouting is done 25-30m ahead working face when needed. Rock support options are presented in ILLUSTRATION 5.7. [Nielsen B, SC2009 pp. 40-41]

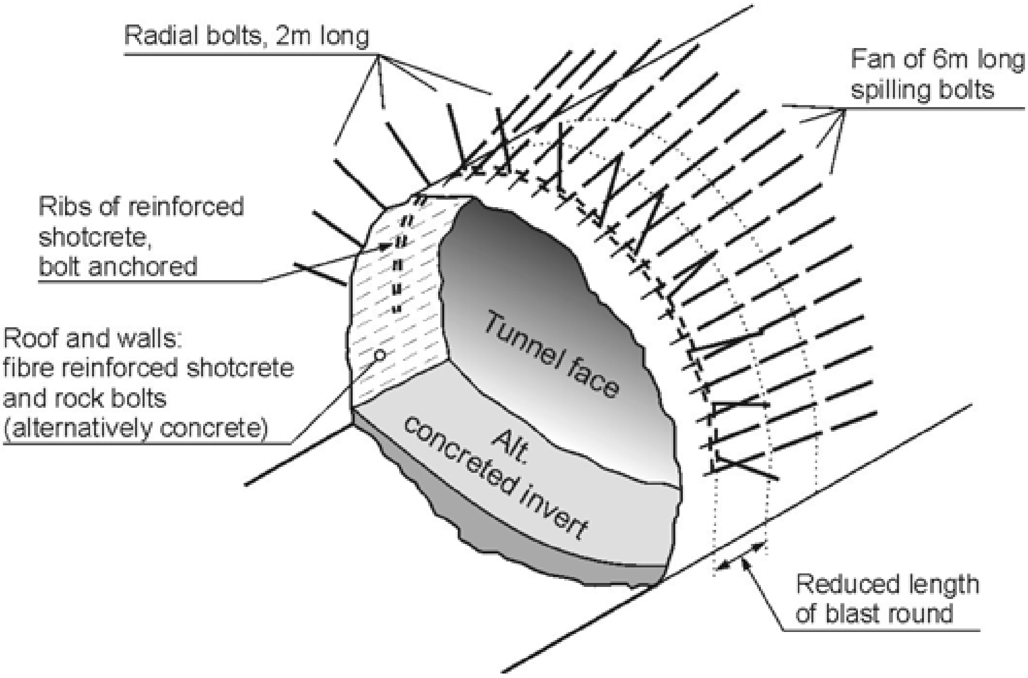


ILLUSTRATION 5.7. Principle of rock support in a tunnel [Nielsen B. et al, 2009]

Where both hard and soft rocks are on tunnel path also combination of immersed and bored tunnel is proposed for consideration and further investigations. This would minimize need for complicated soft rock tunneling and is also a way to lower needed gradients. [Ingerslev L.C.F.; SC2009 pp. 362-364] These constructions however have not realized yet, but Bosphorus crossing in Turkey is designed to construct in combination of TBM bored tunnel and immersed tunnel. Another possible combination is a bridge-and a tunnel. The Great Belt Link is a tunnel and bridge combination. A shorter tunnel is needed, and possible unfavourable geological conditions can be avoided. However, tunnel construction is in many cases more economical.

5.4 Risk management and work safety

Careful risk assessment has proven an excellent method for identifying and dealing with different risk scenarios. Constant monitoring of conditions at construction site provides necessary information to update risk scenarios according to current situation. Specific instructions include fire extinguishers in all vehicles and rescue masks for personnel. Also a method to rescue injured personnel from a tunnel should be planned in advance. Work in a tunnel should be preferably carried out in pairs to increase safety.

Sometimes risks do realize even when precautions are taken in to concern. Up to date rescue scenarios help to recover from problems and prevent further damage. Some risks such delays need to be taken and budgeted. Following safety steps help to improve safety on a construction site:

- Safety training for workers to understand the safety protocols followed on a construction site.
- Simulations on safety situations.
- Continuous monitoring of safety with specific criteria on work site.
- Fire extinguishers available on every vehicle in a tunnel, and compressed air & masks available for evacuation purposes.
- First aid kits in construction vehicles and a first aid cabinet at construction office.
- Access control in tunnels to know the number of workers in a tunnel in a case of evacuation and location of workers in the tunnel known all the time
- Safety training for visitors on site.
- Work carried out in pairs whenever possible.
- Noise control and use of auditive protection for workers.
- Air quality and dust control to ensure working conditions and enough fresh air.
- Anti trapping means such as hydraulic jacks and release cushions by inflation.

- Back upped signalling and communication system from work site to ground with radio and fixed line connection.

Escape chambers such steel containers with sealed doors and breathing air system may be used to provide protection to personnel in a case of bad air quality. These are not usable in a case of fire however. Fire protected chambers may also provide safety for tunnel workers in a case of emergency to provide safety until rescue operations are able to take over. In reality providing to two completely autonomous escape routes during all possible work phases may prove impossible. Most important issue concerning work safety is overall attitude toward safe working practices. This applies to every stage of organization from individual to whole construction project.

6 Threats in rail tunnels

Risks in rail tunnels are handled with various stages of protection. Ladders of safety measures are illustrated in ILLUSTRATION 6.1.

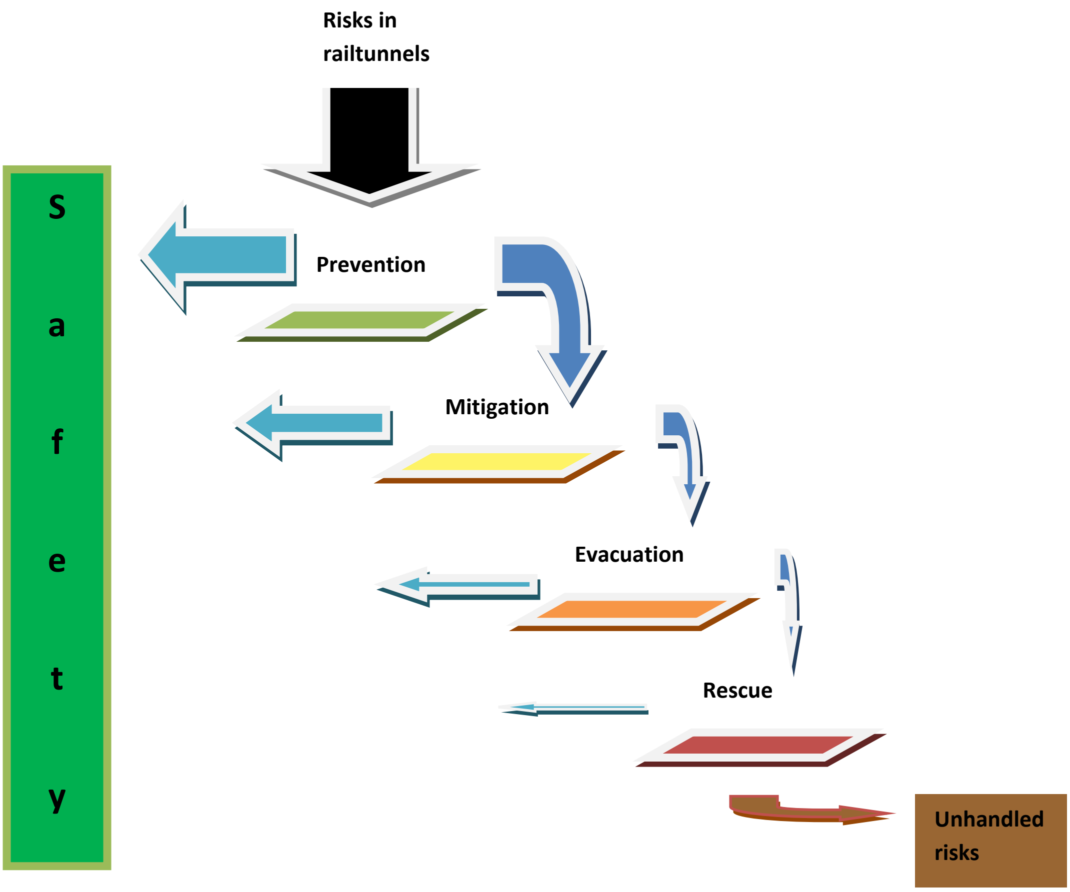


ILLUSTRATION 6.1 Risk management stages. [Modified from EU Rail tunnel directive EU 20/XII/2007 6450]

6.1 Traffic accidents

Most severe kind of an accident in a tunnel is a fire, and the generated heat and smoke. A fire could develop as an example from electrical short-circuiting or a terrorist attack. If the fire can't be extinguished in a train the train needs to be stopped and passengers evacuated. This should preferably take place in special emergency stations, where conditions for evacuation should be favourable. First problem for humans is the toxic smoke released in a fire.

Tunnels where trains operate only in single direction at time are quite resistant to collisions of any kind and it is predicted that even a derailment does not affect tunnel stability. In addition, foreign objects are highly unlikely in tunnel environment which further reduces the risk of derailment. Naturally evacuation is necessary in this situation as well.

A blackout or serious problem in a train can stop the train so that passengers need to evacuate. As technical systems trains are vulnerable to failures, even though their number is subjected to be minimal by careful maintenance. Critical systems should be doubled to ensure backup electricity in blackout situations.

6.2 Water leaks

Water seepage is a problem for fracture zones, and affects to rock mass stability as well. Also pumping excessive amounts of water is both problematic and expensive. Therefore effort should be taken in order to minimize water leaks.

The tolerated amount for water seepage is typically defined in the designing phase based on geological conditions and use of an underground space. In Norwegian low-use road tunnels typical maximum water seepage is targeted to 300L/min per km. In Finland strict tolerances may require seepage of only 10 to 20 L/min per km, and normal level is around 100L/min per km. Sufficient grouting is needed to archive the target. [Nielsen B et al; SC2009 pp 42] [Ilkka Vähäaho, 2009] [Suomen Betoniyhdistys, BY53 Kalliotilojen injektointi; 2006]

Most notable safety risk in subsea tunnel construction is a sudden water inflow accident during tunnel construction [Rongxi S; 2008 pp. 385-388]. When tunnel has been constructed it is in stable condition and collapse is not likely to happen. Keys to avoid problems during construction are careful pre-investigation filled with monitoring deformations in constructed tunnel. Another proven concept is careful emergency plans acknowledging also minor accidents and thinking through what if scenarios. Different risks can be identified and addressed with their relevance. Therefore identified risks can be either avoided or accepted with minimizing detriments.

6.3 Tunnel Fires

In a rail tunnel combustible masses are moving, which is quite a different situation compared to an underground bunker for example. This must be taken in to account when selecting suitable safety guidelines for a traffic tunnel. Onboard fire suppression systems have an advantage of reacting immediately after sensing the fire, not needing the train to stop for fire suppression to take place. Another considerable advantage is also the possibility to avoid fire from escalating to full scale by rapid suppression measures. This however requires carrying the suppression system and other necessary reserves such water or foam onboard. [Haack A.; ISTSS2008, pp46-48]

Characteristic for tunnel fires is that they develop violently and rapidly reach temperature of 1000 C. This may cause serious deformation in rock which increases risk of collapse. In road tunnels large fires escalate in five minutes. Designed fire load of an Eurostar train was 7MW, however, the Channel Tunnel fire in 1996 had power from 10MW to 50MW before activating supplementary ventilation according to later investigations. Investigations suggest that fire has peaked the power of 350MW by assistance from ventilation systems. Average fire power was assumed to about 150MW, and temperatures reaching 1300^{o}C. Estimations for maximum fire power were results of usable oxygen in tunnel and the amount of burning material. [Channel Tunnel Fire, 1996] [Watson, K; 2007]

To get an impression of scale of fire heat release a typical motor coach could be simulated using a theoretical 20MW fire. In test fires actual trucks can be burned, or simulated with wooden pallets or gasoline cans calculated for similar heat release. Maximum fire power can be regulated in rail tunnels easily restricting allowed goods in transportation. This is very different case compared to road tunnels, where vehicles can be loaded with much less restrictions.

Priority is naturally preventing the fire in the first place. If it still escalates rapid response and quick extinguishing is the best option. Sprinkler systems are not usually designed to be suppressing a fire completely, but limit its strength and keep it from spreading further. Actual fire extinguish is carried out by fire brigade. After a fire first action is ventilate tunnel with fresh air and then damage control and repairs take place. Ventilation and smoke control during the fire is also a challenging issue in tunnel fires.

6.3.1 Active and passive fire protection

Fire protection can be divided in two sections: passive protection preventing a fire from happening and active protection to extinguish escalated fire. Both active and passive protections are always applied together when concerning fire safety of underground spaces. The choice to be made is how to focus and balance between different approaches. Passive safety consists methods and structural solutions to prevent fire by choosing fire proof materials and designing usage of the space in a such way that risk for a fire is minimal. Active systems are fire detection systems, sprinklers, ventilation and guidance for users. Sensors detect fire, sprinklers are used to suppress the fire and guidance helps users to find their way to a safe place. Ventilation is needed to control and remove smoke. Gas extinguishers could be used, but they are out of question in tunnels where humans are present.

6.3.2 Sprinkler systems

Advantage of fixed sprinkler systems is rapid response after a fire is detected. However, they have some serious disadvantages as well. Most important problem is their tendency to complicate evacuation of the users. It is under debate when and how the sprinkler systems should be launched in order to get best efficiency in rescue operations. Water vaporizes to steam which significantly reduces visibility and toxic smoke gases reduce human performance. Sprinkler systems are normally not designed powerful enough to completely extinguish an escalated fire, but may have important role cooling down equipment in vicinity and thereby prevent fire spreading. Costs and benefits of fire suppression are also debated, keeping in mind that as an active system they need constant maintenance and testing which evidently causes costs. Key variable when determining fire suppression capability of a sprinkler system is amount of water delivered to extinguish area. Typical amounts range from two litres per square meter up to $15L/m^2$. Naturally the necessary volume of pipelines and water reservoirs grows as designed water amounts rise. Key benefits are reducing the heat spread and cooling down area around the fire thereby preventing fire from spreading. [Hughes Associates, Test Report; 2006]

Current instructions suggest a small delay before launching sprinkler systems. This allows users to search evacuation route with good visibility and the rescue personnel are able to get an overall picture on situation where remote monitoring is installed. Launching the sprinklers reduces significantly visibility, not only because of sprayed water but more importantly by air currents mixing the smoke around the space. Normally sprinkler systems are launched manually by rescue teams in spaces which are under monitoring but automatic operation is a possibility as well. [Järvinen Marko, 2010]

6.3.3 Water mist systems

Water mist systems developed at least by FOGTEC and Marioff have proven a feasible option for sprinkler systems. Water mist systems use a special nozzle to spread water to fine mist rather than drops, which possibly saves lot water. Water usage is reduced by factor of 10 in best scenarios. [Kratzmeir, S. & Lakkonen,M.; SC2009 pp 334-335] Smaller water reservoir requirement allows water mist systems to be installed also inside a vehicle. Water mist systems may deploy in tunnel scale systems or fitted in vehicles or both. Suppression system installed in vehicle itself has advantage of rapid response to escalating fire. Extinguishing fire at early stage also has clear positive effect regarding smoke, steam and other issues, too. Drawback is naturally installations which are needed in every vehicle in need of protection. In tunnel environment this would mean fitting new systems in existing vehicles which may prove challenging. Installations on new vehicles in the other hand should not cause big trouble when needed space may be reserved already when planning interiors. Compared to sprinkler based suppression systems mobile water mist installations may still be very cost effective.

Water mist systems provide excellent heat isolation as result of natural properties of water mist. In test combustible material 5m away from fire did not ignite. This is serious advantage bearing in mind catastrophe in sprinkler equipped St. Gotthard tunnel where vehicles ignited even 50m away from fire. Good heat isolation and cooling effect notably eases work of fire fighters. [Kratzmeir, S. & Lakkonen, M.; SC2009 pp 334-335]

Considering water mist systems have shown their capabilities in small and medium scale fires, still more investigations could be made comparing the efficiency of water mist systems to conventional sprinkler systems in very large scale fires. As also water mist systems are dependent on amount of used water in a large scale fire, it could be worth of investigating how much water can be saved for an example in a 50MW fire using a water mist system.

6.3.4 Essentials for active fire protection

In order to be effective water based fire suppression systems need pressurized water, which means that water lines are constantly wet or they are filled when needed. This also has serious effect on response time, as pressurizing water lines easily takes minutes and advantages of rapid response are lost. Pressurized or not, water pipes need also constant maintenance to ensure correct function in case of emergency. Finnish Savio railway tunnel is equipped with non pressurized water supply system for fire brigade. The system is supposed to be usable in ten minutes according to Finnish authorities. Savio tunnel is not used for passenger traffic.

One problem worth of noticing is also fire detection systems and sensors. Different techniques may be used to detect heat or smoke but in complex systems malfunctions for individual sensors are unavoidable. This area is under constant development and many operating problems in tunnels are caused by malfunctioning sensors.

6.3.5 Operations in a case of fire

In many rail tunnels first rule is to drive burning train out from the tunnel if possible. Tunnels may also have designed fire areas, where train is supposed to stop for fire extinguishing if evacuation from the tunnel is not possible.

6.3.6 Emergency Ventilation

Ventilation is also one key issue in case of fire fighting. Smoke may be blown to desired direction using ceilings and ventilation fans to ease fire fighters to approach fire area. Successful smoke ventilation is suggested to need airflow of 3,5m/s to control smoke spreading in a tunnel with a fire below 100MW. [Nielsen B. et al; SC2009 pp. 38] This needs very heavy ventilation in a long tunnel and also lower rates for smoke control are occasionally accepted. Finnish Savio rail tunnel in freight use has a requirement of 2m/s for air flow. [Järvinen Marko, 2009]

Tunnel ventilation can be arranged two possible ways, which are longitudinal ventilation and transversal ventilation. In longitudinal ventilation fans are used to produce airflow through the tunnel making it a large duct. In transversal ventilation special ducts run along the whole tunnel supplying fresh air extracting polluted air by ventilation fans [Fiorentino A.; SC2009 pp. 127-132]. The Extra ventilation ducts in transversal ventilation require a lot of space and even more powerful fans are required to achieve necessary airflow. The advantage is that tunnel itself should be free of smoke outside the actual fire area which should increase safety. Longitudinal ventilation is used in rail tunnels. The principles of longitudinal and transversal ventilation is presented in ILLUSTRATION 6.2.

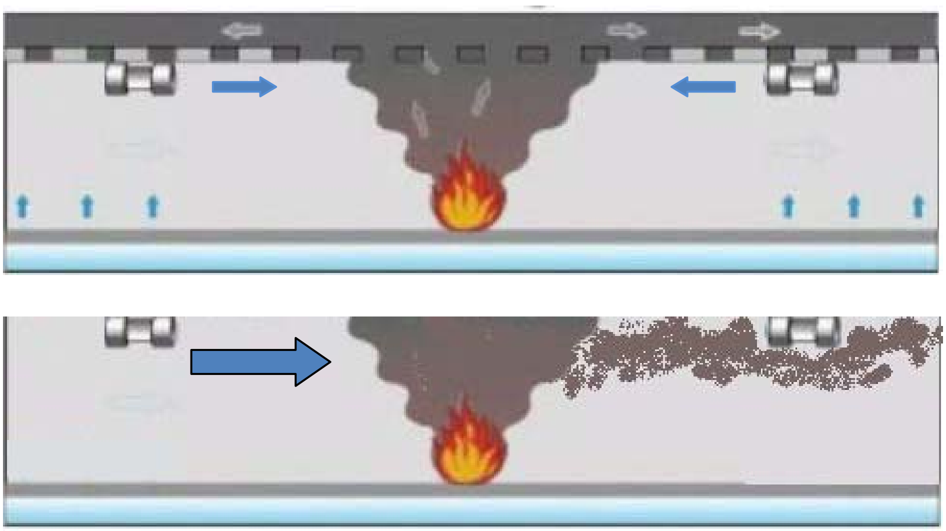


ILLUSTRATION 6.2. Principles of longitudinal and transversal ventilation [Modified from: Fiorentino A. 2009]

Ventilation shafts are equipped with separate sections for smoke exhaust or fresh air supply and the direction of airflow is controlled with fans. Both arrangements require powerful ventilation and when distances between the shafts grow some auxiliary accelerator fans are needed along the tunnel.

6.3.7 Structural fire protection

Fire protection can be enhanced with thicker layers of concrete and with additional reinforcement. Other method is to use fire resistant boards or separate cladding with mineral boards. Passive structural fire protection does not require operational maintenance or costs, but reduces clearance of available space and increases construction costs. Also the substructure itself cannot be inspected directly anymore and cladding needs renewal in 25 to 30 years. During the life-cycle of a tunnel this means three to four installations. These means of fire protection may be installed in existing tunnels as well.

When considering new structures recommended solution is fireproof concrete material which is achieved by using a 80mm layer of concrete quality C25/30 and replacing chalky aggregates with quartzite. Harder concrete qualities are have less porosity, and are more prone for fracturing in high temperatures. In addition for better fire resistance also 3kg/m^3 polypropylene fibres are recommended and optionally basaltic gravel as extra aggregate. However, mixing high concentrates of polypropylene fibres is still technically challenging on construction site. Currently, mix ratio of 2kg/m^3 is used in practise. Advantages with fireproof concrete are evident, as technique does not require additional work steps and fire protection is achieved almost immediately. Special concrete mix naturally costs slightly more than conventional solutions but the difference is not very significant. Also structure may easily be inspected and should last for whole tunnel life cycle of 100 years. [Hjohlman et al; ISTSS2008 pp 90-93] [Kari Sorjonen, 2009-2010]

In cold climate also freezing at tunnel entrances requires additional isolation. Usual method for this is use of polyethene boards covered by concrete layer. If a fire is powerful enough to break through the concrete layer isolation boards increase fire load in tunnel. However, this won't happen during the evacuation phase, but if a tunnel fire would take place near a tunnel entrance, isolation layer should be checked for damages.

Concerning structural changes in a tunnel fire, spalling is the most important issue. Concrete looses its cohesion by the generation of water vapour and destructures layer by layer. Damages however are limited near the area of fire and after the fire concrete can be replaced. Additionally, instead of mixing polypropylene fibres other options are available.

- Spraying layer (~10mm) of cementitiuous material mixed with mineral composite
- Fireproof plates (20-30mm) bolted to walls

These solutions for sure provide protection for limited time, but protective measures are always balanced with financial realities. [Fiorentino A.; SC2009 pp. 127-132]

6.4 EU Standards concerning tunnel safety

EU standard regulations cover tunnels up to length of 20km, and for longer tunnels additional safety measurements are suggested by a special safety assessment carried out for every tunnel individually. Basic principles are applicable in longer tunnels too. The main concept is to protect passengers and personnel from heat and smoke and ensure trains mobility until it gets out of tunnel or to a specific evacuation area or station. [EU Rail tunnel directive EU 20/XII/2007 6450, Chapter 1] These areas can provide additional evacuation capabilities such as a broader platforms and more cross passages.

Safe areas are required to provide environment suitable for staying alive, accessed assisted and without assistance and equipped with a communication to traffic control. Safe areas provide either possibility to rescue in open air or conditions to wait for rescue. EU regulations realize that serious hazards in tunnels are rare and not much may be done realistically in a case of escalated large scale freight train fire. They state minimum requirements for safety but for each project individual safety solutions are needed to be considered according to planned use.

6.4.1 Risk Categories

Risks in tunnels are divided in three categories in EU regulation. Most severe risk in a tunnel is a fire. It is referred as a hot risk. In a scenario a fire, explosion, or release of toxic gas is supposed to take place in one wagon. During 15 minutes period hazard is detected and an alarm is sound. Primary action is to drive train out of tunnel or to a specified evacuation station for evacuation to take place. Alternatively when this is not possible passengers are evacuated to a safe zone by personnel.

Cold risks include a collision or derailing. Evacuation takes place to a safe zone, but dangers of fire do not limit actions. Third category is prolonged stops, which by themselves are not a danger, but may influence panic and uncontrolled evacuation which exposes passengers to dangers of tunnel environment. Third category of risks is not a concern in tunnels solely for freight traffic.

6.4.2 Priorities for rescue operations

Priority for rescue operations is to protect human lives, not infrastructure. In a hot situation this means rescuing users not capable of reaching safe zone on their own, first aid for evacuated persons and limiting damages and risks of a fire. In a cold situation priority is to provide first aid for injured and rescuing trapped persons followed by evacuating human beings.

6.5 Tunnel instrumentation for rescue operations

Tunnel must be instrumented to allow sufficient operation conditions for evacuation and rescue operations in an emergency situation.

6.5.1 Emergency lightning and electricity

Tunnels must be equipped with emergency lightning which is constantly on or can be lighted from tunnel in 250m intervals or from tunnel control. Emergency lightning and communications must stay in operation for 90 minutes without external power. All emergency equipment must be shielded against a collision and fire. Also electrical supply should be back upped to maintain full output also when some part in supply system is out of function. [EU Rail tunnel directive EU 20/XII/2007 6450, Chapter 4.2 Evacuation]

Channel tunnel takes the advantage of a separate service tunnel where the Alps tunnels rely on twin tube solutions enhanced with special rescue stations. Rescue station provides good conditions for rapid evacuation of passengers and facilities for service personnel to inspect and repair a failure in a train. The train stops to an emergency station and evacuation takes place. Emergency station consists of a train length platform with access to protected area by cross passages. An evacuation station must provide space and adequate conditions for all train passengers and protection from smoke and heat. Evacuation is possible elsewhere in a tunnel as well, but in considerable worse conditions.

Rescue route out of tunnel should also be easily accessible and 40m3/s airflow should be ensured by ventilation to satisfy fresh air need for evacuated passengers. Protected area is over pressured to prevent smoke inflow and fireproof doors are used to secure the area when users have successfully evacuated. Main functions of a rescue station are repairing trains and evacuating passengers in a rare event of an operational problem. [Bopp R. et al; 1996]

If a train is forced to stop outside an evacuation station passengers get out of the train and move along tunnel to cross passages and the parallel tunnel where the further evacuation takes place. Evacuation is simulated with computer models in planning phase to reveal design failures on escape routes. Later, simulations are carried out in real environment to ensure evacuation situation and to train personnel. In optimal conditions train should be evacuated in 4-6 minutes after train has stopped. Challenge is injured passengers, who still need to get out of the emergency train with help from rescue personnel. [Ettel, C; UGCiMI1998, pp. 20]

6.5.2 Emergency communication

Emergency communication can be handled with GSM-R technology, and radio communication must be secured to ensure working possibilities for rescue teams. Fixed phone lines may also be used as backup communication. An important aspect is that communication problems may also have significant negative aspect concerning the development of the situation. A lot effort should be put to successful and sufficient communication in different situations.

6.6 Security in tunnels

Safety problems to prevent unauthorized personnel from entering tunnel are dealt with normal security, locks and surveillance. Methods are not different from other underground spaces where access is restricted.

6.7 Precautions and risk management

Safety issues are after all always compromises. What is the cost of safety and how much resources can be spent to avoid accidents and dealing with the worst case scenarios. Even simple and nonthreatening operating problems may develop to major catastrophes if panic takes place among passengers. Heat, lack of information and congestion may raise restlessness among crowd if the situation is not handled carefully. Railway risks according to EU directives are presented in ILLUSTRATION 6.3.

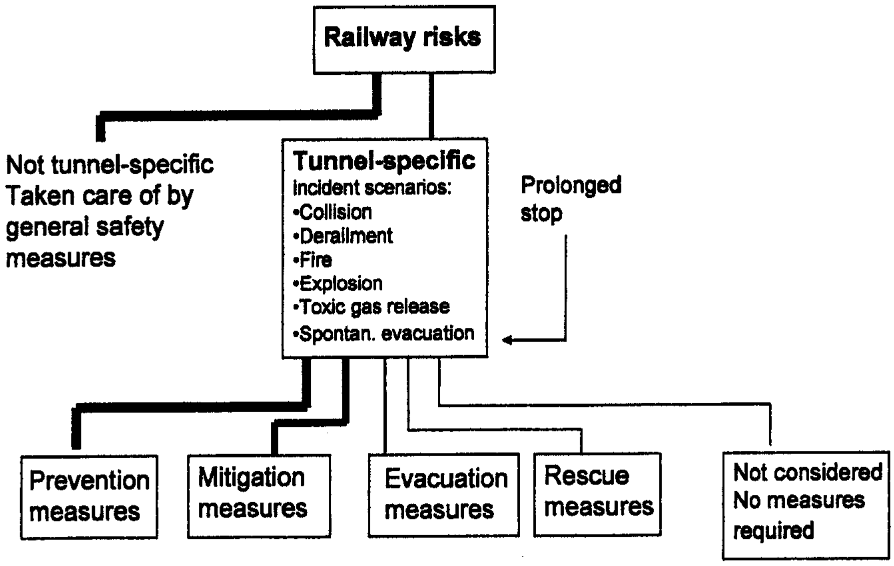


ILLUSTRATION 6.3. Railway risks according to EU directives [EU Rail tunnel directive EU 20/XII/2007 6450]

Human behavior has proven to be serious issue of uncertainty. Despite careful design and preparations humans in real situation are likely to behave unexpectedly. They do not follow given instructions, use cross passages or walk to desired direction. [Dix A.; SC2009 pp. 19] Therefore human behavior must be studied way further to improve behavior in emergency situations.

Concept of safety consists of different levels in preventing problems. These include preventive methods in minimizing probability of different problems and limiting damages if problems still are encountered. Usually when a disaster happens many things have went wrong simultaneously. This is why also smaller problems should be investigated thoroughly to identify the reasons to further improve safety concepts.

To ensure constant super visioning and development for safety systems a good practice seems to be having a separate and autonomous safety coordinator to maintain the concept of tunnel safety and related procedures.

7 Risk management during tunnel life cycle

Risks are present in every part of a tunnel's life cycle. The key aspect in risk management is the identification of risks, forehand assessment of threats. Procedures should be developed to avoid the risks and to handle the situation if it emerges. Probabilistic risk management method has been under constant interest, but will not be dealt in precision in this thesis. The method is effective in identifying the most important risk scenarios. During the construction phase risks may be distinguished according to Rival el al:

"(1) Imprecision, small deviations normally taken into accounting the project through reasonably conservative margins of safety and interpretation

(2) Unexpected events, that are not included in the design (due to their low probability for instance but that can be identified and for which solutions can be defined by advance before these events occur

(3) Unforeseen events that cannot be forecast at all and that can only be coped with through a financial provision." [Rival F. et al; WTC2009 pp. 41 – 43]

Fogarasi et al address same issues but in addition they underline environmental conditions and the significance of pre-investigations. Authors also address distribution of risk between project stakeholders. In tendering phase the distribution can have a significant influence on total budget of the project as risk costs are integrated in the total price. [Fogarasi I et al; WTC2009 pp. 15-17]

Risk in operational phase is managed by mitigating the risks in various stages by reducing the possibility of a risk and minimizing potential damages. An important part of risk management is operation models for emergency scenarios and practices to ensure correct actions in real situation. Tunnel systems and their correct operation needs to be under constant surveillance and maintenance with the aim of ensuring flawless performance. Additionally, periodical tests should be carried out to check operation capabilities. Division of responsibilities related to each function needs to be defined clearly, and organizations should address an official person for the task.

An underground project should be evaluated by careful assessment on full Life-Cycle Costs & Benefits. High initial capital costs may scare investors away even when an underground option would be a viable and sustainable option in detailed consideration. [Parker H. et al; WTC2009 pp. 31-36]

8 Conclusions

8.1 Tunnel fire safety and transportation of dangerous goods

Fire is the main concern in tunnels mainly because the toxic smoke it creates. Minimizing the risk of fire is one of the key issues in terms of safety. Despite all the precautions, in a case of fire, effective operation procedures for extinguishing it at an early state are crucial and may prevent larger scale emergency. By minimizing the amount of burning material in tunnels possibility of fire is efficiently reduced. Special operational procedures should exist for transporting of dangerous goods to limit the consequences of a potential hazard.

8.2 Construction methods

Concerning building practices in variable hard rock environment conventional drill&blast excavation method has shown its strengths in flexibility, efficiency and reliability. However, advantages of TBM tunnelling should be carefully studied in relation to planned project and surveyed geological conditions. A twin tube tunnel is the standard for reliable and efficient operation and construction both in freight and passenger traffic. The debate is if the separate service tunnel is needed or not, but it can be seen as an additional safety factor and ease the maintenance of the main tunnels. An additional advantage of a separate service tunnel is the possibility to utilize the underground connection for various other purposes. Nonetheless, possible other ways of use and their effect to safety of the whole tunnel system needs additional research.

8.3 Significance of pre-investigations

At constructions phase the significance of pre-investigations can hardly be underestimated. Feasibility of the whole project is highly dependant on the accuracy and correct interpretation drawn from pre-investigations. Feasibility of a long tunnel project is a complex equation, but effects of a tunnel project should be considered in long term taking in to account the whole life cycle of a tunnel.

8.4 Operation reliability

Reliable operation is important in tunnel traffic and special attention should be paid to ensure it. Clear and detailed operation procedures should exist for handling abnormal situations. It is important to bear in mind that even small adversities may damage the public image of a tunnel operation and without right kind of response small problems may lead to serious disasters.

8.5 General means of safe operation

Construction of long subsea rail tunnels is already technically possible. Safety issues can be dealt with to ensure safe and reliable operation in normal use and effective rescue operations in different potential risk situations. As every individual project has their own special characteristics, the safety assessments need to be carried out recognizing specific features of the project. Constant concern on safety is one of the main challenges for a tunnel project. Reliability and ease of maintenance should be highly concerned when making decisions on tunnel systems.

8.6 Appliance to Helsinki-Tallinn vision

Bearing in mind that every tunnel project is a highly individual and has many special characteristics, nothing should be stated too powerfully concerning details on safety issues or building practises. These issues are subjects of further studies and plans. However, necessity of careful pre-investigation is clearly shown its significance in earlier projects both in terms of safety and feasibility. The next logical approach is carrying out basic pre-investigations with seismic surveys followed by electromagnetic surveys on visioned tunnel routes. Later pre-investigations would consist of drillings as well. Earlier projects show that risks should be clearly identified in advance to allow flexible reactions when problems are faced.

Concerning geology, safety systems and construction methods there are no reasons why the tunnel vision could not be brought to reality. Problems can be solved, and tight teamwork between all stakeholders is necessary to accomplish the best possible outcome.

After all, Helsinki is a remote place from Central-Europe, and improved transportation possibilities could liven up business around the whole Baltic area. Decisions should be made with eyes open for new possibilities considering all available options.

8.7 Proposal for first step site investigations of Helsinki-Tallinn tunnel

As the information available on geological conditions in the sea area of Gulf of Finland is currently quite imprecise, detailed pre-investigations are needed. Steps for further investigation are proposed as follows:

1) Geophysical surveys utilizing aero geophysics, marine geophysics and core drillings in later phase should be conducted to identify topography and geology of the seabed at Gulf of Finland. Surveys between Helsinki and Tallinn should cover a wide enough area

(~100km) to locate the most feasible lining for tunnel construction. The most important findings of the surveys are the depth of bedrock, locations and alignment of weakness zones. Detailed information on rock types and sedimentary properties are gathered from core drillings.

2) Combining and interpreting gathered data to a constantly updating geological map, and making constructability map including rock quality, weakness zones, hydrogeological and geological conditions of study area.
3) Choosing possible tunnel route taking into account constructability, weakness zones and other geological properties.
4) Additional core drillings to refine information for basis of a detailed map of rock conditions through selected tunnel line.

Pre-investigation steps are followed by a feasibility study and a tendering process if project looks feasible and construction is considered necessary.

8.8 Further research

Further research should focus on safety issues in soft ground tunnel construction, safety of immersed tunnels, safety of high speed trains in long tunnels, and costs of different safety solutions. In relation to Helsinki-Tallinn vision also geological properties around the possible tunnel route should be studied more carefully as base for more precise feasibility studies on the Helsinki-Tallinn vision. The possibility to combine a tunnel-bridge solution and taking advantage of artificial island could be studied further. Concerning feasibility, innovative alternative use for the tunnel and possible artificial island should be studied. New possibilities for telecommunication, energy production, transportation of fresh water and electricity could be established in combination with other possibilities in the future.

REFERENCES:

Reports, Seminar papers, journals and books:

Avrami E. et al; Terra Literature Review, An Overview of Research in Earthen Architecture Conservation; The Getty Conservation Institute, 2008 (Available: http://www.getty.edu/conservation/field_projects/terra/terra_publications.html)

Bopp R. et al: Rescue Stations in Long Railway Tunnels, Concepts for the Planned Alptransit Base Tunnels through the Swiss Alps; Proceedings of Tunnel Incident Management, First International Conference 1996

Carlson, Liisa 2004. Bentonite mineralogy. Part 1 : Methods of investigation - a literature review. Part 2 : Mineralogical research of selected bentonites. Posiva. Working report 2004-02. Olkiluoto: Posiva. 105 p.

Dix A.: Safety and security in Strait Crossings; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Eskesen S.D. et al.: The.Guidelines for Tunneling Risk Management; Tunneling and underground Space Technology, 19/2004

Ettel C.: Effects of fire and smoke propagation on passengers sheltering in an emergency station of a long railway tunnel; UGCiMI1998: Proceedings of Underground Construction in Modern Infrastructure, Stockholm Sweden 1998

Fiorentino A.: Fire Protection and Fire Fighting in Tunnels; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Fogarasi I. et al; Risk factors and risk sharing at tenders and contracts of tunneling and underground projects; WTC2009: Proceedings of World Tunnel Congress, Budapest Hungary 2009

Gillot, F.; Righi, D.; Räisänen, M. L. 2001. Layer-charge evaluation of expandable clays from a chronosequence of podzols in Finland using an alkylammonium method. Clay Minerals 36 (4), 571-584.

Haack A.: Active and Passive Fire Protection – which Way should we go? ISTSS2008: Proceedings from Third International Symposium on Tunnel Safety and Security, Stockholm Sweden 2008

Hjohlman M. et al.: Fire Testing of Concrete and Concrete Protection Systems for Tunnels in Sweden - An Overview; ISTSS2008: Proceedings from Third International Symposium on Tunnel Safety and Security, Stochom Sweden 2008

Ingerslev L.C.F.: Undersea Tunnels and World Perspectives; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Instanes A.: Climate change and possible impact on coastal structures; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Jinxiu Y. & Shoujie Y.: Risk evaluation and Control of Yesanguan Railway tunnel on Yiwan railway line, China; WTC2009: Proceedings of World Tunnel Congress, Budapest Hungary 2009

Kalliala, M; Talsinki Island– A 21st Century Pragmatic Utopia; Master's thesis in architecture, Helsinki University of Technology, 2008

Kratzmeir S. & Lakkonen M.: Road Tunnel Fire Protection by Water Mist Systems – Innovative Solution for Special Tunnels; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Korhonen, K. et al; Lineament Interpretation of the Olkiluoto Area; 2005 <URL: http://www.posiva.fi/tietopankki/tyoraportit/lineament_interpretation_of_the_olkiluoto_area.395.xhtml?cd_offset=390

Lehtimaa R. et al; Saaristolaisen käsikirja. Kokemäki 1996. (Available: <URL http://www.wakkanet.fi/loisto/docshtml/lehtimaa_meri.html)

Matikainen V-M.: Yhteiskäyttötunneleiden Riskiarviointi; Geo 91/2007 Helsinki 2007; ISBN: 978-952-473-935-1

MTR ry.;The Fourth Wave of Rock Construction, Porvoo 1997; ISBN: 951-96180-2-3

Mashimo H.: Current State of Road Tunnel Safety in Japan; Tunnelling and Underground Space Technology Volume 17, Issue 2, April 2002, Pages 145-152.

Nielsen B. & Henning J.E.: Thirty Years of experience with subsea tunnels; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Niini, H. et al; Kalliorakennusgeologia, Espoo 2000

Niini, H, et al; Kallioruhjeet louhinnan kannalta; Maansiirto 12:1; 1971

Niini, H. et al; Korkea-aktiivisen ydinjätteen loppusijoitukseen vaikuttavat kallion materiaaliominaisuudet; GTK Tiedonanto 22 G; 1983; Available:
<URL: http://arkisto.gtk.fi/yst/Tiedonanto_22.pdf

Olis, A: The Rapid Estimation of the Layer Charges of 2:1 Expanding Clays; Clay Minerals (25/1990)

Panthi K.K.: Uncertainty analysis for assessing rock mass quality and water inflow in hard rock subsea tunnels; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Parker H. & Reilly J.: Life Cycle Cost Considerations using risk management Techniques; WTC2009: Proceedings of World Tunnel Congress, Budapest Hungary 2009

Pennington T. & Richards D; Subsea Tunneling: Site Investigations and Risk Management Strategies; SC2009: Proceedings of the Fifth Symposium on Straits Crossings, Trondheim Norway, June 2009

Schatzmann A. et al: Safety Aspects and Tunnel Configuration; Proceedings of Fourth International Conference on Safety in Road and Rail Tunnels, Madrid Spain 2001

Righi, D.; Gillot, F.; Elsass, F.; Räisänen, M. L. 2001. Alteration of Podzol smectites from Finland over the last 10,000 years. In: Mid-European clay conference '01, September 9-14, 2001, Stará Lesná, Slovakia : book of abstracts. Bratislava: National Clay Groups of Croatia, Hungary, Poland and Slovakia

Rival F. et al: Geological Risk: a Methodological Approach and its Application to 65km of Tunnels under Alps in France; WTC2009: Proceedings of World Tunnel Congress, Budapest Hungary 2009

Rongxi S.: Research of Water Inrush on Subsea Tunnel Construction; Journal of Wuhan University of Technology (Transportation Science Engineering), 32/2008

Watson K.: Channel Tunnel Rail Link section 2: designing a safe, high-speed railway; Proceedings of the institutions of civil engineers: Civil engineering vol. 160, November 2007

Publications and directives, geolocical maps:

Channel Tunnel Fire; Inquiry into the fire on Heavy Goods Vehicle shuttle 7539 on 18 November 1996

EU Rail tunnel directive EU 20/XII/2007 6450. Available: <URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:064:0001:0071:EN:PDF

Hughes Associates; Test Report No. HAI-5022-010-2: Approval testing of a HI-FOG water mist system for protection of highway transport tunnels for heavy goods vehicles, 2006

Koistinen, T.(editor), 1994. Precambrian basement of the Gulf of Finland and surrounding area, 1:1 mill. Geological Survey of Finland, Espoo

Länsimetron Hankesunnitelma 2008. Available: <URL: http://data.lansimetro.fi/Ryhmat/HANKESUUNNITELMAN_SELOSTUS_140308.pdf

Norwegian tunneling society, publication n. 18 "Subsea tunnels"; Oslo, 2009. Available: <URL: http://tunnel.no/downloadfile.php?i=94f6d7e04a4d452035300f18b984988c

Ratatekniset ohjeet osa 18 Rautatietunnelit (RATO 18); Ratahallintokeskus 2008

Suomen betoniyhdistys; Kalliotilojen injektointi BY53; ISSN 0358-5239; 53; Helsinki 2006

Valkeapää R, et al, 2008; Helsingin kaupungin tulvastrategia, Available: <URL: http://www.hel.fi/wps/wcm/connect/d637b4004f58c8e581d1c7ddf57f027f/tulvastrategia1_1_2009.pdf?MOD=AJPERES

Personal discussions:

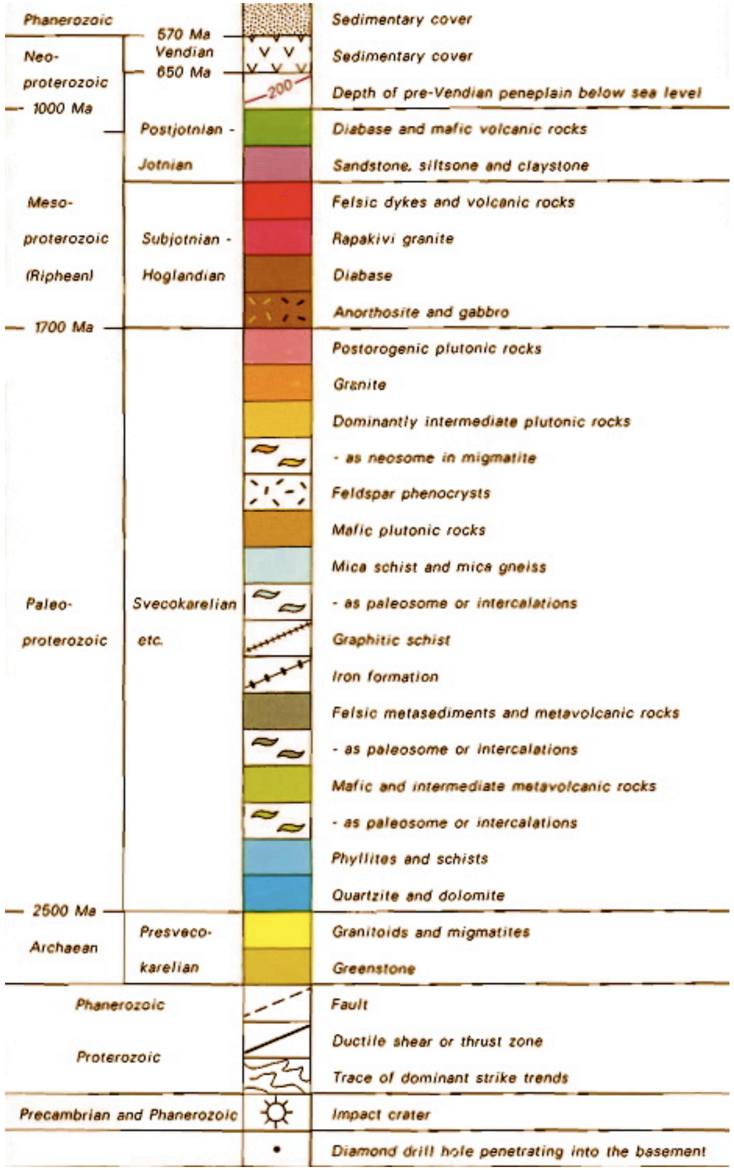
Järvinen Marko, Helsinki Rescue Department, 2009-2010

Leveinen Jussi, Aalto University, 2009-2010

Sorjonen Kari, Pöyry Infra Oyj, 2009-2010

Vähäaho Ilkka, Helsinki Geo, 2009-2010

Annex 1. Geological map and cross section in the surroundings of Helsinki and Tallinn



↑ Geological map in the surroundings of Helsinki and Tallinn [Source: Koistinen, T.(editor), 1994. Precambrian basement of the Gulf of Finland and surroundingarea, 1:1 mill. Geological Survey

↓ Geological cross section in the surroundings of Helsinki and Tallinn [Source: Koistinen, T. (editor), 1994. Precambrian basement of the Gulf of Finland and surrounding area, 1:1 mill. Geological Survey of Finland, Espoo]

Annex 2. Railway tunnels around the globe (a non complete list)

Tunnel	Country	City	Comission	Length (km)	Type	Build method	Linkit
Seikan tunnel	Japan	Honshu – Hokkaido	1988	54	C	DnB	http://web.archive.org/web/20060503142919/ http://www.pref.aomori.jp/newline/shinkan/shinkan/newline-e/sin-e08.html http://en.wikipedia.org/wiki/Seikan_Tunnel,
Channel Tunnel	England-France		1994	50	A	TBM	http://www.eurotunnel.com/ http://en.wikipedia.org/wiki/Channel_Tunnel
Lötschberg	Switzerland	Frutigen, Berne	2007	35	B	TBM	http://en.wikipedia.org/wiki/L%C3%B6tschberg_Base_Tunnel
Guadarrama tunnel	Spain	Madrid	2007	28	B	TBM	http://en.structurae.de/structures/data/index.cfm?id=s0007961 http://en.wikipedia.org/wiki/Guadarrama_Tunnel
Iwate-Ichinohe	Japan		2002	26	C		
Wushaoling Tunnel	China	Gansu	2006	21	B	TBM	http://en.wikipedia.org/wiki/Wushaoling_Tunnel
North East MRT Line	Singapore	Singapore	2002	20	B		
Simplon Tunnel	Switzerland	Brig	1906	19	B		http://www.fordham.edu/halsall/mod/1905simplon.html http://en.wikipedia.org/wiki/Simplon_Tunnel
Vereina	Switzerland		1999	19	C		
Qingling	China		2002	19	B		
Gotthard Rail Tunnel	Switzerland	Göschenen	1882	15	B		http://en.wikipedia.org/wiki/Gotthard_Rail_Tunnel
Romerike Tunnel	Norway	Oslo	1999	14	B		http://en.wikipedia.org/wiki/Romeriksporten
Savio Rail Tunnel	Finland	Helsinki	2008	14	C		
Lieråsen Tunnel	Norway	Lieråsen	1973	11	B		http://en.wikipedia.org/wiki/Lier%C3%A5sen_Tunnel
Arlbergtunnel	Austria	Arlberg	1884	11	C		http://en.wikipedia.org/wiki/Arlbergtunnel_(railway9)
Finse Tunnel	Norway	Finse	1993	10	B		http://en.wikipedia.org/wiki/Finse_Tunnel
Great Belt tunnel	Denmark	Copenhagen	1997	8	B		http://www.storebaelt.dk/www-storebaelt-dk/Engelsk/Broen/ http://en.wikipedia.org/wiki/Great_Belt_Fixed_Link
Anton Anderson Memorial Tunnel	U.S Alaska	Whitter	1943	4	B (combo)		http://en.wikipedia.org/wiki/Anton_Anderson_Memorial_Tunnel http://www.dot.state.ak.us/creg/whittiertunnel/index.shtml
Drogden Tunnel	Denmark	Copenhagen	2000	4	A (combo)	Immersed	http://www.ita-aites.org/cms/fileadmin/filemounts/general/pdf/ItaAssociation/Prod

Legend:

A = Twin tube with service tunnel

B = Twin tube without service tunnel

C = Single tube tunnel

Annex 3. Tunnel projects around the globe (a non complete list)

Tunnel	Country	Comission	Length (km)	Type	Phase	Links
Gotthard Base Tunnel	Switzerland	2018	57	B	construction	http://neat.ch/en/?no_cache=1 http://en.wikipedia.org/wiki/Gotthard_Base_Tunnel
Lyon-Turin	France-Italy	2020	53	B	planning	
Koralm	Austria	2016	33	B	planning	
Hakkoda	Japan	2010	27	C	construction	
Pajares	Spain	2010	25	B	construction	
Prague-Beroun	Czech Repuplic	2016	25	B	planning	
Iyama	Japan	2013	22	B	construction	
Vaglia	Italy	2010	19	C	construction	
Ring Rail Link	Finland	2014	18	B	construction	http://www.keharata.fi/ http://en.wikipedia.org/wiki/Ring_Rail_Line
Malmö City Tunnel	Sweden	2010	17	B	construction	http://en.wikipedia.org/wiki/City_Tunnel,_Malm%C3%B6, http://www.citytunneln.com/en
Ceneri	Switzerland	2018	15	B	planning	
Firenzuola	Italy	2010	15	C	construction	
Wienerwald	Austria	2012	14	B	construction	
Länsimetro	Finland	2015	14	B	construction	http://www.lansimetro.fi/ http://fi.wikipedia.org/wiki/L%C3%A4nsimetro
Bussoleno	France-Italy	2020	13	B	planning	
Lainzer	Austria	2012	11	C	construction	
Hallandsås	Sweden	2015	9	A	construction	http://www.banverket.se/pages/4439/Skanska-Vinci%20eng.pdf http://www.banverket.se/sv/Amnen/Aktuella-projekt/Projekt/1869/Hallandsas.aspx http://en.wikipedia.org/wiki/Hallands%C3%A5s_Tunnel
Bærum Tunnel	Norway	2011	6	C	construction	http://en.wikipedia.org/wiki/B%C3%A6rum_Tunnel
Stockholm City Line	Sweden	2017	6	C	construction	http://www.banverket.se/en/Amnen/Corrent-Projects/The-City-Line-in-Stockholm.aspx http://en.wikipedia.org/wiki/Stockholm_City_Line

Legend:

A = Twin tube with service tunnel B = Twin tube without service tunnel C = Single tube tunnel

Annex 4. Tunnel project visions & the longest road tunnels

Tunnel	Country	Type	Length (km)	Comission	Phase	Links
South-Korea-China	South-Korea-China	A	250		vision	
South-Korea-Japan	South-Korea-Japan	A	210		vision	
Sakhalin Tunnel	Russia	B	124	2030	vision	http://en.wikipedia.org/wiki/Sakhalin_Tunnel
Bering Strait bridge	Russia – USA (Alaska)	A (combo)	103		vision	http://www.nowpublic.com/russia_plans_worlds_longest_tunnel_a_link_to_alaska http://en.wikipedia.org/wiki/Bering_Strait_bridge
Helsinki-Tallinn	Finland-Estonia	A	80	2050	vision	
Austria – Italy		A	56		planning	
Gibraltar tunnel	Spain-Marocco	A	38	2025	planning	http://layijadeneurabia.com/2008/06/30/gibraltar-tunnel-under-troubled http://en.wikipedia.org/wiki/Gibraltar_Tunnel

Finnish Road Tunnels	City	Comission	Length (km)	Type	Phase	Links
Rantaväylän tunneli	Tampere	2015	2,30	Road Tunnel	planning	http://www.tampere.fi/liikennejakadut/projektit/rantavaylantunneli.html http://fi.wikipedia.org/wiki/Rantav%C3%A4yl%C3%A4n_tunneli
Karnaisten tunneli	Lohja	2008	2,25	Road Tunnel	operation	http://fi.wikipedia.org/wiki/Karnaisten_tietunneli

Long Road Tunnels	Country	Comission	Length (km)	Type	Phase	Links
Gotthard Road Tunnel	Switzerland	1980	24,5	Road Tunnel	operation	http://www.gotthard-strassentunnel.ch/ http://en.wikipedia.org/wiki/Gotthard_Road_Tunnel
Lærdal Tunnel	Norway	2000	24,5	Road Tunnel	operation	http://en.wikipedia.org/wiki/L%C3%A6rdal_Tunnel

Legend:

A = Twin tube with service tunnel

B = Twin tube without service tunnel

C = Single tube tunnel