Workshop on

NATM & TBM TUNNELLING INCLUDING RISK MANAGEMENT – ISSUES & CHALLENGES

6 - 8 February 2018, New Delhi

COURSE MATERIAL

Organised by

Tunnelling Association of India

Central Board of Irrigation & Power

NEW DELHI

under the aegis of

International Tunnelling and Underground Space Association

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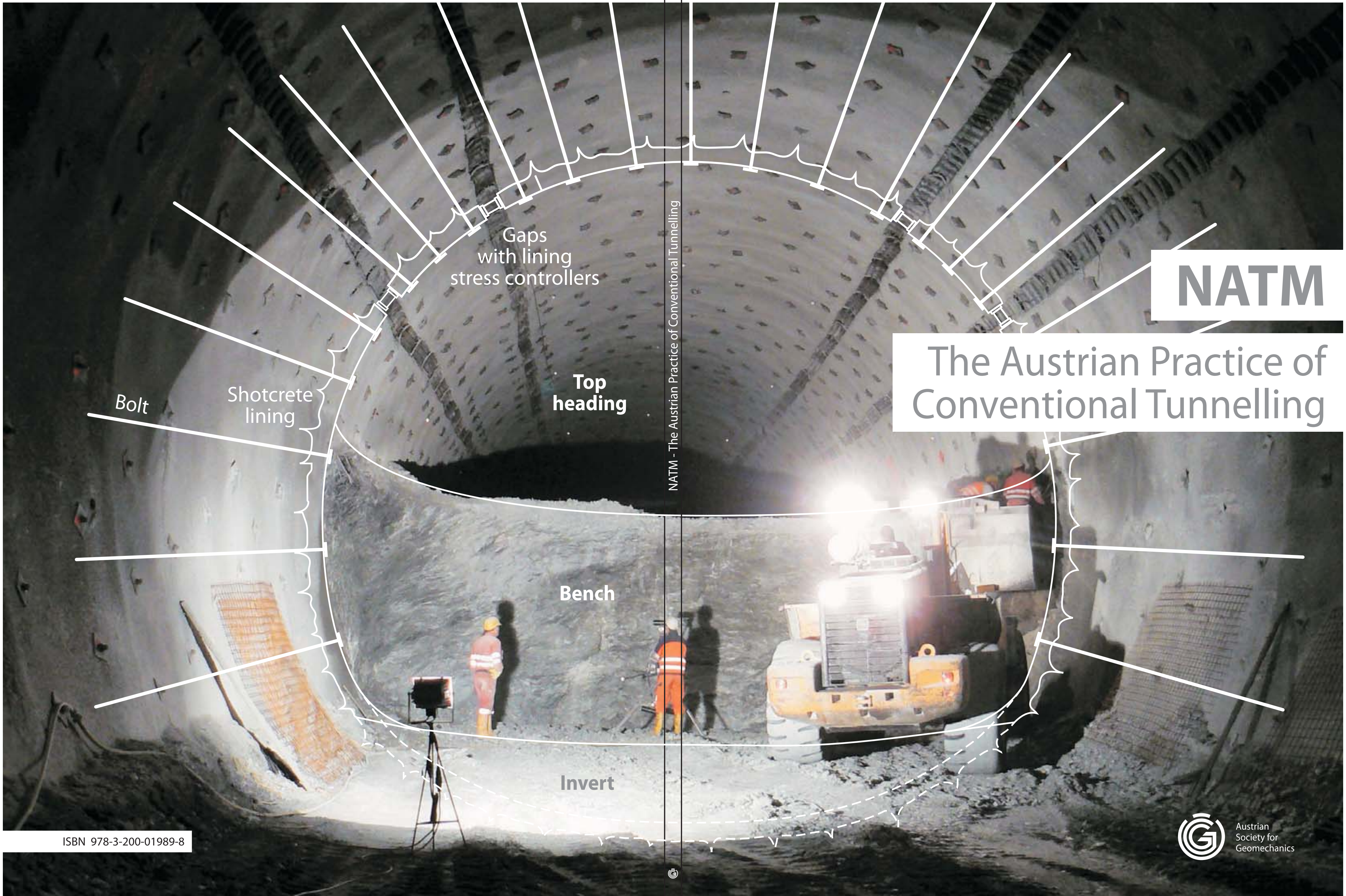

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NATM - The Austrian Practice of Conventional Tunnelling

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Austrian
Society for
Geomechanics

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Austrian Society for Geomechanics
Division "Tunnelling"
Working Group "Conventional Tunnelling"

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Preface

The development of tunnelling methods and construction practices within a particular nation are influenced by many geographical, political, social and cultural factors. Such factors include the following:

- Geographical situation, topography, existing infrastructure and buildings, environment, natural resources, geological and hydrogeological conditions
- Demand for underground works
- Political, social, and economic situation
- Technical standards
- Legal status and competence of owners
- Availability of qualified workforce
- Mining tradition
- Contractual practice

Situated in central Europe, Austria is and has always been a vital corridor for the transportation of both people and goods. The country is mainly mountainous and partly hilly; large plains and wide valleys are rare.

In terms of tunnelling, the geological conditions in Austria are generally difficult and tend to change rapidly along a tunnel route. Tunnelling in the Alps is characterised by high overburden and, in some cases, heavily squeezing rock. However large scale underground construction projects are also common in urban areas where the protection of both the population and the natural environment is paramount.

In the 1950s tunnels in the Alps were primarily constructed in conjunction with hydroelectric projects. Since 1970 an increasing number of tunnels for infrastructure have been built. During this period, owners experienced in tunnel design and construction together with specialised contractors developed an on-site decision making procedure, which became common practice in Austrian tunnelling.

At this time Austria had a number of brilliant engineers like Rabcewicz, Müller, Pacher, Lauffer, Seeber, et.al. who greatly influenced and promoted the development of tunnelling in Austria with innovative ideas. Their most important contribution was the development of NATM (New Austrian Tunnelling Method), which included the observational approach.

Since 1950 new materials, namely shotcrete and rock dowels, replaced the old timber support and a permanent, in-situ concrete lining was provided in lieu of the traditional masonry lining. In addition, the standardised use of synthetic membranes and fabrics significantly improved the quality of tunnels in terms of water tightness. The technological development along with improved engineering practices paved the way for new theoretical explanations to substantiate an economically beneficial design approach.

The Austrian methodology of tunnelling is based on a procedure which requires both construction partners to make immediate, joint decisions with regard to ground conditions. The flexibility to make such decisions is incorporated into the contractual framework to ensure an immediate and effective response to changes in ground conditions. The successful application of the NATM is made possible through the collaboration of qualified and experienced owners, designers, contractors and site engineers working with a knowledgeable, experienced workforce within the framework of a suitable contractual model.

Within the Austrian tunnelling community emphasis is placed on good cooperation between all parties involved. Technical questions regarding safe, fast and economical tunnelling take priority over contractual considerations. This approach is of general benefit to all parties. It is based on a profound technical expertise and a willingness to cooperate. As a general rule, tunnelling projects in Austria are executed on the basis of a unit price contract.

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Contents

1 Purpose

This document summarises the state-of-the-art techniques that are characteristic of NATM. The main topics include:

- Principles of conventional tunnelling
- Design stages
- Overview of ground investigations
- Geotechnical design and geotechnical safety management
- Monitoring and data evaluation
- Tunnelling contract structure
- Construction site organisation

2 Definitions

GROUND

Part of the earths crust, composed of rock and/or soil, frequently with anisotropic properties, including discontinuities, and voids filled with liquids or gases

ROCK

Aggregate, consisting of mineral components, developed from natural processes, characterised by the types and amount of the minerals and grain structure

INTACT ROCK

Mineral aggregate, whose properties predominantly are determined by the physical/chemical bond

ROCK MASS

Accumulation of various rock units which form a structural framework including discontinuities

SOIL

Accumulation of inorganic, solid particles with occasional organic admixtures. The properties are predominantly governed by the granulomeric composition, the compaction, and the water content

DISCONTINUITY

General term for any mechanical discontinuity in a rock mass having zero or low tensile strength. Collective term for most types of joints, bedding planes, schistosity planes, weakness zones and faults

GROUND TYPE (GT)

Ground with similar geotechnical properties

GROUND BEHAVIOUR (GB)

Reaction of the ground to the excavation of the full profile without consideration of sequential excavation and support

BEHAVIOUR TYPE (BT)

General categories describing similar Ground Behaviours with respect to failure modes and displacement characteristics

SYSTEM BEHAVIOUR (SB)

Behaviour resulting from the interaction between ground, and support, separated in:

- System Behaviour in the respective excavation area
- System Behaviour in the supported section
- System Behaviour in the final state

BOUNDARY CONDITIONS

Conditions influencing construction processes and methods which are not of a geotechnical nature

FRAMEWORK PLAN

Summary of the Geotechnical Design, including relevant parameters used in the design, and application criteria for the assignment of excavation and support methods

REQUIREMENTS

Definition of required parameters to safeguard serviceability, safety, and the environment

3 Application of NATM

3.1 General Approach

NATM is based on the concept that the ground around the tunnel not only acts as a load, but also as a load-bearing element. Typically, the excavation and support activities are continuously adjusted to suit the ground conditions, always considering the technical/design requirements. The ground reaction, in the form of lining displacements is measured in order to check the stability of the opening and to optimise excavation and support process.

Depending on the project conditions (e.g. shallow soft ground tunnel, deep rock tunnel) and the results of the geotechnical measurements, the requirements for a specific support are determined. Contractual arrangements must be flexible to ensure that the most economical type and amount of support is used.

The typical support elements in NATM are shotcrete and rock dowels. Steel ribs or lattice girders provide limited early support before the shotcrete hardens and ensure correct profile geometry. If ground conditions require support at or ahead of the excavation face, face dowels, shotcrete, spiles or pipe canopies are installed as required.

The excavation cross-section is subdivided into top heading, bench and invert depending on both ground conditions and logistical requirements (i.e. to facilitate the use of standard plant and machinery). Side drift galleries are provided to limit the size of large excavation faces and surface settlements.

3.2 Construction Methods

The increased demand to construct road and railway tunnels with large cross-sections, spurred the further development and standardisation of specific construction methodology. Particularly, standard methods were developed for the excavation of tunnels in hard rock conditions, squeezing ground conditions, and soft ground conditions.

3.3 Hard Rock Conditions

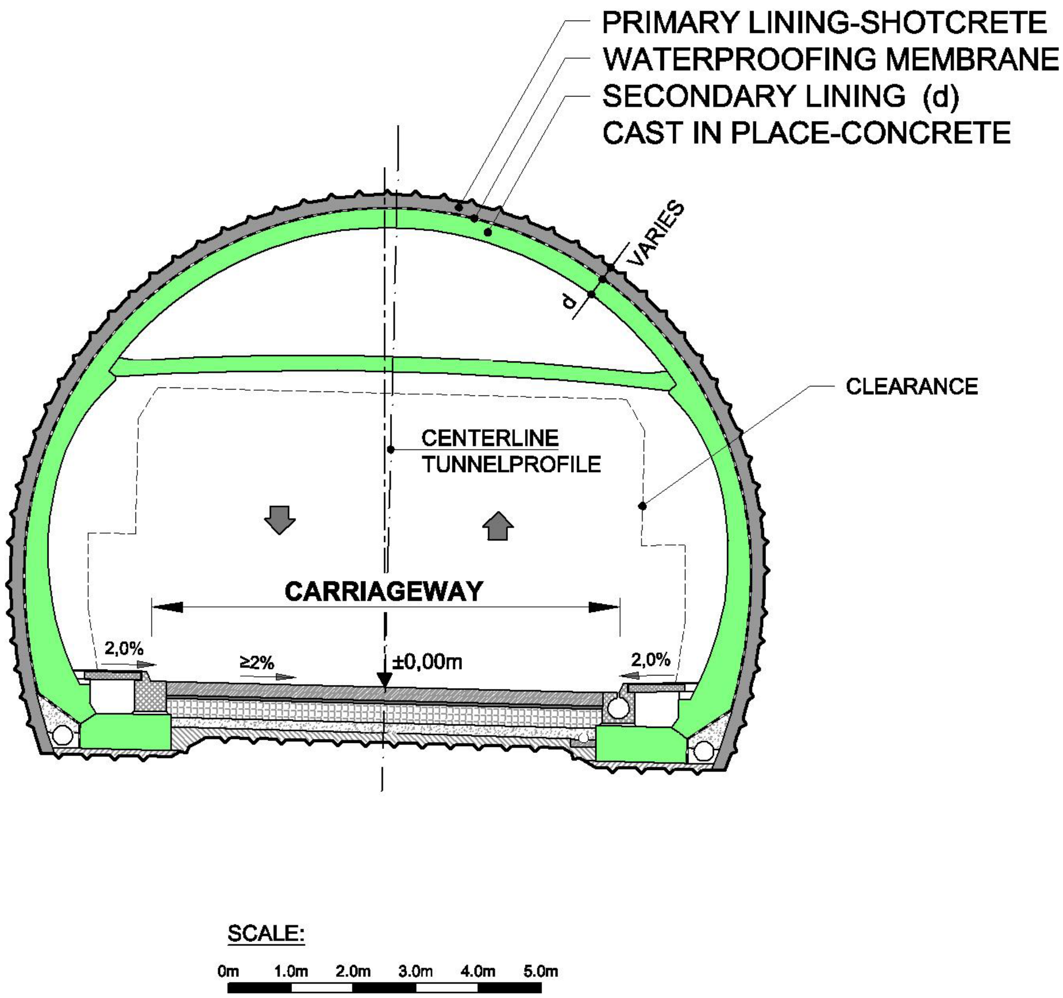


Fig. 1: Example of cross-section in hard rock conditions

The basis for the design of tunnels in rock depends on both the ground conditions and the usage of the tunnel (water, road, railway tunnel, etc.). Tunnels excavated in sound rock are generally horse-shoe shaped, whereas tunnels excavated in poor rock generally require an invert arch to ensure stability.

The tunnel is typically advanced by drill and blast following a sequential excavation method (top heading, bench, invert). However if favourable rock conditions are anticipated, full-face excavation can be used.

The bench is excavated simultaneously to the top heading, up to a few hundred meters behind the excavation face, providing a ramp for access to the heading. Some distance behind the bench, the invert is excavated. If ground conditions are unfavourable, an invert arch is provided to close the lining, forming a complete ring.

Fig. 2: Pilottunnel in hard rock conditions

In a separate operation following the excavation, concrete abutments and plastic drainage pipes are installed. The tunnel profile is checked by scanning the surface and is corrected if necessary. The primary lining and the dowel heads are covered with a smoothening layer in preparation for the installation of the waterproofing system.

The secondary lining is typically unreinforced and cast in 8.0 m to 12.0 m long bays using a steel formwork mounted on a carrier. The steel formwork provides a high-quality surface. The concrete mix is designed to allow for one concreting cycle in 24 hours.

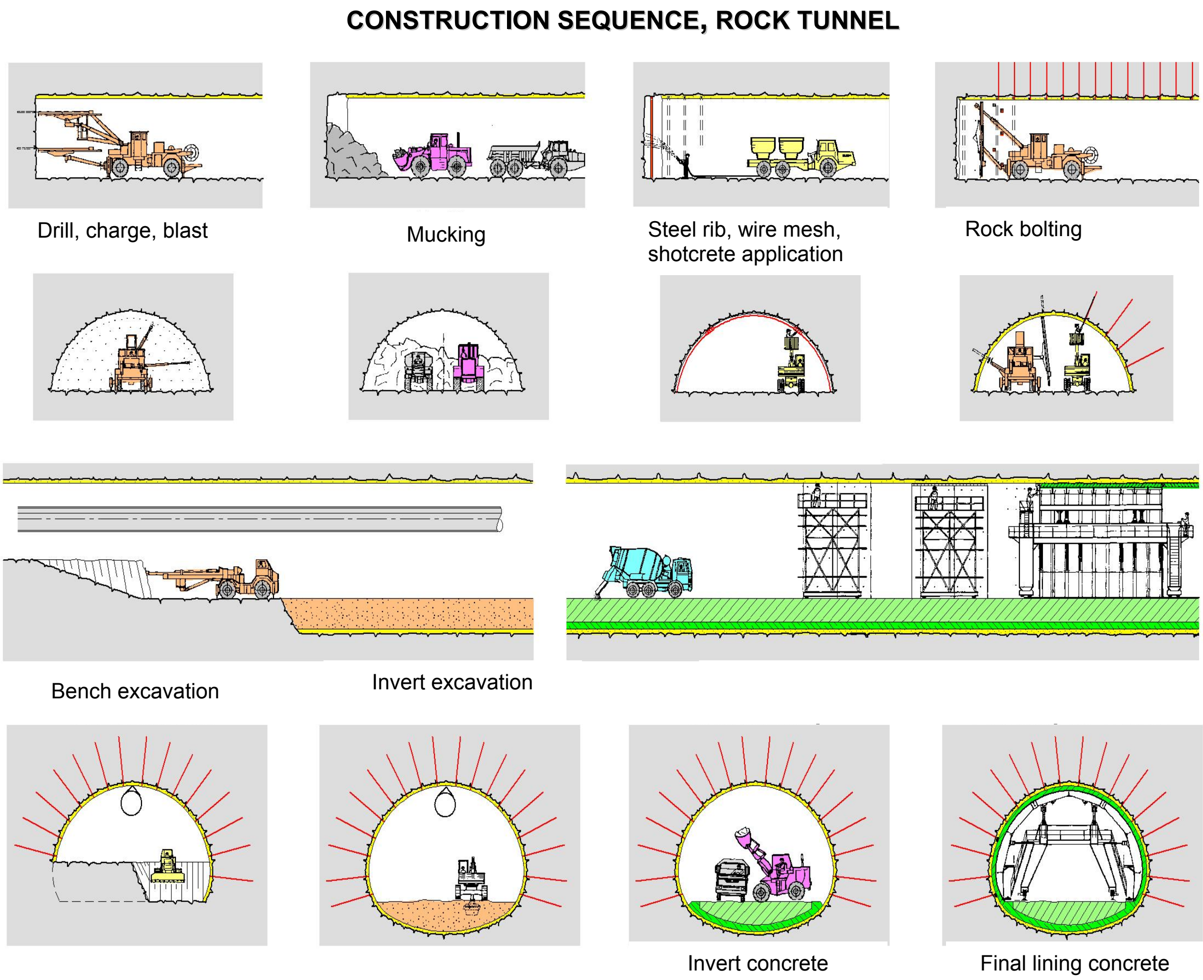


Fig. 3: Construction sequence including invert arch

3.4 Squeezing Rock Conditions

Tunnels excavated in weak rock and high overburden exhibit fracturing and large deformations due to high stresses around the opening which exceed the ground strength. In order to effectively manage these large deformations, a number of important design parameters must be established. These include definition of the over-excavation required to provide the deformation allowance, as well as the determination of support measures. A support system which allows controlled deformation is chosen to limit the required support resistance and to achieve stability.

To increase the shear strength of the rock mass, the key support element is the use of rock dowels. The shotcrete lining thickness is typically 0.2 m to 0.3 m. In case of large displacements longitudinal slots in the shotcrete lining and yielding support elements are placed to allow deformation without damage to the lining. Once the rock pressure is significantly reduced and stabilisation of the opening is confirmed by monitoring, the slots in the lining are closed with shotcrete.

Fig. 4: Yielding elements installed in longitudinal slots in the top heading

Yielding elements are integrated into the shotcrete lining. These yielding elements act to limit the normal forces in the shotcrete lining, thus preventing overstressing and preserving the support capacity. Fig. 4 shows the use of the deformable support system.

Following breakthrough, the installation of the waterproofing system and secondary lining is identical to a hard rock tunnel.

3.5 Soft Ground Conditions

Shallow tunnels in soft ground situated in an urban environment require the use of both a rigid support and a predetermined sequence of advance. In conventional soft ground tunnelling, the emphasis is on a rigid shotcrete lining, a short advance length and a rapid invert closure. If required, the cross-section is divided into side and centre drifts. Auxiliary measures like dewatering wells, compressed air, jet grouting or even ground freezing are also applied where necessary.

In addition to the geological, hydrogeological and geotechnical conditions, the design of tunnels in soft ground must also consider the usage of the tunnel, environmental factors and minimising surface settlements.

The installation of the waterproofing system, secondary lining and the technical equipment after breakthrough, is identical to a hard rock tunnel.

The applicability of various excavation methods and support types to a range of overburden depths and tunnel types are presented in the following examples.

3.5.1 Example 1: Road Tunnel, Overburden 50 m

The example describes a tunnel with a drained lining system excavated in sandy, silty gravel with interbedded layers of silt. The cross-section is similar to that of a hard rock tunnel, however, an invert arch, consisting of shotcrete and reinforced or unreinforced concrete, is provided throughout (see Fig. 5). In contrast to a hard rock tunnel, the main support element is shotcrete applied to a substantial thickness (0.3 m – 0.4 m). The thickness of the secondary lining is to be determined by structural analysis.

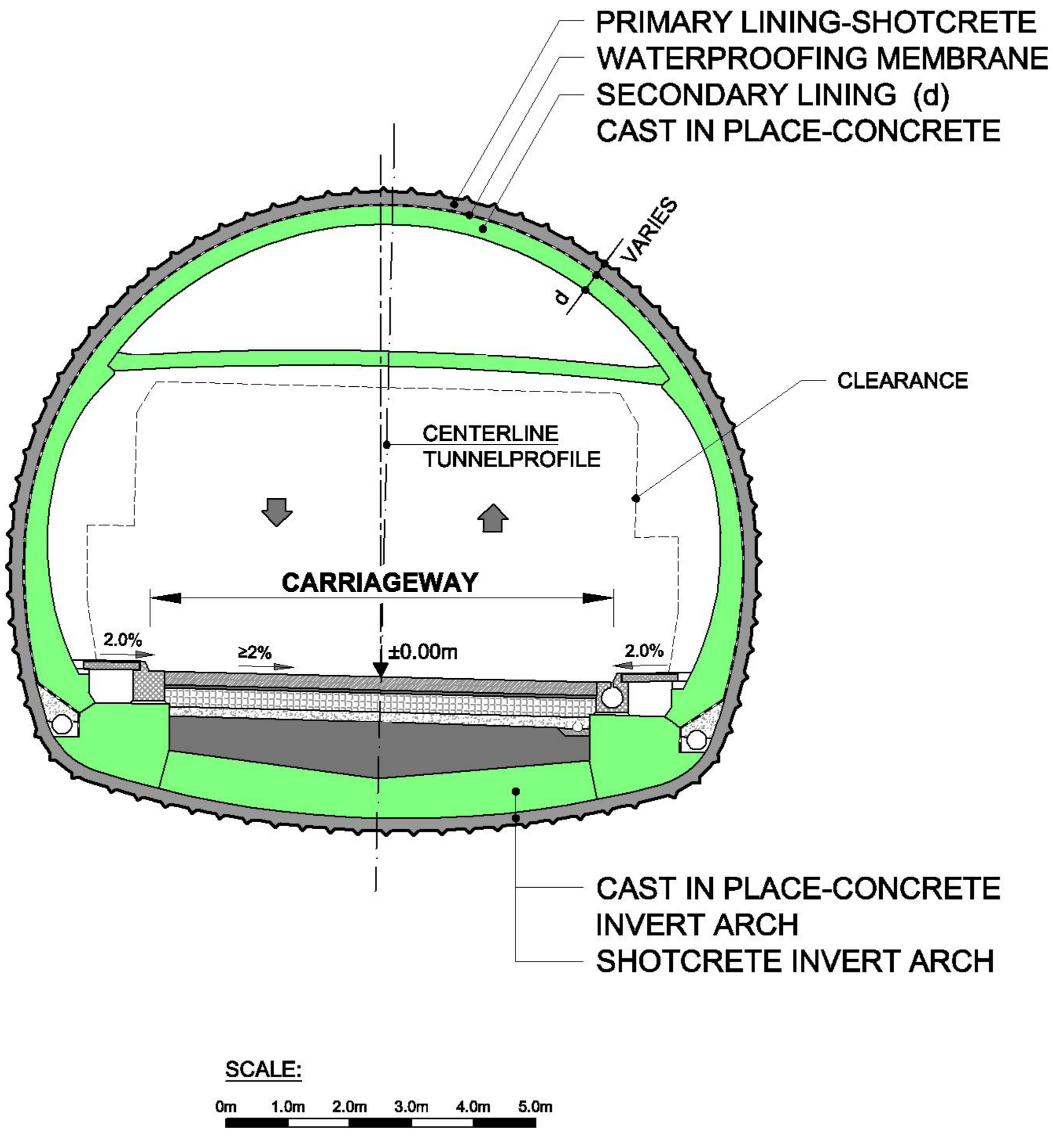


Fig. 5: Example of cross-section in soft ground conditions

The excavation sequence is top heading – bench – invert. Face support (supporting core), elephant feet, a temporary invert in the top heading and the arrangement of a pipe canopy can be employed (see Fig. 6 and 7).

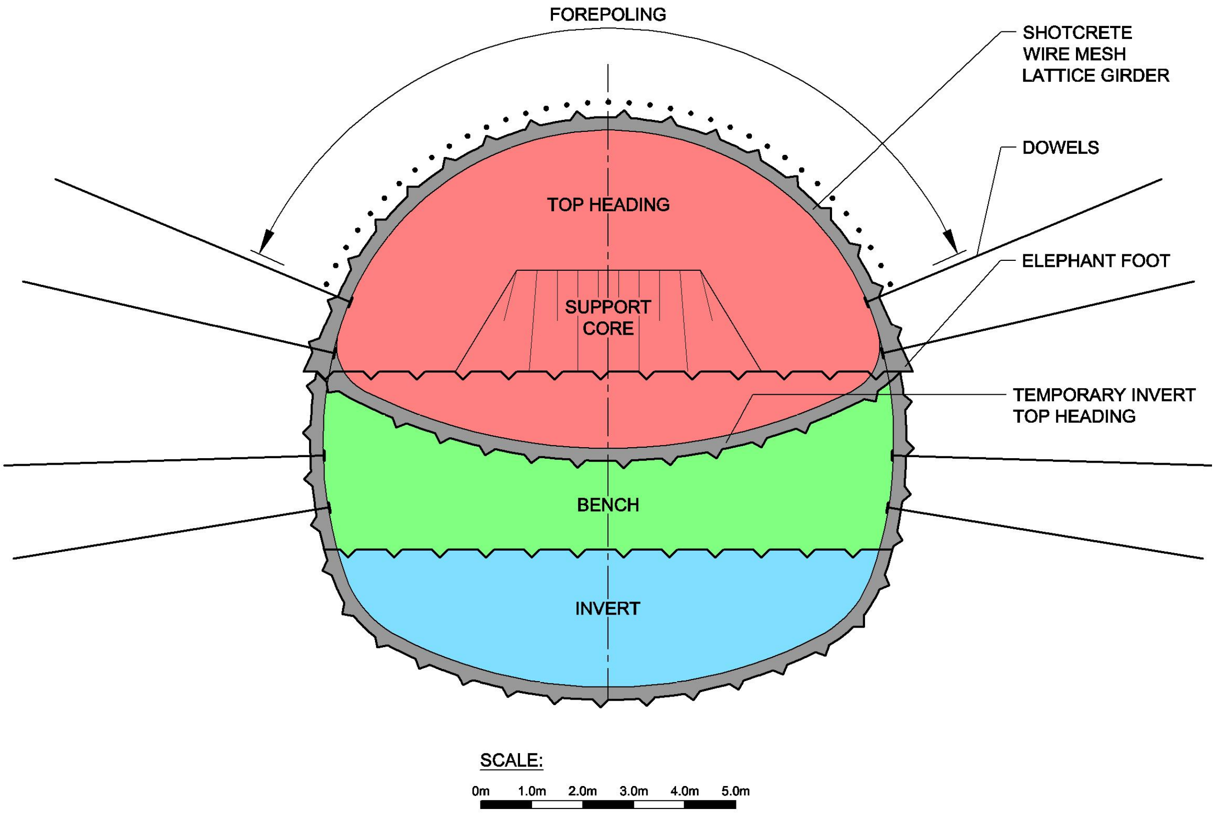


Fig. 6: Typical excavation and support in soft ground conditions

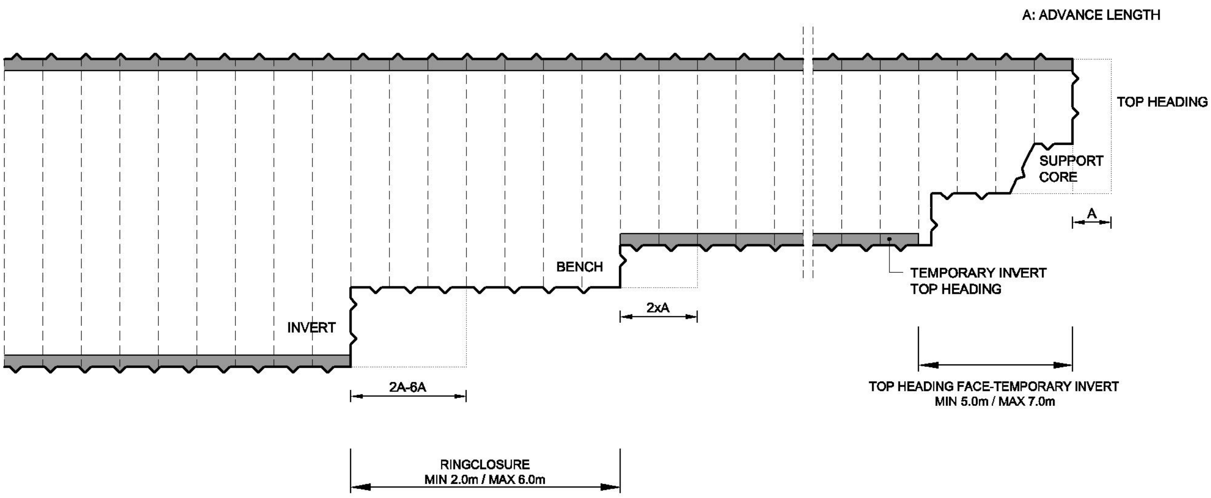


Fig. 7: Typical excavation sequence in soft ground conditions

The length of the excavation rounds for this example is limited to a maximum of 1.0 m in the top heading, 2.0 m in the bench and 4.0 m in the invert. The closure of the temporary invert follows 5.0 m to 7.0 m behind the face of the top heading. The closure of the invert follows 2.0 m to 6.0 m behind the face of the bench. The advance rate is related to the quality of the young shotcrete. In this example it is restricted to 5.0 m in 24 hours in the top heading and 8.0 m in 24 hours in the bench and invert to limit stresses in the primary lining.

3.5.2 Example 2: Twin-track Metro Tunnel, Shallow Overburden, Urban Environment

The excavation of a shallow tunnel in an urban environment requires that surface settlements be minimised. The limitation of ground settlements necessitates that a stiff support is applied soon

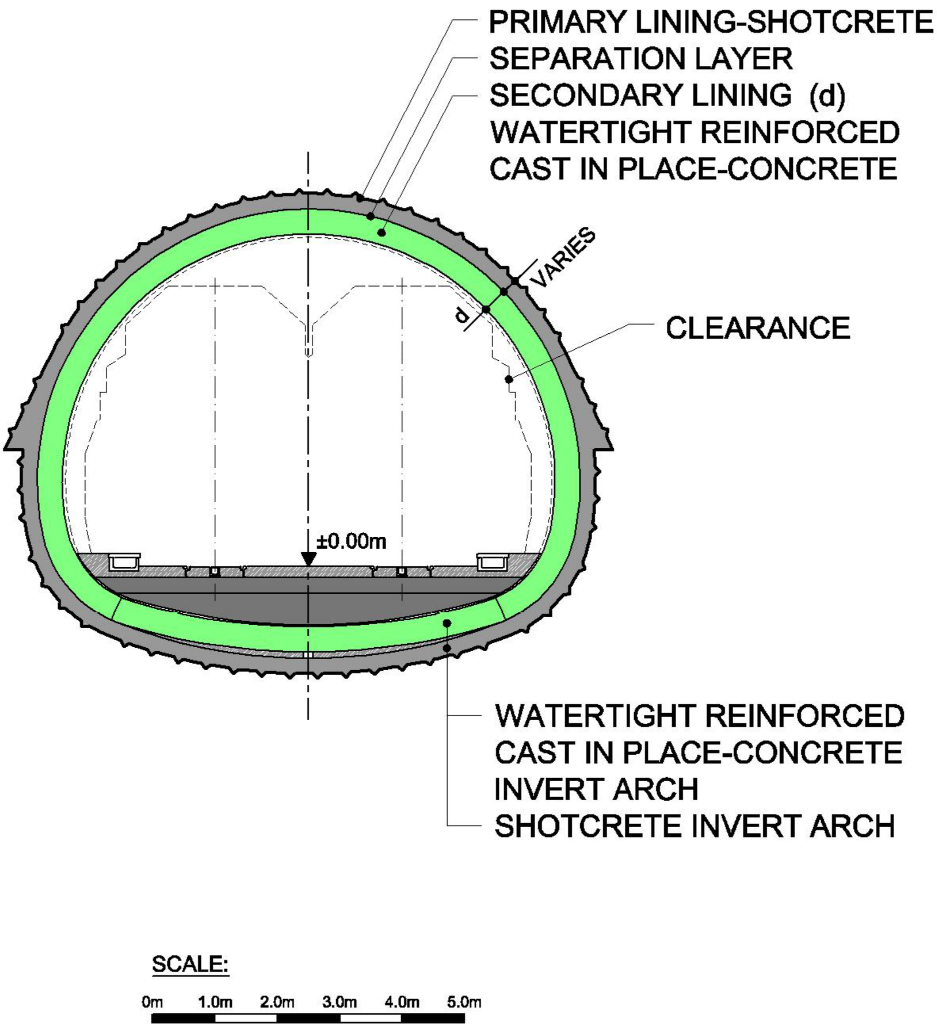


Fig. 8: Example of cross-section in soft ground conditions, fully tanked lining

after excavation, with no attempt made to reduce lining loads by allowing deformations of the opening. Therefore, the most effective means to advance this type of tunnel is the combined use of a strict sequence of short advance rounds with a closed ring of shotcrete of substantial thickness.

Example 2 demonstrates the excavation of a double-track tunnel with a cross-sectional area of 60 m² (see Fig. 8). The circumstances require that the groundwater level be lowered using a system of dewatering wells. The tunnel cross-section is excavated in partial face sections where flowing layers of soil are present within the gravel layers. Substantial support of the excavation face using shotcrete and dowels or ground treatment by grouting ahead of the face is occasionally required to ensure safe tunnelling conditions (see Fig. 9 and 10).

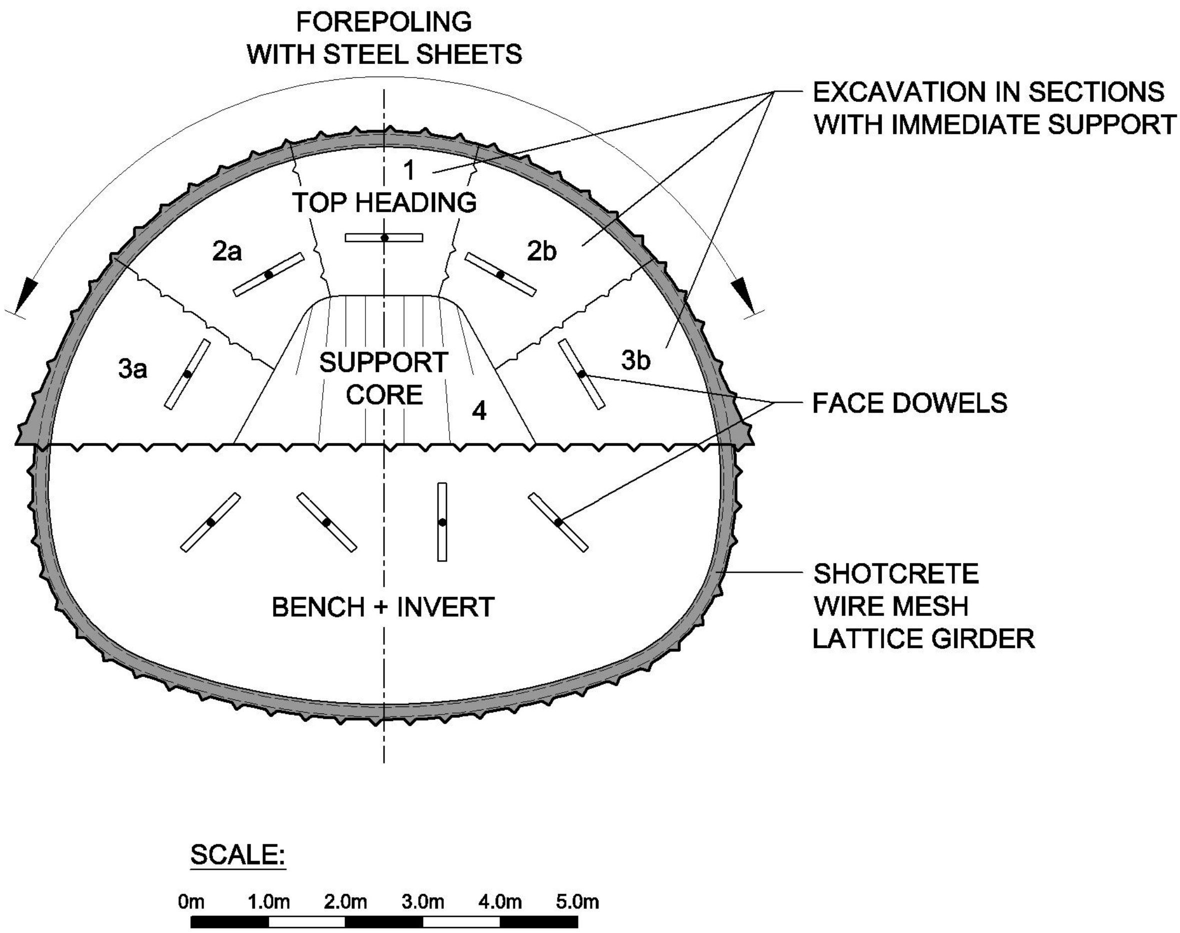


Fig. 9: Example of excavation in soft ground conditions, urban environment

Fig. 10: Metro tunnel in soft ground conditions

For top heading, bench and invert the thickness of the shotcrete lining, the lattice girder spacing and the distance from the tunnel face to the invert closure is defined in the design. Instrumentation is used to monitor the surface settlements as well as the performance of the primary lining and to validate the design.

The length of the excavation rounds for this example is limited to a maximum of 1.0 m and the closure of the invert followed 5.0 m behind the face. The advance rate is restricted to 4.0 m in 24 hours to limit stresses in the recently placed primary lining shotcrete.

A fully tanked secondary lining system is installed, since a permanent drainage system for groundwater pressure release is not acceptable. The drainage system used during construction of the tunnel is sealed with grout. Water tightness is achieved by a reinforced concrete secondary lining, which is designed to sustain the full hydrostatic pressure and all permanent loads.

3.5.3 Example 3: Railway Tunnel, Shallow Overburden

The excavation of tunnels with large cross-sections in shallow overburden requires that the size of the excavation face be reduced to limit surface settlement. This can be achieved by using an excavation sequence consisting of two sidewall drifts and a centre core (see Fig. 11 and 12).

In this example the side wall drifts are staggered and served as both a pilot tunnel and a foundation for the crown support. The side wall drifts are advanced individually employing an excavation sequence with a short top heading followed by early invert closure as shown

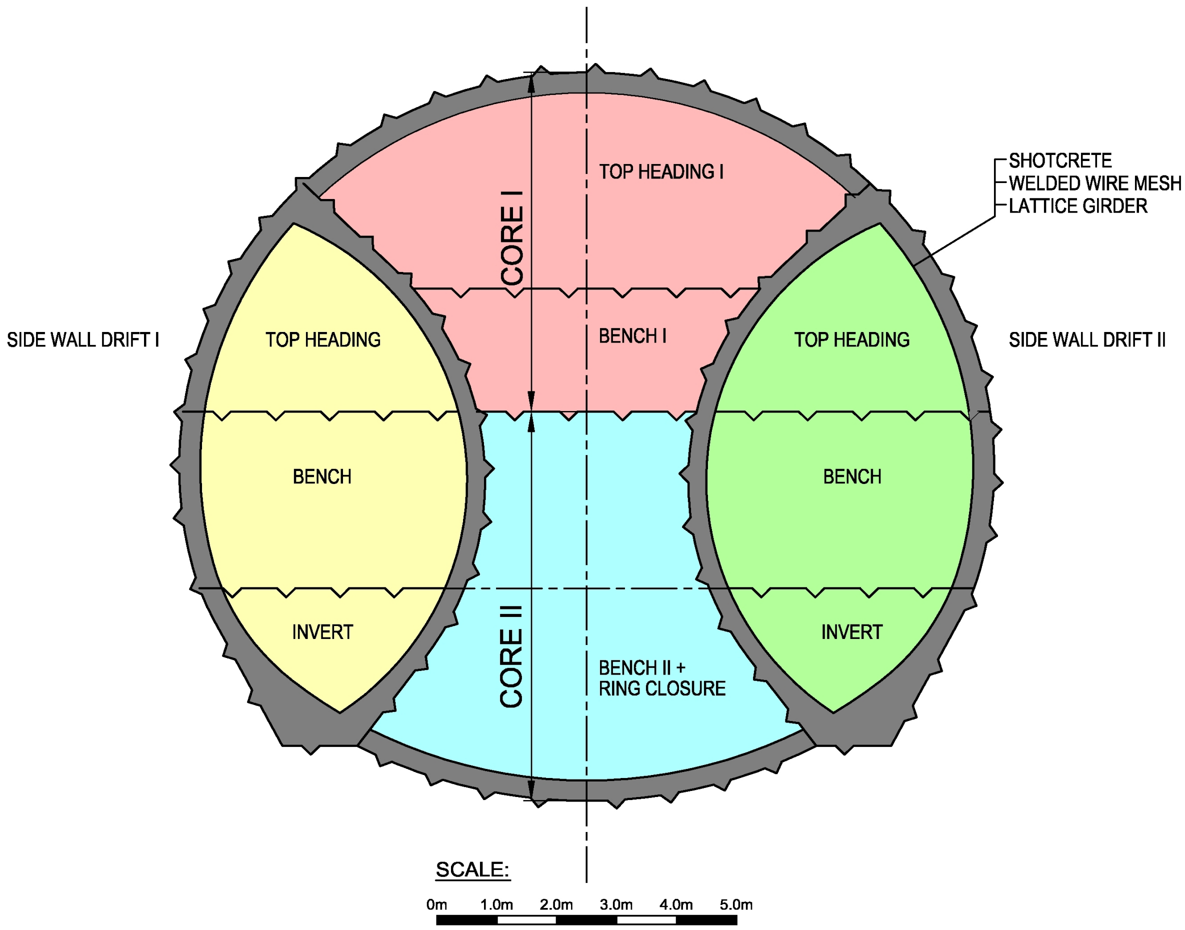


Fig. 11: Typical excavation and support for side wall drift method

Fig. 12: Double-track railway tunnel in urban environment

in Fig. 11. The size of a side wall drift has to meet space requirements for the intended excavation plant. Also the shape of temporary side walls has to be designed in a way that does not deviate too much from an oval shape with sharp bends in the crown and invert.

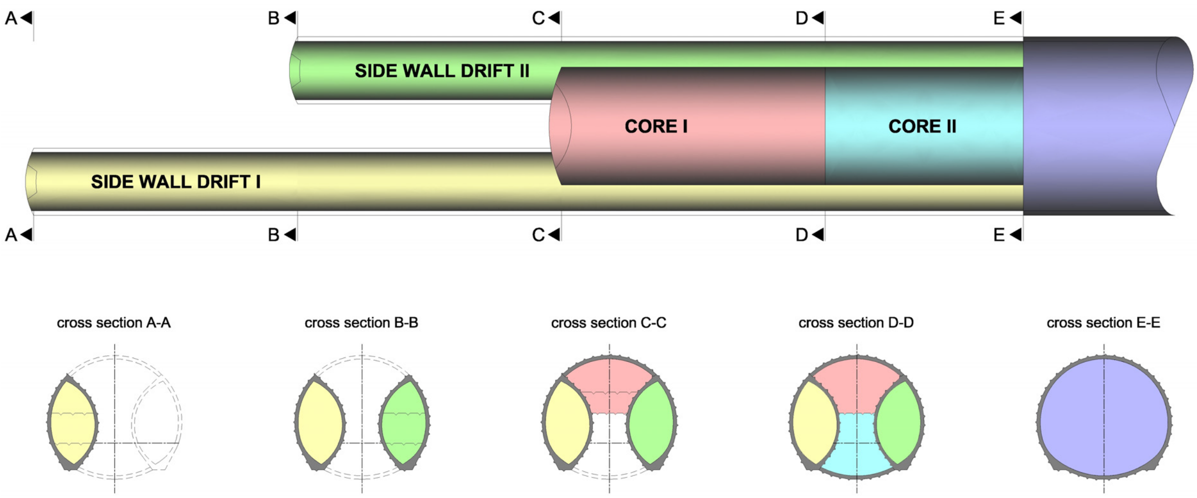


Fig. 13: Typical excavation sequence for side wall drift method

Particular attention is given to facilitate the connection of side wall drift linings with the crown support and invert of the core.

After breakthrough, or at a substantial distance behind the side wall drifts, core 1 is advanced as an essentially independent operation, using 1.0 m long rounds and a top heading and bench sequence (see Fig. 13). Core 2 excavation follows at a distance which is dependent on the arrangement of plant employed by the contractor. Just before ring closure of the complete cross-section (in typically 2.0 m long advance rounds) the temporary side walls are removed at this location.

4 Design Stages

4.1 General

In general, tunnel design can be carried out by the client's own engineering team, by the design engineer appointed by the client or by the construction contractor's design team. In Austria, a client would typically appoint a design engineer to be responsible for the design in all stages of a conventional tunnel project. However, on rare occasions, multiple design consultants are appointed, each being responsible for a different stage of the project.

The design of a tunnel project is subdivided into four principal stages:

- Conceptual design including feasibility study
- Preliminary design
- Tender design
- Final design

In Austria national standards and guidelines regulate the design and construction of tunnels, e.g. standardised cross-sections, structure geometry, dynamic envelopes, safety requirements, etc.

4.2 Conceptual Design

For the design of tunnels the following aspects are to be considered:

- Type and purpose of the underground structure
- Alignment
- Topographical conditions
- Geological and hydrological conditions

- Environmental impact including noise, vibration, air pollution
- Legal aspects
- Safety requirements
- M & E requirements
- Risk assessment and analysis

The purpose of the conceptual design is to select or finalise the tunnel alignment and to provide a cost estimate.

The design documents and drawings produced at the conceptual design stage include:

- Definition of design basis
- Comparison of alignment alternatives and selection of preferred alignment
- Geological and hydrological information available
- Proposal for further investigations
- Assessment of the impact of the tunnel on the environment (e.g. influence on groundwater regime, surface settlements, noise, vibration, dust etc.)
- Cost estimate
- Construction programme

The design engineer is also responsible for tasks involving public relations and project management.

4.3 Preliminary Design

In the preliminary design stage, the conceptual design of the project is refined based on the selected alignment and an Environmental Impact Study is carried out. In this stage the main focus is on environmental matters, particularly on the legal aspects of water resources, forestry and nature protection.

Different clients and authorities may require individual substages for railway or road tunnels. However, the common target in the preliminary design is to receive the approval for construction of the project by the authorities.

The preliminary design stage involves the following tasks:

- Contribution to the site investigation programme by the design engineer
- Site investigation
- Evaluation of site investigation and laboratory test results
- Geotechnical prognosis and identification of typical ground characteristics
- Definition of ground properties (key parameters) for analysis
- Development of typical cross-sections based on the geotechnical requirements
- Selection of excavation and support methods
- Identification of portal locations and design of portal structures
- Tunnel waterproofing and drainage concepts
- Integration of operational systems to address tunnel safety requirements (e.g. emergency escape, ventilation, fire fighting, lighting, telecommunication etc.)
- Definition of construction concepts, including water and power supply, location of construction roads and muck deposits and their impact on the environment with respect to noise-, dust-, air pollution-, vibration-, hydrological- and other environmental influences during construction and operation
- Permanent muck deposits
- Documentation regarding land acquisition

- Construction programme
- Cost estimate
- Risk assessment and analysis

4.4 Tender Design

The scope of the tender design is to detail the works to the extent that the exact pricing of each work item can be determined. At this stage, the contractual documents are compiled.

The tender design stage includes the following tasks:

- Additional site investigations to meet requirements of the authorities
- Updating geotechnical prognosis, support drawings, distribution of excavation and tunnelling classes, detailing of auxiliary construction measures and provision of information as required by the national standards and guidelines
- Preparation of contract documents including:
  - Instruction to bidders
  - Project description
  - Information on geotechnical conditions, monitoring and evaluation of monitoring results, etc.
  - Drawings
  - Technical specifications for materials and workmanship
  - Construction programme, time, duration and staging of the project
  - Conditions of contract
  - Itemised bill of quantities, measurement and payment
  - Framework design
- Tender assessment

4.5 Final Design

The scope of the final design is to detail the work described in the tender stage for construction purposes.

The final design stage includes the following tasks in the design office:

- Detailed drawings and shop drawings (e.g. formwork drawings, reinforcement drawings and schedules, etc.)
- Framework design

The final design stage includes the following tasks on site:

- Refinement of the framework design within contractual limits based on the geological/geotechnical conditions encountered during excavation (a particular aim of conventional tunnelling)
- As-built documentation

5 Ground Investigations and Description of the Ground Conditions

5.1 General

The geological investigations form the basis for developing a geological model. The geological investigations are the client's responsibility. Geological, hydrogeological and geotechnical investigations shall be planned and supervised by experienced geologists in close cooperation with the design engineer and the client.

All investigated data (geological, hydrogeological, geotechnical) are summarised in a report. Full disclosure of all data is provided for geotechnical design.

5.2 Methods

The following methods are primarily employed to investigate the ground conditions:

- Analysis of existing records and documents related to ground conditions (e.g. for structures already built in the same or similar geological formations)
- Application of remote sensing technology (analysis of satellite or aerial photos)
- Field mapping
- Exploratory boreholes and in-situ borehole testing
- Trial pits
- Geophysical measurements
- Field tests
- Laboratory tests
- Exploratory adits and galleries (pilot tunnels)

5.3 Extent of Site Investigations

The extent of the site investigation programme carried out is always project-specific. The investigations are executed in steps which correspond to the design stages and the complexity of the geological conditions. In zones of predicted hazards (such as faults, high in-situ stresses, mass movements, cavities, etc.), in portal areas and in zones with shallow overburden the ground must be investigated in greater detail.

During construction, further site investigations especially probing ahead of the face may be required depending on the remaining degree of uncertainty, the type of hazards predicted, the sensitivity of excavation method to changes in ground conditions and the actual conditions encountered.

5.4 Geological Conditions

A complete understanding of the geological structure of the area forms the basis for the description of the geological conditions. This includes the regional geological environment, the lithological sequences and the tectonic setting.

A description of the geological conditions shall be provided for each geological unit, which is defined by comparable lithology and structure. The qualitative description shall be accompanied by quantitative information.

In the description of soils, geological units are normally grouped according to the origin of the geological formations (e.g. moraines, river gravels, colluvium, and clay deposits). Soils are described according to their geotechnical properties and are classified into standard groups. These properties include the following:

- Grain sizes
- Shape, degree of roundness, degree of weathering, strength, swelling capacity etc.

- Soil structure (layering, anisotropy)
- Plasticity, compaction
- Special features like the presence of blocks or organic constituents
- Density
- Sensitivity when exposed to water

For rock the description does distinguish between intact rock and rock mass. The intact rock description includes the following elements:

- Mineral content
- Structure and texture
- Petrographic identification

The description of a rock mass includes the following elements:

- Geological composition (e.g. stratification, foliation, density)
- Intact rock
- Discontinuities (identification of discontinuity sets and their properties, e.g. type, orientation, shape, roughness, spacing, aperture etc.)
- Degree of weathering
- Karst formation
- Hydrothermal alteration
- Fault zones
    - Tectonic origin
    - Orientation
    - Width
    - Composition
    - Constituents: fault gouge, cataclasite, remnants of host rock

Fault zones are treated as individual homogeneous zones when they are of special significance to the project.

5.5 Hydrogeological Conditions

A description of hydrogeological conditions must include both local and regional characteristics. In particular, aquifers, their possible interaction, confined/unconfined aquifers and water barriers as well as the flow conditions and the connection to water at the surface are summarised.

In particular the following items are required:

- Groundwater levels
- Permeability
- Type of circulation (e.g. porous aquifers, water flow along discontinuities and/or in karst structures)
- Type of aquifer (heterogeneous, homogeneous, anisotropic, isotropic)
- Direction of water flow
- Velocity of water flow
- Hydraulic conductivity
- Transmissivity
- Water chemistry
- Carbonate reaction, carbonate equilibrium
- Pore pressure, hydraulic head, gradient
- Location of springs and wells with registration of field parameters
- Storage capacity of rocks and soils
- Recharge – discharge area, water balance

5.6 Geotechnical Investigations and Tests

Geotechnical parameters which are relevant for design and construction are determined in laboratory and field tests. The following parameters shall be measured:

- Primary stresses
- Geophysical properties (e.g. dynamic Young's modulus)
- Strength properties (e.g. UCS, cohesion, angle of friction)
- Young's modulus, deformation modulus
- Swelling potential
- Conductivity, transmissivity
- Abrasivity

When defining the testing programme, the number of tests, size of specimen, internal structure of specimens in relation to testing direction, type of failure mode and the range of values shall be indicated. Comparative values, empirical values and estimates shall be denoted as such. The sources of testing shall be given. If available, standard procedures for testing such as provided by the ISRM may be adopted.

For rock, it is necessary to clearly distinguish between the geotechnical data for the intact rock and the rock mass including discontinuities (i.e. rock boundaries, fracture surfaces, weathering) and their properties.

5.7 Additional Information

The following additional aspects are investigated depending on the specific relevance to the project:

- Gas occurrence (type of gas, potential gas source, gas reservoir with migration paths)
- Creep movements / landslides

- Neotectonic occurencies
- Temperature (ground, groundwater)
- Seismic activity
- Substances generating health hazards (quartz, asbestos etc.)
- Radioactivity
- Residual waste or contaminated ground
- Groundwater contamination

6 Geotechnical Design

6.1 General

A sound and economically viable tunnel design depends on a realistic geological model, an accurate ground characterisation and the assessment of key contributing factors such as primary stresses, groundwater and kinematics. Despite this requirement, a tunnel design based primarily on experience and basic empirical calculations. In addition, modifications to excavation and support designs made on site are often based on site specific analysis. To improve transparency of the design and construction process a *Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation* was developed and published by the Austrian Society for Geomechanics.

6.2 Geotechnical Design Procedure

The main task of the geotechnical design is the economic optimisation of the construction considering the ground conditions as well as safety, long term stability, and environmental requirements. The variability of the geological composition including the local ground structure, ground parameters, stress and groundwater conditions requires that a consistent and specific procedure be used during the design process. The key influences governing the geotechnical design are the ground conditions and Ground Behaviour. In spite of all uncertainties in the description of the ground conditions, underground engineering needs a strategy, allowing a consistent and coherent design procedure that is traceable throughout the entire project, and an optimal adjustment of the support measures to the actual ground conditions encountered on site. Geotechnical design is typically accomplished in two main phases, namely the design phase and the construction phase.

PHASE 1: DESIGN

This phase involves the determination of expected ground properties, the classification into Ground Types (GT), the assessment of the Ground Behaviours (GB), its categorisation into Behaviour Types (BT), as well as the determination of support measures derived from the Ground Behaviour under consideration of the project specific boundary conditions. On this basis the expected System Behaviour (SB) is predicted.

Excavation classes are then determined according to the rules stipulated in ONORM B 2203-1.

The results of all phases of the geotechnical design are summarised in a geotechnical report. The geotechnical report must clearly state the ground conditions, boundary conditions, and other assumptions on which the design is based. The framework plan is part of the geotechnical report. This plan has to contain clear application criteria, and shall indicate which measures shall not be modified during construction without consent of the designer, as well as the criteria for possible modifications and adjustments during construction.

PHASE 2: CONSTRUCTION

During construction, all ground parameters relevant to the geotechnical design have to be collected, recorded, and evaluated to determine the Ground Type. Considering these influencing factors, the actual System Behaviour in the excavation area is assessed according to the stipulations of the design. Excavation and support measures have to be chosen based on the criteria laid out in the framework plan and the safety management plan. The geotechnical design and the framework plan have to be continuously updated based on the findings on site. The improved quality of the geotechnical model allows an optimisation of the construction while observing all safety and environmental requirements. The relevant data and assumptions made for all decisions during design and construction have to be recorded. Relevant information in connection with the ground properties, Ground and System Behaviour has to be documented, evaluated and analysed in both phases.

The guideline [6] shall help to follow a systematic procedure. All concepts, considerations and decisions shall be recorded in a way that a review of the decision making process is possible.

The basic procedure for geotechnical design begins with the determination of the Ground Types and ends with the definition of the excavation classes. The outline of the design procedure is illustrated in the flow chart shown in Fig. 14.

Statistic and/or probabilistic methods should be used to account for the variability and uncertainty in the key parameters and influencing factors.

6.2.1 Phase 1 – Design

STEP 1

DETERMINATION OF GROUND TYPES (GT)

The first step starts with a description of the basic geologic composition and proceeds by defining geotechnically relevant parameters for each Ground Type. The values and distributions of the key parameters are determined from available information and/or estimated with engineering and geological judgement. Ground with similar properties is classified into Ground Types (GT). The number of Ground Types depends on the project specific geological conditions.

STEP 2

DETERMINATION OF GROUND BEHAVIOUR (GB)

The second step involves evaluating the potential Ground Behaviours considering each Ground Type and local influencing factors, including the relative orientation of relevant discontinuities to the excavation, ground water conditions, stress situation, etc. The Ground Behaviour is defined for each section having similar ground properties and influencing factors. The Ground Behaviour has to be evaluated for the full cross-sectional area without considering any modifications including the excavation method and sequence as well as support or other auxiliary measures. The evaluated project specific Ground Behaviours shall be assigned to basic Ground Be-

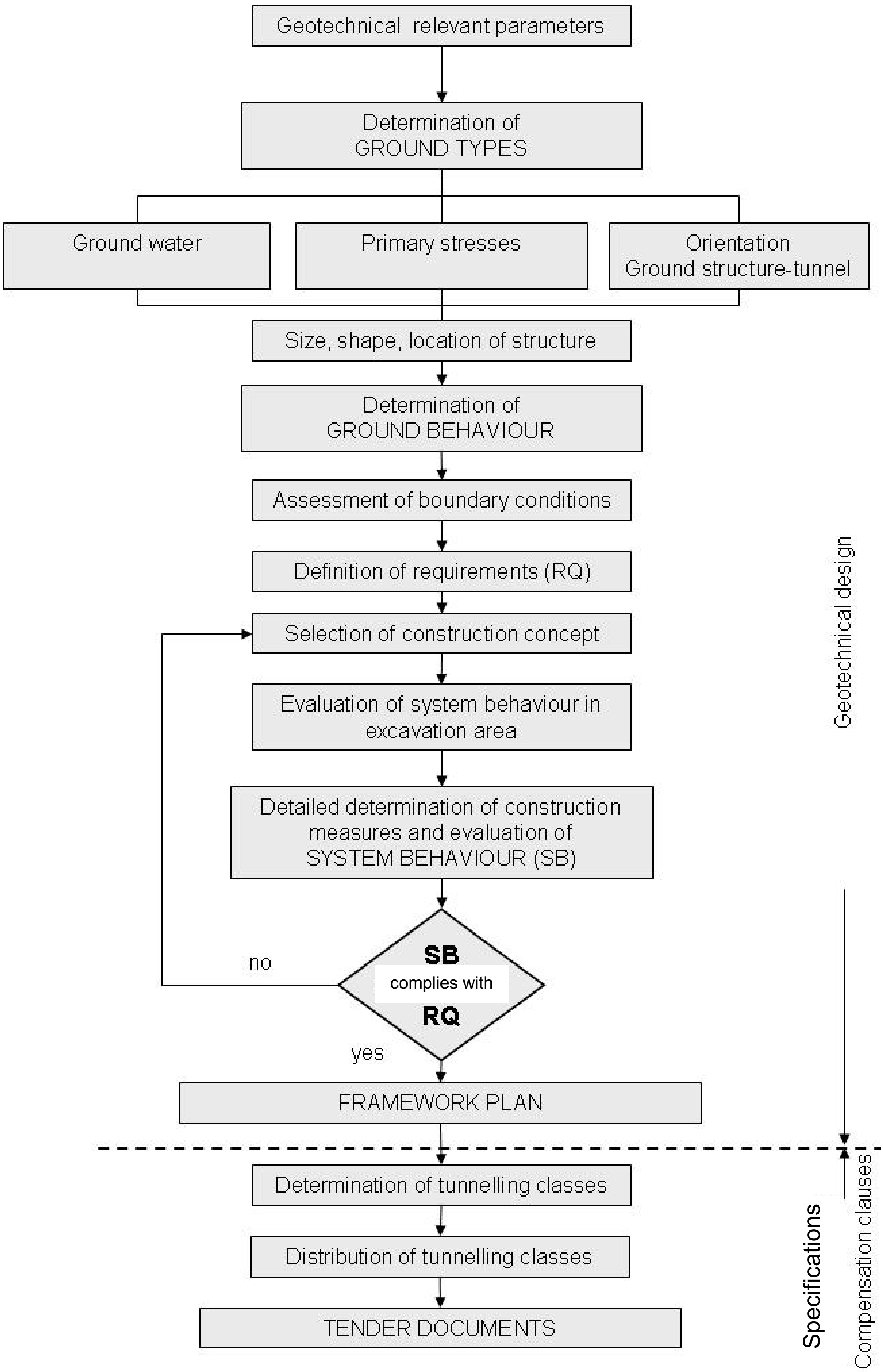


Fig. 14: Flow chart showing the geotechnical design process

haviour Types (Tab. 1). Project specific conditions may require a further subdivision of the Ground Behaviour Types, as well as a detailed description of the single expected behaviours.

Basic categories of Behaviour Types (BT)		Description of potential failure modes/mechanisms during excavation of the unsupported ground
1	Stable	Stable ground with the potential for localised gravity induced falling or sliding of small blocks
2	Potential of discontinuity controlled block fall	Discontinuity controlled, gravity induced falling and sliding of blocks in large volumes, occasional local shear failure on discontinuities
3	Shallow failure	Shallow stress induced failure in combination with discontinuity and gravity controlled failure
4	Voluminous stress induced failure	Stress induced failure involving large ground volumes and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy
6	Buckling	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Crown failure	Overbreak in the crown of large volumes with progressive shear failure
8	Ravelling ground	Flow of dry or moist, intensely fractured, poorly interlocked rocks or soil with low cohesion
9	Flowing ground	Flow of intensely fractured, poorly interlocked rocks or soil with high water content
10	Swelling ground	Time dependent volume increase of the ground caused by physical-chemical reaction of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter
11	Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variations of stresses and deformations over longer sections due to heterogeneous ground (i.e. in heterogeneous fault zones; block-in-matrix rock, tectonic melanges)

Tab. 1: Categories of Ground Behaviour Types

STEP 3
SELECTION OF CONSTRUCTION CONCEPT

A feasible construction concept is chosen based on the ground characteristics and the determined Ground Behaviour for each characteristic situation. The concept includes a description of the excavation method, sequence of excavation, support and auxiliary methods.

STEP 4
ASSESSMENT OF SYSTEM BEHAVIOUR (SB) IN THE EXCAVATION AREA

Under consideration of the construction concept, including sequence of construction, stability of the face and perimeter, and the spatial stress distribution, the System Behaviour in the excavation area is assessed (see Fig. 15)

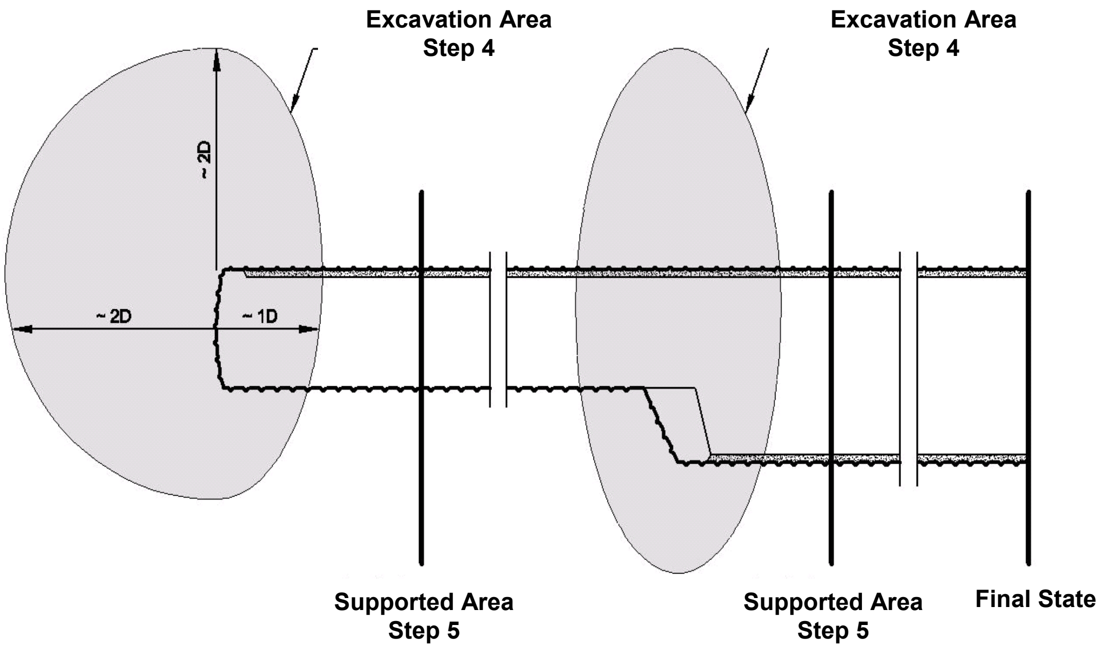


Fig. 15: Division of sections for the System Behaviour

STEP 5
DETAILED DETERMINATION OF THE EXCAVATION AND SUPPORT METHOD AND EVALUATION OF SYSTEM BEHAVIOUR IN THE SUPPORTED AREA

The excavation and support methods are fixed in quality and quantity, considering probable further excavation steps, and the System Behaviour determined. The evaluated System Behaviour is then compared to the requirements.

STEP 6

GEOTECHNICAL REPORT – FRAMEWORK PLAN

Based on steps 1 through 3 the alignment is divided into sections with similar excavation and support requirements. The framework plan indicates the excavation and support methods available for each section, and contains limits and criteria for possible variations or modifications on site.

STEP 7

DETERMINATION OF EXCAVATION CLASSES

In the final step of the design process, the excavation classes are defined based on the evaluation of the excavation and support measures. The excavation classes form a basis for compensation clauses in the tender documents. In Austria the evaluation of excavation classes is based on the regulations in ONORM B 2203-1.

6.2.2 Phase 2 – Construction

STEP 1

DETERMINATION OF THE ENCOUNTERED GROUND TYPE AND PREDICTION OF GROUND CHARACTERISTICS

To be able to determine the encountered Ground Type, the geological information documented during construction must include the relevant parameters specified in the design (see Fig. 16). Additional observations, like indications of overstressing, deformation

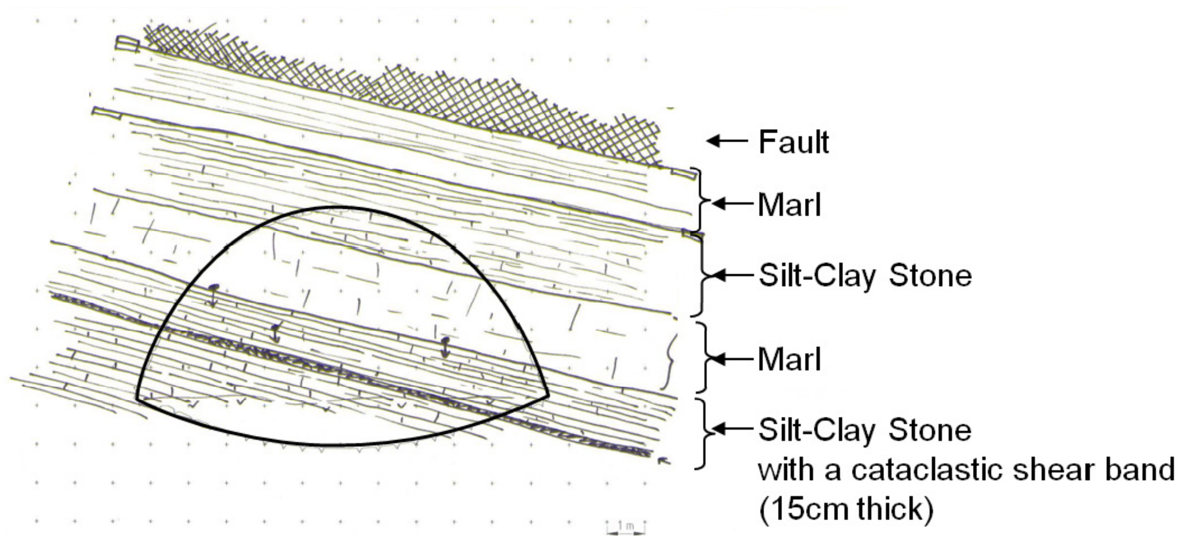


Fig. 16: Example of face mapping with extrapolation showing the surrounding ground

and failure mechanisms, as well as results from probing ahead and the evaluation of the geotechnical monitoring are used to update the ground model and predict the conditions ahead of the face.

STEP 2
ASSESSMENT OF SYSTEM BEHAVIOUR IN THE EXCAVATION AREA

Based on the predicted ground conditions the System Behaviour in the section ahead has to be assessed under consideration of the influencing factors, in comparison to the framework plan. Particular attention has to be paid on potential failure modes.

STEP 3
DETERMINATION OF EXCAVATION AND SUPPORT MEASURES AND PREDICTION OF SYSTEM BEHAVIOUR IN SUPPORTED SECTION

To determine the appropriate excavation and support measures the criteria laid out in the framework plan have to be followed. Consequently, it has to be verified whether the actual ground conditions (Ground Type, System Behaviour) comply with the prediction. The additional data obtained during construction form the basis for the determination of the applied excavation and support methods. The goal is to ensure safety and economy during construction of the tunnel. The System Behaviour has to be predicted for the next excavation section, considering the ground conditions and the chosen construction measures. Record of this process must be kept.

Note: Both excavation and support, to a major extent, have to be determined prior to the excavation. After the excavation only minor modifications, like additional bolts, are possible. This fact stresses the importance of a continuous short-term prediction.

STEP 4
VERIFICATION OF SYSTEM BEHAVIOUR

In monitoring the System Behaviour, compliance with the requirements and criteria defined in the geotechnical safety management plan can be verified. When differences between the observed and predicted behaviour occur, the parameters and criteria used during excavation for the determination of the Ground Type and the excavation and support have to be reviewed (see Fig. 17). When the dis-

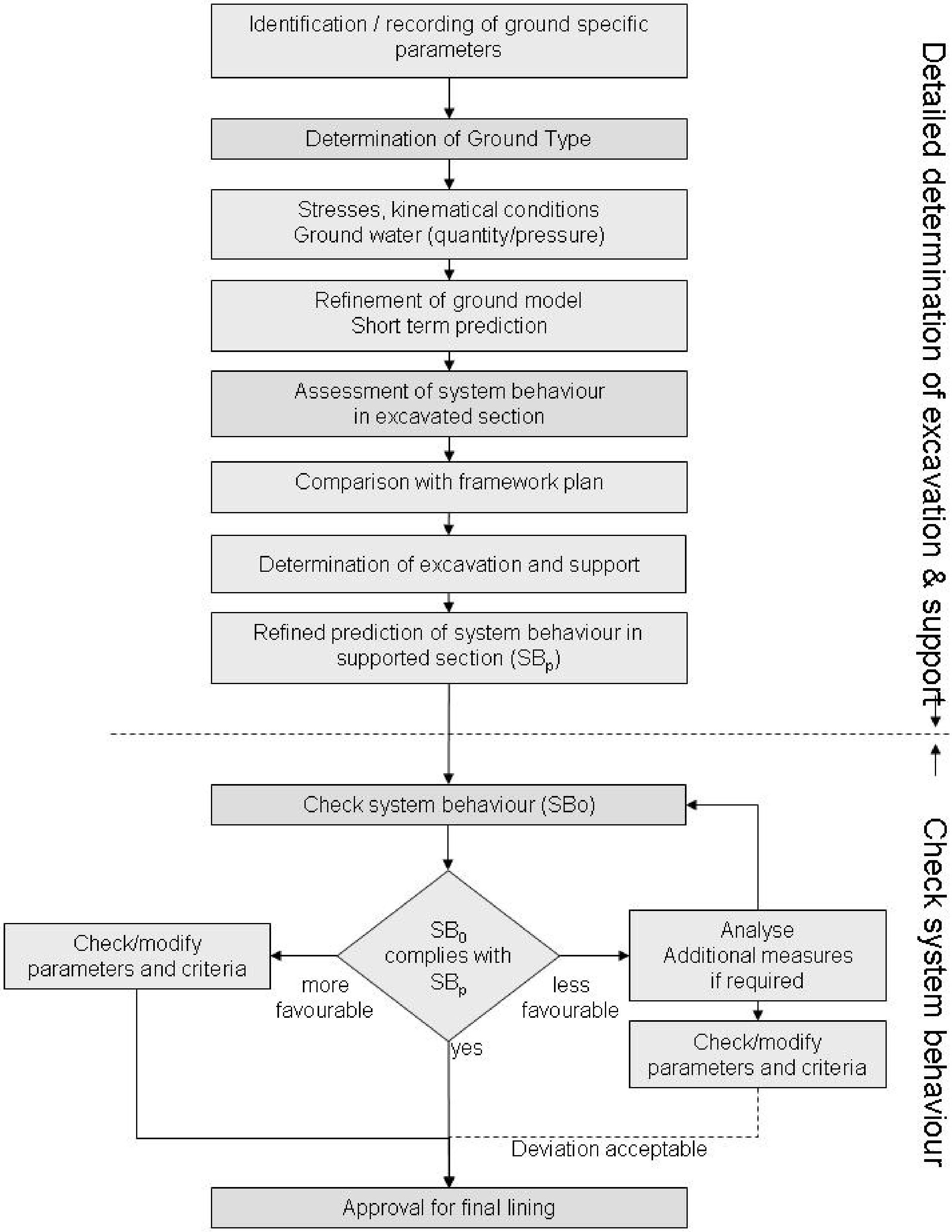


Fig. 17: Flow Chart outlining the procedure during construction (SBp=predicted System Behaviour; SBo=observed System Behaviour)

placements or support utilisation are higher than predicted, a detailed investigation into the reasons for the different System Behaviour has to be conducted, and mitigation measures (like increase of support) must be implemented if required. In case the System Behaviour is more favourable than expected, the reasons must also be analysed, and the associated parameters modified if appropriate. This allows for continuous improvement and refinement of the method for selecting the most appropriate excavation and support methods.

7 Geotechnical Safety Management

7.1 General

Stability of the underground structure is a key concern during design and construction. The measures employed to ensure stability will vary depending on the geotechnical and boundary conditions.

In the design of underground structures, the geotechnical conditions, the static system and the load-bearing capacity of the ground and support can be quite variable. As such, the design of underground structures cannot be compared to the structural design of buildings, where the loads and the material properties are well known.

Uncertainties in the geotechnical model increase the risks associated with underground construction. To minimise these risks, a safety management system shall be implemented.

The safety management system must cover the following topics:

- Design requirements for excavation and support; criteria for the assessment of stability during construction
- Monitoring plan including all technical and organizational measures to allow continuous comparison between the expected and actual conditions
- Management plan to deal with deviations from the predicted System Behaviour

7.2 Contents of a Safety Management Plan

The Safety Management Plan must include the following elements:

- Definition of the expected System Behaviour during construction
- Definition of relevant parameters to be measured

- Definition of the expected measurement results and acceptable deviations (Trigger values, alert levels)
- Determination of the evaluation methods of monitoring data
- Management of the data evaluation process (collection of data, evaluation, interpretation and communication between the parties)
- Contingency measures in case of deviations from the expected System Behaviour
- Procedure to be followed in the event that trigger values / alert levels are exceeded (definition of lines of report and command)
- All technical aspects to guideline the application of excavation and support are summarised in the geotechnical report and framework plan

8 Monitoring, Observation, Interpretation

8.1 General

Systematic and frequent monitoring, observation and interpretation are important components of the NATM. The programme for monitoring, observation and interpretation is designed to capture the range of expected System Behaviours. The main function of the programme is to determine whether the observed System Behaviour lies within expected limits and to validate the appropriateness of the excavation and support measures. Another aspect is the prediction of the System Behaviour and the update of the geological/geotechnical model.

Monitoring and observation use various sources of information, such as geological documentation and exploration, visual inspections of face and lining as well as geotechnical measurements.

Combined information from various sources creates a clear picture of the ground response, ground-support interaction, and spatial ground structure.

8.2 Geotechnical Monitoring

Typically 3D displacement measurement in the tunnel and on the surface (if required), extensometers, sliding micrometers, inclinometers, load cells for dowels, strain gauges, pressure cells and piezometers are used to observe the System Behaviour.

To enable a quick visualisation, reliable evaluation and interpretation of the monitoring results, special software is used.

8.2.1 Optical 3D Measurements

Measurements are done by using a total station (tachymeter) and targets. Precise prism-targets as well as bireflex-targets (reflectors) are used to obtain their spatial position.

Geotechnical conditions govern the intervals and layout of the monitoring sections. Typically 3 to 7 targets are installed in a monitoring cross-section (see Fig. 18). The distance between measurement cross-sections is typically 5.0 m to 25.0 m, depending on the Ground Behaviour and the sensitivity of the project environment.

The targets are mounted on special bolts with an adapter (see Fig. 19). Targets are installed close to the face and zero readings done immediately after installation. Readings are typically taken daily; the frequency is reduced with distance to the face and decreasing rates of displacements.

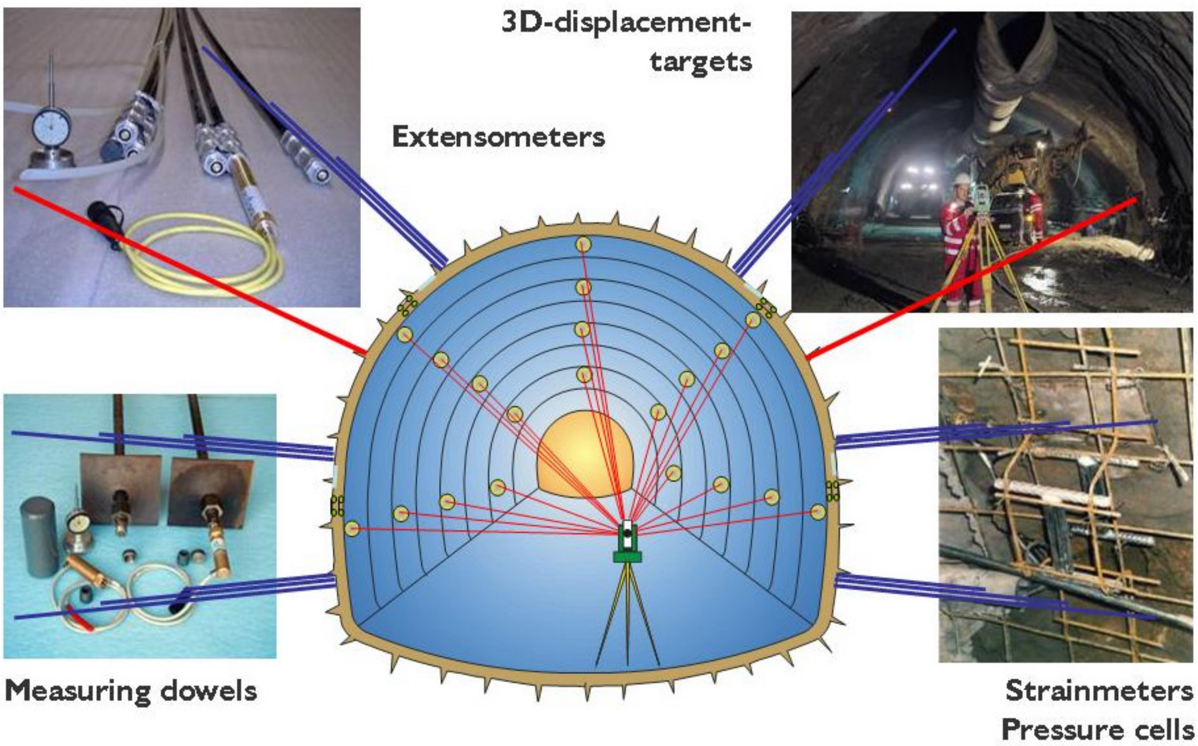


Fig. 18: Example of monitoring section (optical 3D displacement measurements, extensometers, piezometers, measuring dowels, strain gauges and pressure cells)

Fig. 19: Example of monitoring target with protection pipe to avoid damage of the bolt

8.2.2 Extensometers, sliding micrometers, inclinometers

Extensometers and sliding micrometers are used to determine the shortening or elongation (relative displacements) between two points in the ground.

Inclinometers provide information on the deflection along a line in the ground. They are usually installed from the surface to monitor displacements of the ground caused by the tunnel advance. Extensometers and in some cases longitudinal inclinometers are also installed in the tunnel.

8.2.3 Strain gauges, pressure cells and load cells

Strain gauges (strainmeters) are installed to measure the strain in the lining. The pressure between lining and ground as well as the stresses in the lining are obtained by pressure cells.

Occasionally load cells are installed to measure the force in dowels.

8.2.4 Piezometer

Piezometers are used to measure the ground water pressure.

8.3 Presentation of Monitoring Data

Over the last two decades 3D displacement monitoring has become common practice, gradually replacing other techniques because it provides a high quantity of information. At present, other monitoring devices such as extensometers, load cells, strain gauges, etc. are only installed in special circumstances. The following section focuses on the presentation of 3D displacement monitoring data.

Monitoring data are usually presented in the following standardised formats:

- Time - displacement diagram (see Fig. 20, Fig. 21)
- Distance - displacement diagram (see Fig. 22)
- Deflection curve diagram with trend line (see Fig. 23)
- Displacement vector diagram (see Fig. 24)
- Contour plot of the level of loading in the lining (see Fig. 25)
- Contour plot of surface settlements (see Fig. 26)

8.3.1 Time - displacement diagram

Time - displacement diagrams are used to present vertical, horizontal and longitudinal displacement components versus time. Typically, the results of the displacement measurements of all targets in one monitoring cross-section are plotted in one diagram. Construction phases are also presented on the same plot, allowing correlation between construction activities and displacements. The displacement history is used to assess the stabilisation process. Fig. 20 shows an example of a characteristic time - displacement plot.

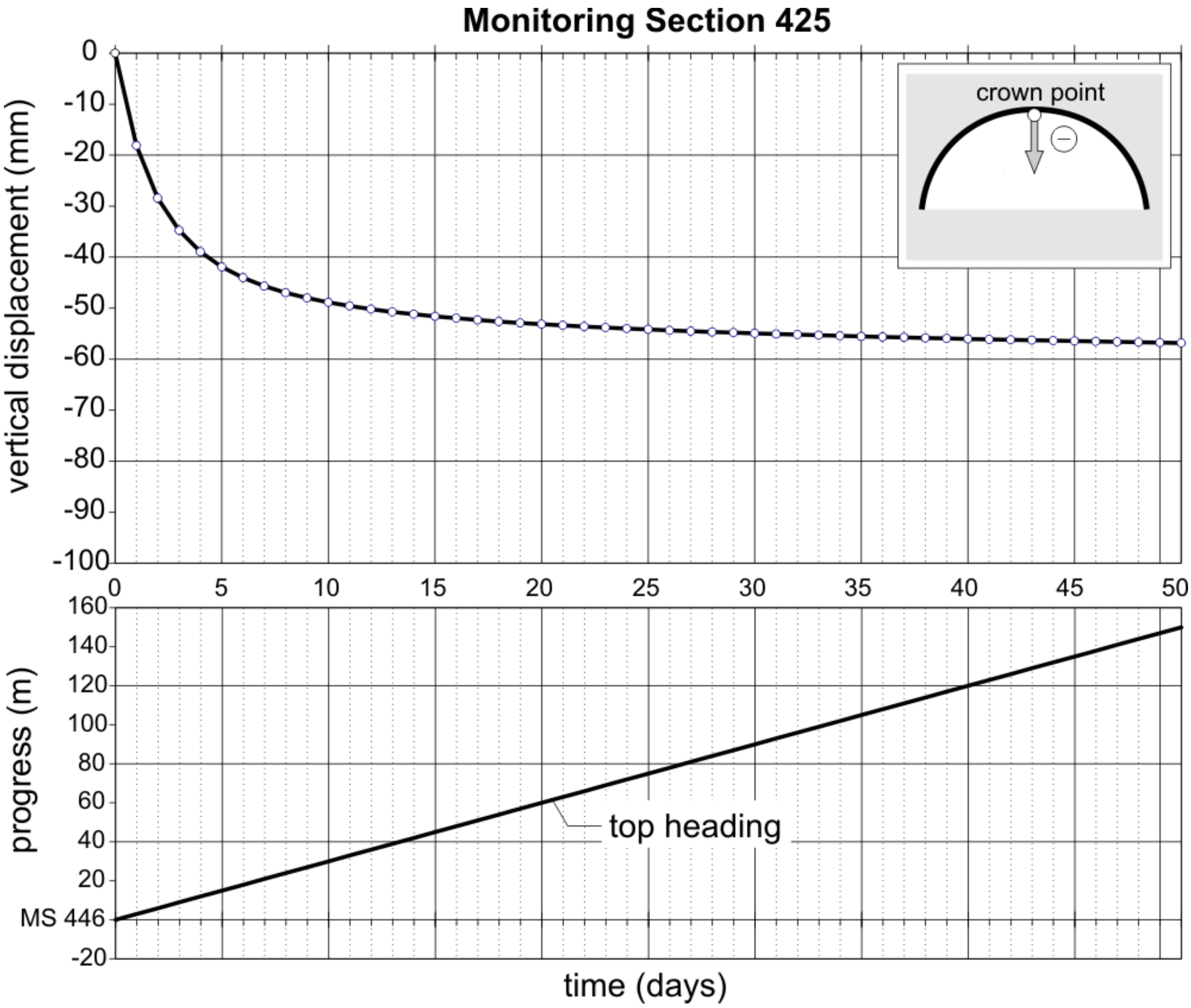


Fig. 20: Typical time - displacement plot for constant excavation rate

Fig. 21 shows an example of the time displacement trend which occurs when the top heading excavation is stopped for several days. After the stoppage, excavation continues with constant advance rate.

8.3.2 Distance - Displacement diagram

Fig. 22 shows the same situation as illustrated in Fig. 21. In this example the vertical displacements are plotted versus the distance to the tunnel face. Time dependent displacements during the stop of the excavation are shown in the vertical offset 6.0 m behind the face.

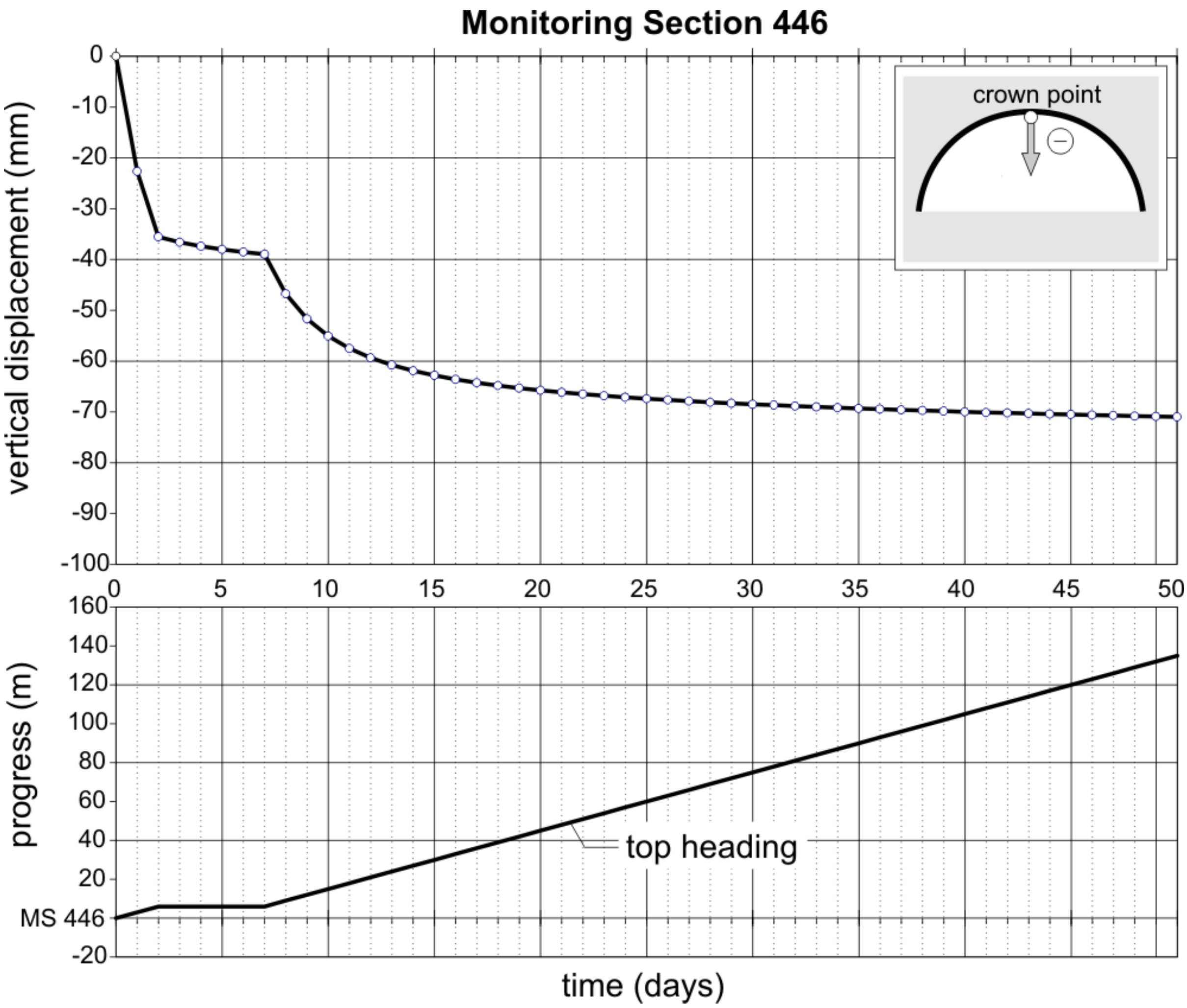


Fig. 21: Typical time - displacement plot for discontinuous excavation

8.3.3 Deflection curve diagram with trend line

Deflection curves are used to observe the stress redistribution process and changing System Behaviour. Therefore it is possible to recognise changing ground conditions in due time (e.g. faults) and to mitigate risk.

A deflection curve represents the status of displacements of one position in cross-section along the tunnel (e.g. crown points) at a particular time. Deflection curves of consecutive readings are plotted on one diagram for each component of the displacement vector (x, y, z-coordinate).

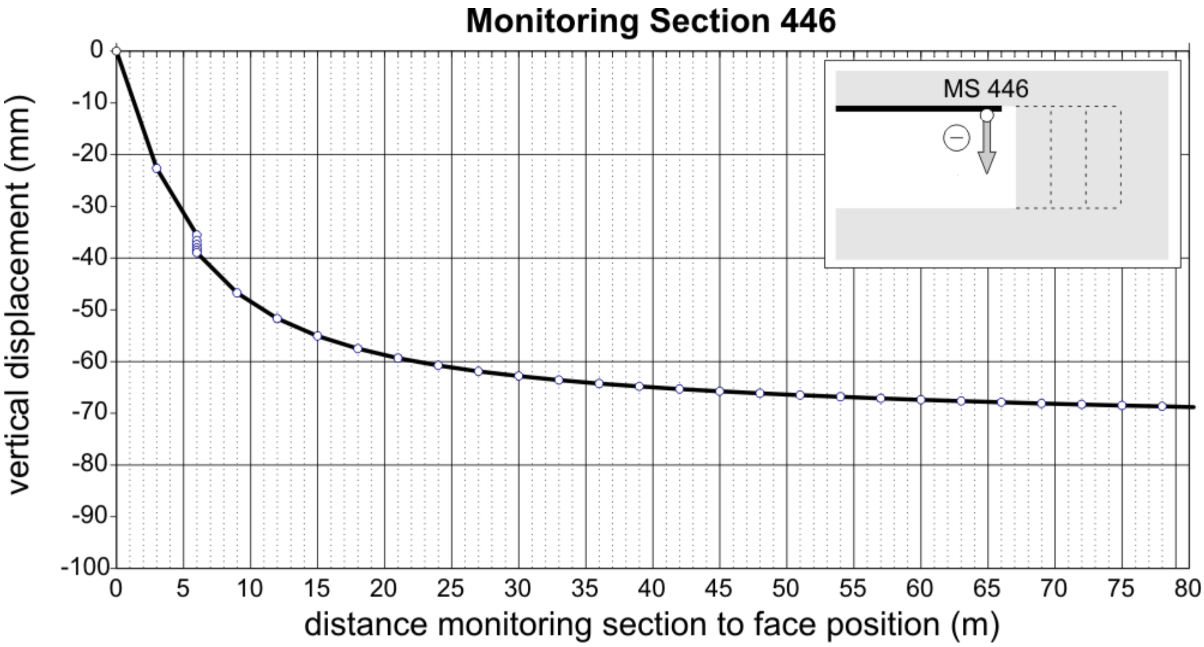


Fig. 22: Distance - displacement plot for discontinuous excavation (same situation as in Fig. 21)

Fig. 23 shows the influence of each excavation step on previously excavated and supported tunnel sections.

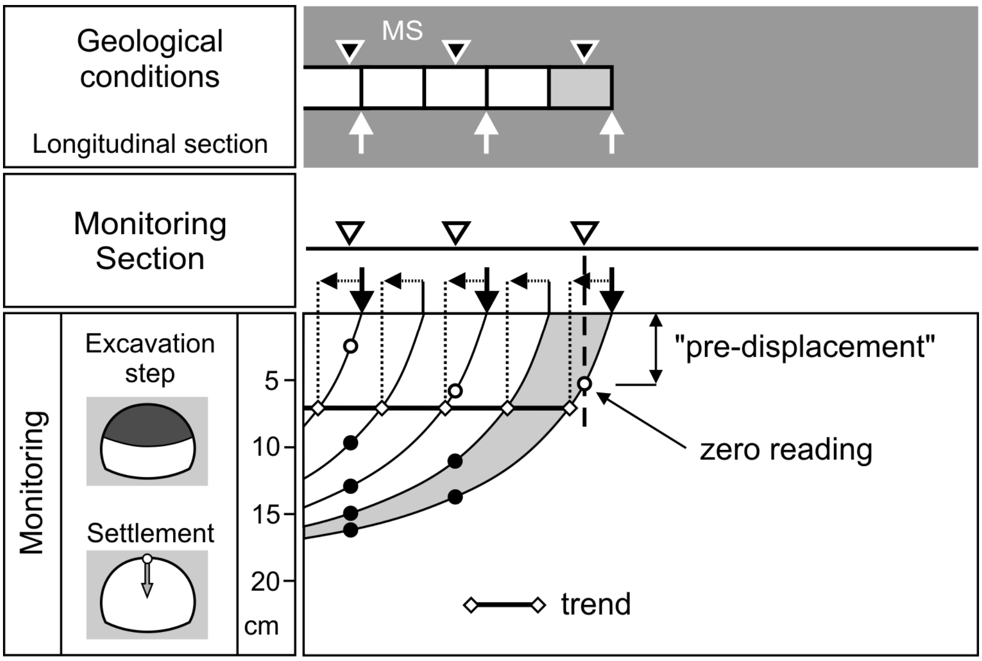


Fig. 23: Deflection curve diagram for crown position showing the estimation of "pre-displacements" and construction of trend line

The “pre-displacement” is the displacement occurring between the face and the zero reading of the first target. This cannot be measured. Therefore it has to be determined by extrapolation and added to compare the measurements.

Deflection curves are usually combined with a trend line. Trend lines are created by connecting values from the deflection curves at a constant distance behind the face (see Fig. 23).

"Onion-shell-type" deflection curves and a horizontal trend line development are obtained when tunnelling in homogeneous ground conditions and uniform boundary conditions.

8.3.4 Displacement Vector Orientation (L/S)

The displacement vector orientation L/S is the ratio between longitudinal displacements (L) and settlements (S) expressed in terms of an angular deviation of the displacement vector from vertical. The L/S trend evaluation is the most appropriate method to identify changes in the ground conditions. A rotation of this displacement vector against the direction of excavation indicates relatively soft ground ahead of the face. In contrast, a rotation in direction of the excavation indicates relatively stiff conditions ahead. Fig. 24 shows the basic development of the vector orientation trend L/S when tunnelling through a zone of relatively soft ground.

The displacement vector trend L/S (in this case for the crown point) deviates from a “normal” orientation against the direction of excavation when approaching the zone of soft ground. The “normal” vector orientation strongly depends on the ground structure and stress conditions and has to be determined separately for each condition.

After entering the soft zone, the vector tends to return to the “normal” orientation. When approaching the stiff ground, an inverse tendency can be observed. The displacement vector deviates in direction of excavation and reaches a maximum at the transition. After entering the stiff zone, the vector returns to normal.

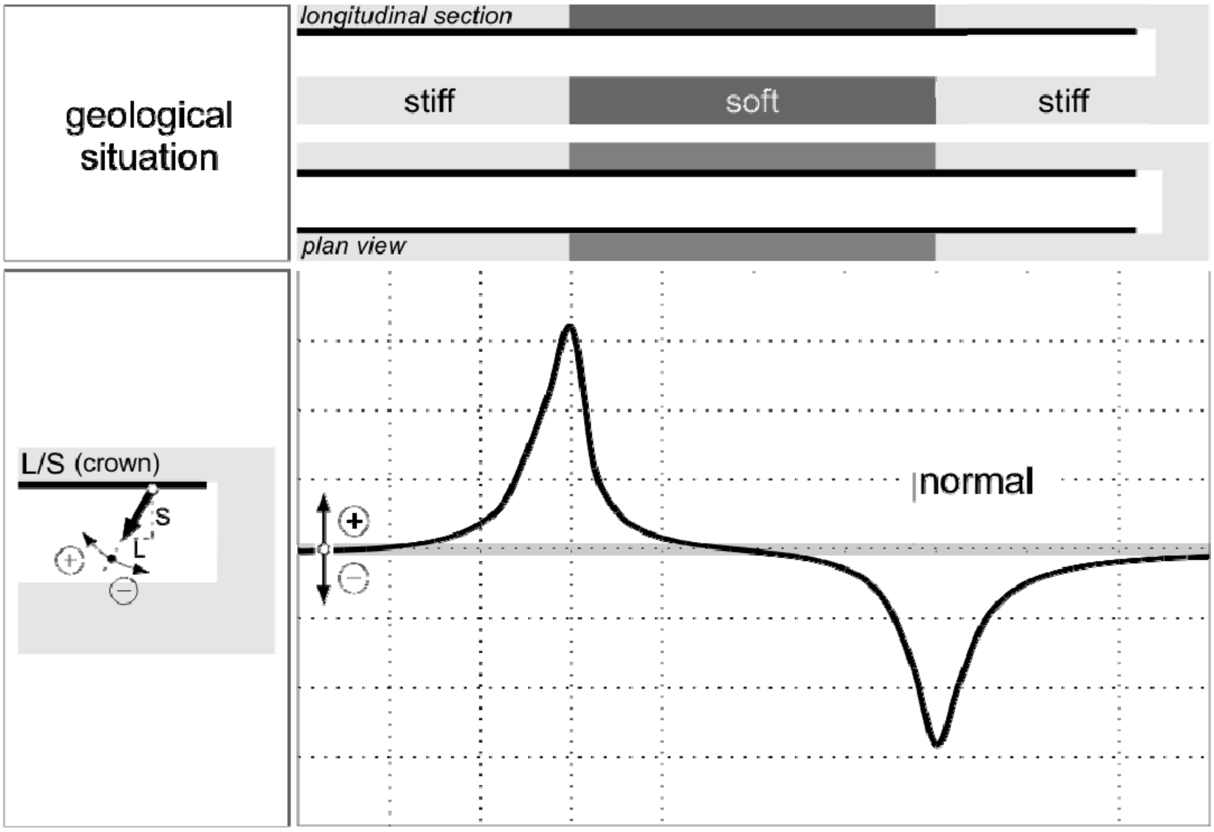


Fig. 24: Example for displacement vector orientation trend L/S when tunnelling through stiff - relatively soft - stiff ground

8.3.5 Combination of different evaluation methods

In addition to the evaluation methods previously described, further methods can be used in order to gain the full benefit of displacement monitoring data. These methods include the following:

- Trend lines of displacement ratios, e.g. ratio between the settlement of the crown point and a point at the sidewall
- Trend lines of displacement differences, e.g. settlement differences for left and right monitoring points, settlement differences between the crown and the left or right sidewall monitoring points
- Orientation of absolute displacement vector by means of stereographic projection

8.3.6 Displacement vector diagram

The displacement vector diagram assists in interpreting the influence of the ground structure (e.g. the orientation of discontinuities) on the behaviour.

Vector plots evaluated for a monitoring cross-section are used to show the orientation of displacements as well as the development of displacements with time (see Fig. 25).

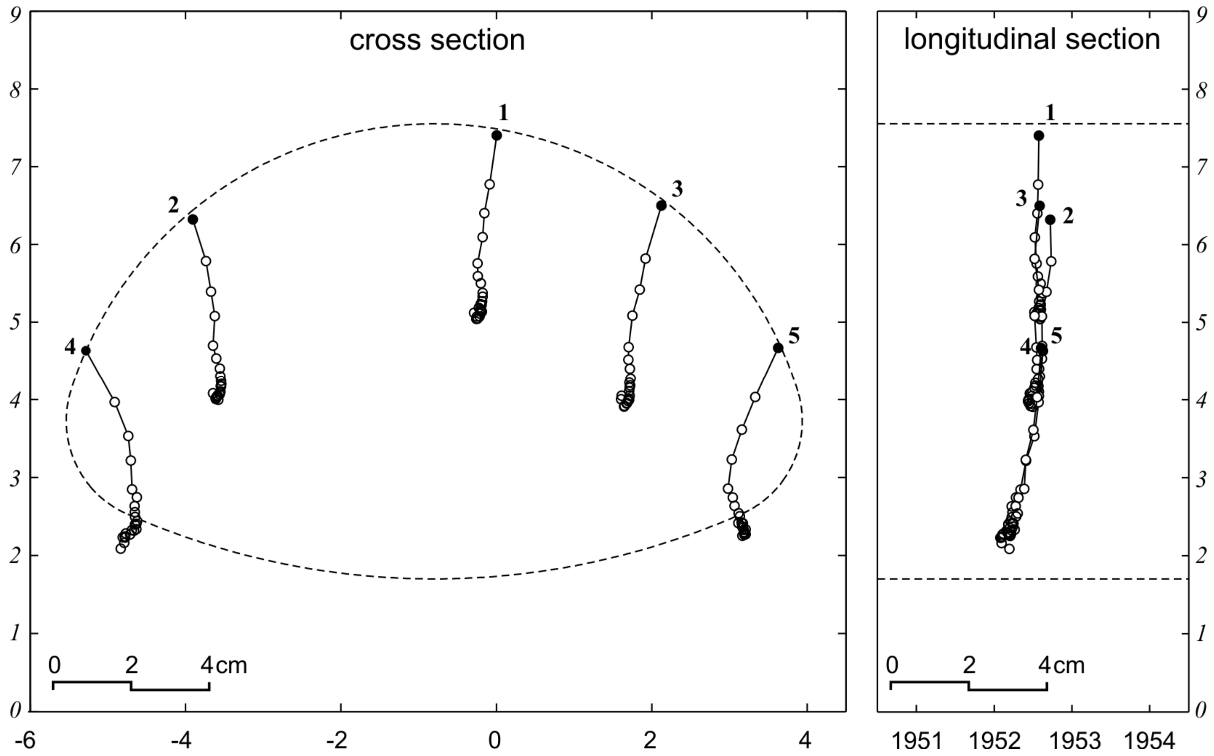


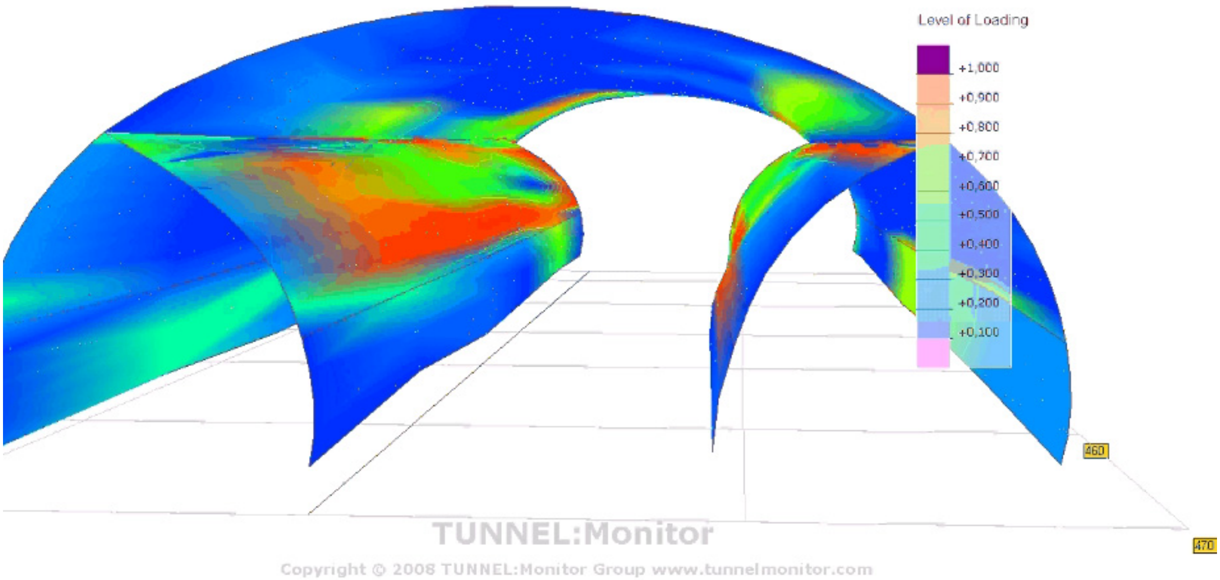
Fig. 25: Example for displacement vector diagram in homogeneous ground

8.3.7 Level of loading in the shotcrete lining

The displacements measured can also be used to evaluate the strains in the lining. The time dependent development of the shotcrete properties is considered in the calculation of the lining stresses.

The level of loading is defined as the ratio between the stress and the ultimate strength of shotcrete. It is usually shown as contour plot.

The example shown in Fig. 26 is from a tunnel with shallow overburden in an urban environment, excavated with side galleries followed by core excavation. The contour plot provides a quick overview of the utilization of the shotcrete lining.



(Note: Red colour indicates very high load level; Blue colour indicates a low load level)

Fig. 26: Example of the distribution of the level of loading in the shotcrete lining at a certain time; Tunnel driven with side wall galleries and core excavation

8.3.8 Surface Settlements

Readings of surface settlements can be summarised in a contour plot. The example in Fig. 27 shows a plan view of the evaluated surface settlements.

The evaluation gives a good indication of the influence of the construction progress on the distribution and magnitude of the displacements. Furthermore, the maximum of differential settlements for buildings, tracks, pipe lines can directly display the areas where limits are exceeded.

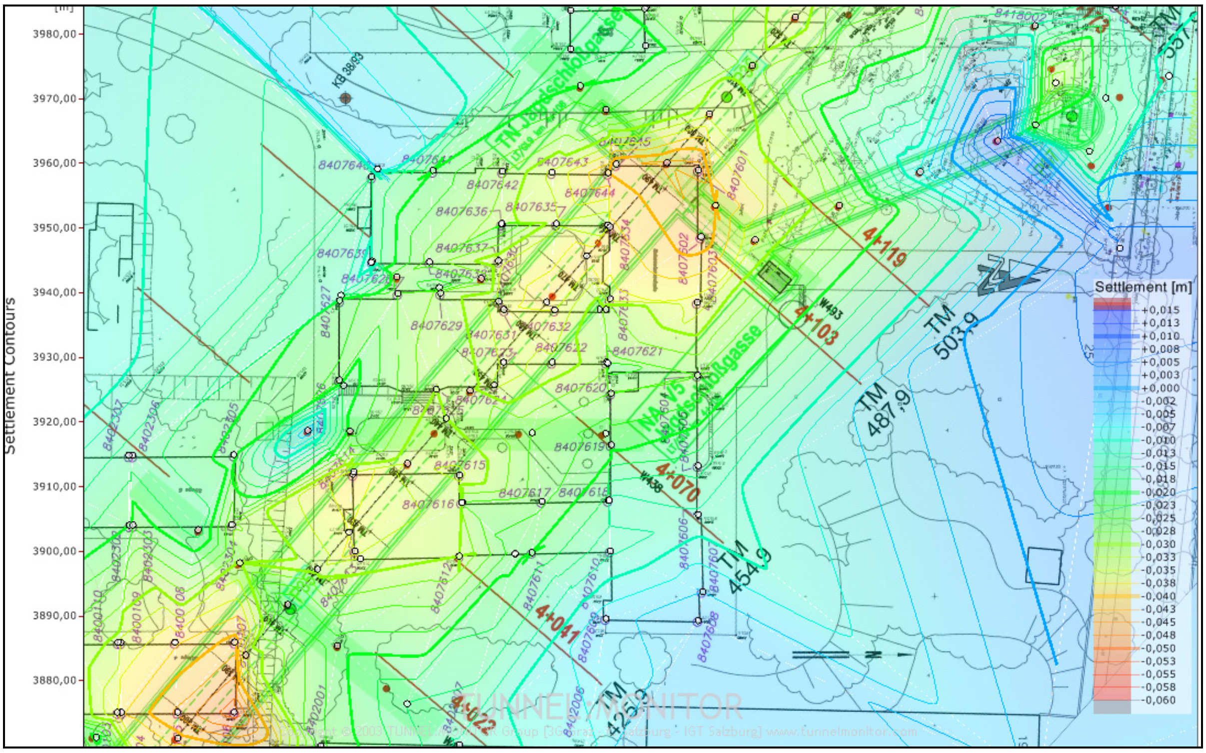


Fig. 27: Example of a contour plot of surface settlements; development and distribution of surface settlements caused by tunnelling under a residential area

8.4 Interpretation

8.4.1 Development of displacements with time

For constant advance rate and uniform boundary conditions, continuously decreasing displacement rates over time indicate a stabilisation process. Subsequent excavation steps, like bench or invert excavation lead to a temporary increase in displacement rates. Increases and decreases in the advance rate result in a change in the displacement rates, making the interpretation difficult in cases where advance rates are variable.

Fig. 28 shows the development of the measured crown settlements for top heading excavation with a temporary top heading invert. The predicted displacements with a temporary invert (green line) and without (blue dotted line) are displayed to provide the basis for comparison with the actual data. Deviation between the measured displacements and the predicted displacements occurs in the graph on January 21st, indicating a failure of the temporary invert.

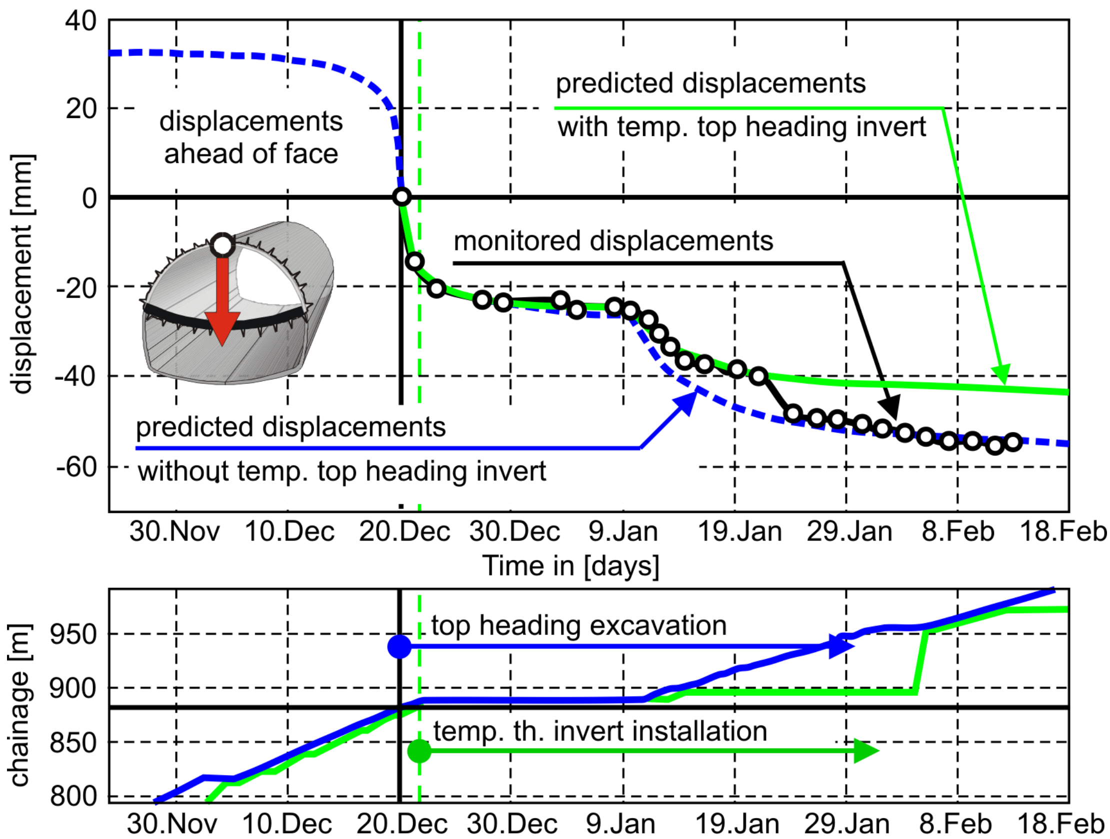


Fig. 28: Example of time - displacement plot showing a deviation between measured and predicted displacements

8.4.2 Displacement vector plot

Plotting the displacement vectors allows the detection of deviations from the normal behaviour caused by features outside the excavated cross-section. Fig. 29 shows an example of the influence of a steeply dipping fault, striking sub-parallel to the tunnel axis. The stress concentration between sidewall and fault causes increased displacements.

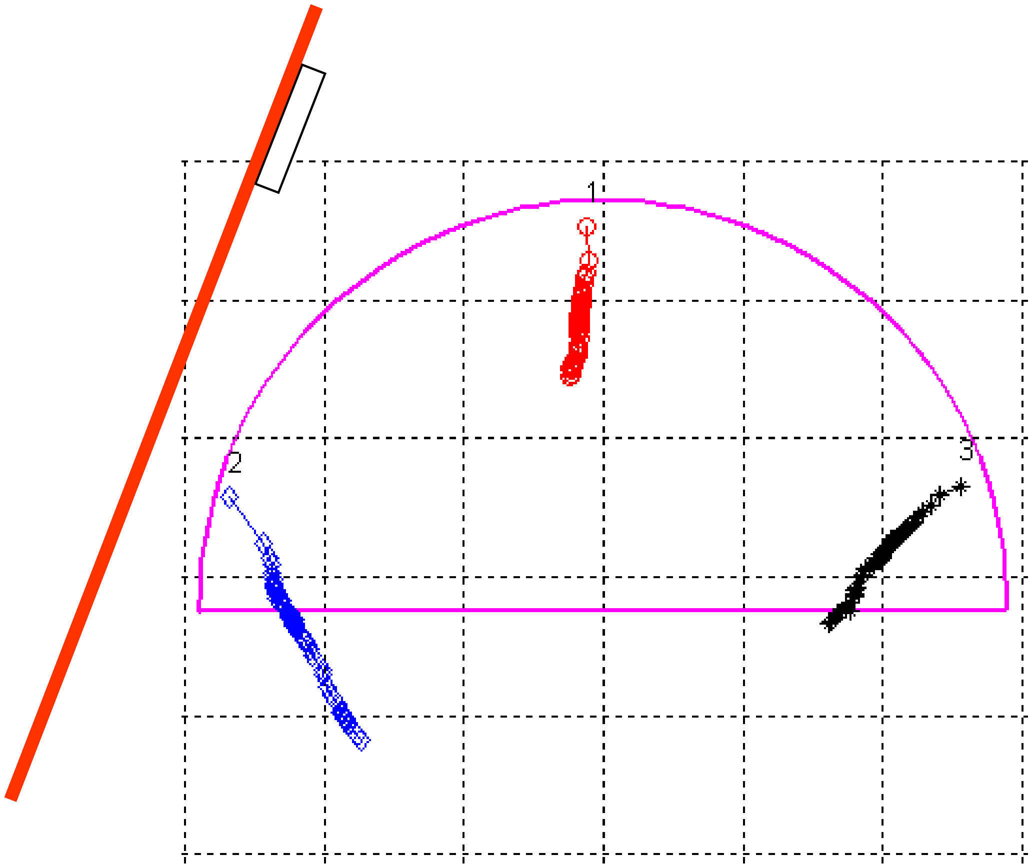


Fig. 29: Displacement vector plot – influence of a fault outside the excavated cross-section

8.4.3 Deflection curve diagram and displacement vector orientation trends

In Fig. 30, the uppermost diagram shows the development of crown settlements of a tunnel section with a length of approximately 120.0 m. The trend line of the ratio of longitudinal displacements and settlements (L/S – displacement vector orientation, evaluated as an angle) is illustrated at the bottom. The settlement curves show a nearly constant development with a small variation. In contrast the development of the displacement vector orientation clearly shows a significant deviation from a certain "normal" range against the direction of excavation. This tendency indicates changing ground conditions, with weaker ground expected ahead of the face. In the case shown here, the range of normal displacement vector orientations is between 4° to 8° against the excavation direction. The "normal" vector orientation depends on the ground structure and the stress conditions and has to be determined separately for each condition.

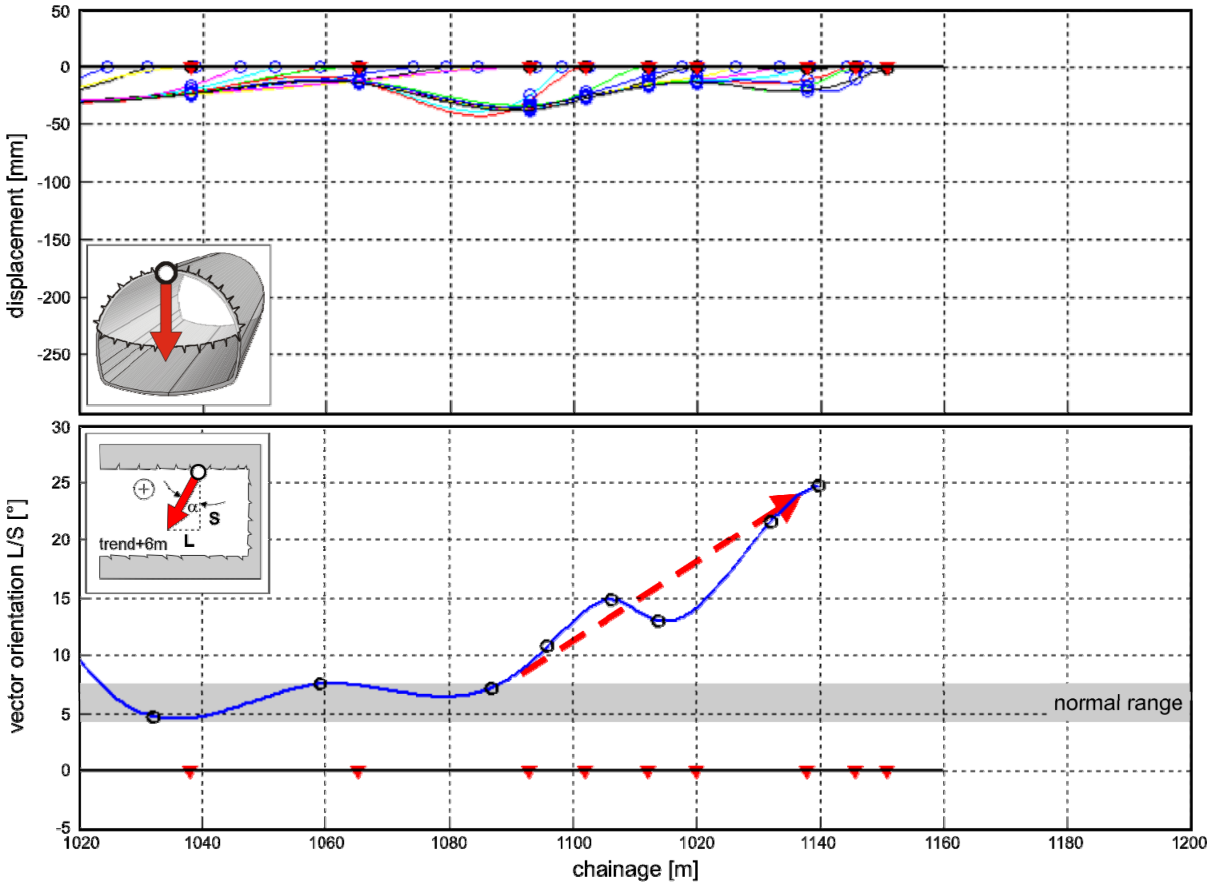


Fig. 30: Deflection curves of vertical displacements of the crown (top) and trend of ratio between longitudinal and vertical displacements (below). Deviation of displacement vector orientation indicating change of ground quality ahead of face

Fig. 31 shows the observed situation with increased displacements in the fault zone.

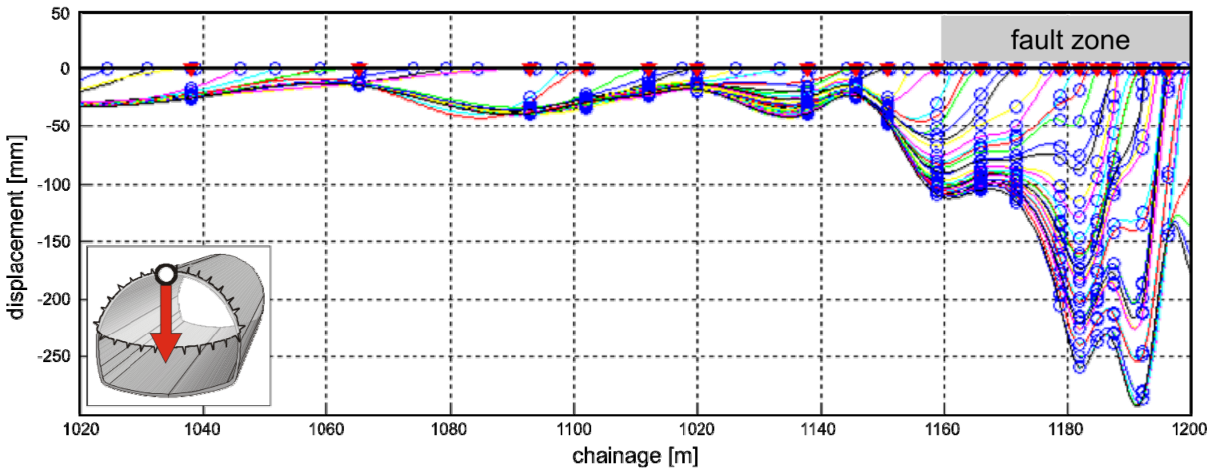


Fig. 31: Deflection curves showing the increased displacements in the fault zone, encountered at around chainage 1160

8.4.4 Value of Evaluation Methods

Different types of plots and evaluation methods were described in this chapter. Fig. 32 summarises the applicability of the various evaluation methods with regard to specific questions. The displacement history plot, for example, is a suitable method for the evaluation and assessment of the stabilisation process, while deflection lines and trend lines are of limited value for this purpose. In contrast, the displacement vector orientations in the longitudinal direction as well as orientation are appropriate methods for predicting ground conditions ahead of the face. Utilising this matrix guides the user in choosing the appropriate evaluation method.

Value of evaluation methods

■ good value
□ limited value
– no value

Value of evaluation methods	Evaluation of stabilization process	Prediction final displacements	Stress redistribution longitudinal	Detection of weak zones outside profile, kinematics	Prediction ahead	Estimate of stress intensity in lining
Displacement history	■	■	–	□	–	■
Deflection lines, trends	□	–	■	□	□	–
Trends of relative displacement values	–	–	–	■	–	–
Vectors in cross section	–	–	–	■	–	■
Vectors in longitudinal section	–	–	–	□	■	–
Spatial vector orientation	–	–	■	■	■	–

(W. Schubert, '02)

Fig. 32: Value of evaluation methods with regard to specific questions

9 Construction Contract

9.1 Contents and characteristics of the tunnelling contract

Tunnelling contracts in Austria are usually based on a detailed scope of work which is broken down into unit price items. The aim is to have a flexible contractual system which provides payment regulations for changing ground conditions.

Considering the tendering procedure emphasis is put on the following aspects:

- Fair competition amongst bidders
- Comparability of bids

The principles of the Austrian Tunnelling Contract are standardized in ONORM B 2203-1 “Underground works – Works contract, Part 1: Cyclic driving (conventional tunnelling)”.

The Austrian contract functions according to tunnelling classes.

The classification system takes into account the excavation round length, the subdivision of the face into partial cross-sections, the support measures installed, and the sequence of the excavation. These key-factors determine advance rates and cost and are summarised in the tunnelling (excavation and support) class matrix. The payment for excavation is based on the tunnelling class actually executed. The payment for support is based on the support measures actually installed.

In addition to these tunnelling classes, items for overbreak (above a defined limit) as a result of geological conditions, over-excavation for the allowance of deformation, and items for imponderabilities during excavation such as high water ingress, gas occurence and mixed-face conditions (soil and rock) are defined.

The construction time is the basis for the payment of all time dependent costs. Generally the time required for excavation and support, as well as the additional time required due to imponderabilities, is variable. To establish a baseline for payment and for calculation of contractual construction time, the contractor must guarantee advance rates for each tunnelling class and reduced advance rates resulting from imponderabilities.

Therefore the milestone for completion of the excavation is not a fixed date but will be adjusted according to the actual tunnelling classes and imponderabilities.

For all other activities such as site installation, final lining and finishing work fixed time periods are foreseen in the contract.

In the Austrian standard for underground works, the allocation of risk is well balanced. The risks for ground conditions and design are carried by the owner while risks associated with means and methods of construction are with the contractor's responsibility.

9.2 Tunnelling (excavation and support) class matrix

The tunnelling class is defined by the round length and by the *support number* (see ONORM B 2203-1).

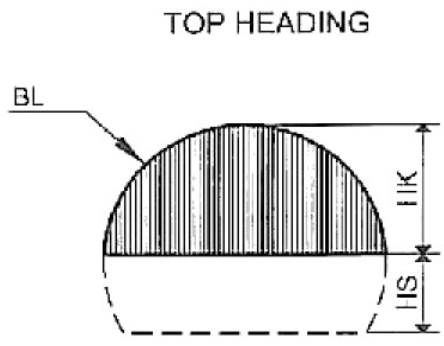
The *support number* ($f_{SUPPORT}$) is defined as the sum of the products of the quantities of the support measures ($q_{SUPPORT}$) and their *rating factors* (f_{RATING}) divided by the *rating area* (a_{RATING}).

$$f_{SUPPORT} = \frac{\Sigma(q_{SUPPORT} \cdot f_{RATING})}{a_{RATING}}$$

The support quantities are related to a tunnel length of one meter.

The *rating factor* (f_{RATING}) reflects the relative time required for the installation of the considered type of support and is given in Table 3 of ONORM B 2203-1.

The *rating area* (a_{RATING}) is defined according to the subdivision of the cross-section into top heading and bench.



Key

HK height of top heading

HS height of bench

BL boundary line = outer final-lining surface as designed

HK, HS and BL to be stipulated by contract.

Fig. 33: Schematic drawing showing rating areas

FIRST ORGANISING NUMBER	ROUND LENGTH UP TO		SECOND ORGANISING NUMBER									
	TOP HEADING or TOP + BENCH HEADING	BENCH	SUPPORT NUMBER									
			1	2	3	4	5	6	7	8	9	
1	No limit	Project-specific specification										
2	4.0 m											
3	3.0 m											
4	2.2 m				4/2.4	4/3.6						
5	1.7 m						5/4.5		5/6.1			
6	1.3 m							6/5.5		6/7.5		
7	1.0 m											
8	0.8 m											
9	0.6 m											

EXAMPLE

Fig. 34: Tunnelling class matrix

The numbers for round length (1st organizing number) and *support number* (2nd organizing number) define the tunnelling class. These numbers are mapped into a matrix.

Both entries of each combination in the matrix would lead to an infinite number of classes. Therefore ONORM B 2203-1, Table 4 defines a certain range of applicability for the round length and the support number. Within a specific tunnelling class the remuneration does not change. This ensures that minor deviations in round lengths or quantities of support measures do not necessarily result in a change of excavation and support class (= tunnelling class).

10 Risk Management

10.1 Objectives

In each design stage, risk assessments for the project shall be carried out in order to ensure compliance with the project objectives and to ensure an accurate cost estimate. In a risk assessment, potential hazards and their consequences are identified. The time and cost impact of the identified risks are evaluated and mitigation measures are established.

Particular attention is focused on the geotechnical risk and as such, a detailed geotechnical safety management plan is developed (see Chapter 7).

The results of the risk assessments must be examined in order to determine whether each particular risk can be avoided, transferred or accepted. The risk management process is an important means to prevent potential deviations from the project objectives. The potential for deviation is dependent on the particular project stage and decreases as the project progresses. The result of the risk assessment must be appreciated when producing the cost estimate at any particular design stage. As such, appropriate provisional funds shall be allocated to the indentified risks.

10.2 Risk Identification

All identified risks have to be evaluated in terms of a specific risk scenario. The risk scenario must identify a potential incident, the root cause of the incident, and any resulting consequences. In order to properly evaluate the risk and to identify the associated cost and/or time implications, the standard project parameters, as well as the particular circumstances resulting from the risk incident must be known. The following items must be considered to complete the risk assessment:

- Definition of the hazard to be considered

- Parameters responsible for the hazard to occur
- Definition of the activity affected by the hazard
- List of measures which are to be implemented to control the risk relevant hazard

Hazards may be attributed to following categories:

GROUND

Unforeseen subsurface conditions (e.g. unforeseen faults, weaknesses zones, subsurface obstacles);

- Unexpected System Behaviour, (e.g. overstressing, damage)
- Ground failure (e.g. collapse of excavation face, excessive ground surface settlement)
- Groundwater (e.g. unforeseen water inflow, unforeseen water chemistry, unforeseen water level, wells)

CONSTRUCTION

- Failure of construction equipment
- Interruption of access to site
- Failure of power supply
- Problems with material quality

PROJECT IMPLEMENTATION

- Change of guidelines
- Environmental regulations
- Safety standards

10.3 Risk Assessment

In a risk assessment, each hazard is evaluated as the product of probability of occurrence (likelihood) and consequence (severity) and the risk is rated for each hazard.

PROBABILITY OF OCCURRENCE

Often, it is not possible to calculate the probability of occurrence by statistical means because the data available from previous tunnelling experience is insufficient. Hence the probability is determined by multi-disciplinary, professionally experienced experts.

CONSEQUENCE

Cost and time implications of risk-relevant hazards are derived from cost estimates and the performance assumptions (e.g. advance rates).

Three different methods of risk assessment are used for tunnelling projects. The type of method to be used depends on the design stage and the complexity of the project:

QUALITATIVE RISK ASSESSMENT

In a qualitative risk assessment the direct consequences of each hazard are described. Using this method the likelihood and the consequence of hazards are not quantified. The consequences of hazards are based on previous relevant experience.

SEMI-QUANTITATIVE RISK ASSESSMENT

Risks are assigned to standardised probability classes and severity classes to determine their potential impact on a project.

QUANTITATIVE RISK ASSESSMENT

The hazards are evaluated with respect to cost and time implications. The probabilities and the consequences are determined using the following two methods:

- Deterministic method
- Probabilistic method

The effects of risks are combined and the associated costs are determined by mathematical models.

11 Organisation of Project Execution

The organisation of the project execution according to the Austrian contract model is outlined in the following figure:

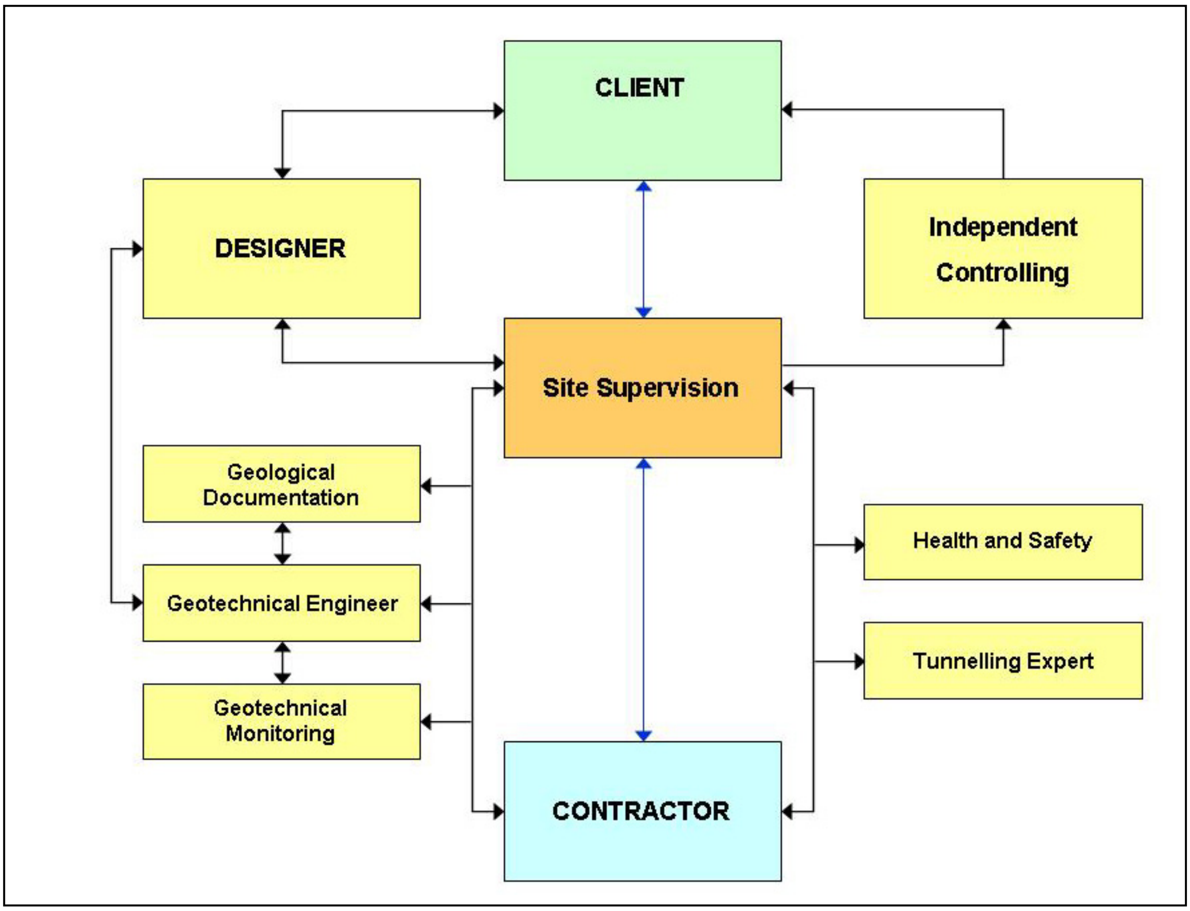


Fig. 35: Organisation chart

11.1 Structure and Responsibilities

11.1.1 Client

The client is finally responsible for the measures implemented to solve technical problems, any variations in cost or schedule and acceptance of remedial measures to correct defects.

The project management is carried out by the client's experienced personnel or by an appointed consultant.

11.1.2 Design Engineer

During construction the design engineer prepares the detailed design in accordance with the contractor's means and methods. Therefore he is to be involved in site decisions which require changes to the design. Upon completion of the work, the design engineer and the site supervision jointly commission the works.

11.1.3 Site Supervision

The client usually appoints a consulting engineer to act as the site supervising engineer, responsible for the overall supervision of the construction work. The site supervision safeguards the interests of the client by ensuring that the work is completed in accordance with the contract conditions.

The resident engineer (site supervising engineer) reviews the encountered geological conditions with the contractor's representative (site manager) and determines the details of the excavation method – e.g. round length, partial opening of the face, amount and type of support measures etc. in mutual agreement. This requires daily meetings with the contractor at the face of the excavation.

Regarding quality and costs of the construction works the supervision engineer has to check the proper use and handling of construction material, establish measurement schedules and review the contractor's invoices. Finally he supervises the remediation of any defects.

11.1.4 Site management of Contractor

The contractor carries out the work according to the contract conditions. Means and methods are the contractor's responsibility. He is also responsible for the safety of works and the health of workers.

The contractor's site manager participates in daily meetings with the client's site supervising engineer, where details of the excavation method and adjustments of the support measures are mutually agreed.

Apart from organisation and execution of the work, the site manager of the contractor must ensure quality requirements are met and completed on schedule.

11.1.5 Geologist

The client appoints geologists which independently record geological conditions at the face and eventually advise on additional probing ahead. It is their task to produce short term predictions for the next round length.

11.1.6 Geotechnical Monitoring

It is general practice in Austria to appoint a monitoring team independently from other surveying works. This team carries out all geotechnical measurements day by day and is responsible for evaluation and distribution of monitoring results.

11.1.7 Geotechnical Engineer

The client usually appoints a geotechnical engineer who supports the site manager and the site supervision in the interpretation of the geotechnical monitoring results and in the determination of the support measures taking into account the geological documentation and short term predictions.

The preferred solution is to appoint the design engineer to take over this position.

11.1.8 Tunnelling expert

Rather than retaining an independent dispute resolution board, the Austrian standard stipulates that for technical disputes an independent expert is selected by the client in agreement with the contractor during the tender process.

The commitment of a dispute review board is a recommended alternative.

11.1.9 Health and Safety Ordinance

The implementation of health and safety measures is controlled by an independent ordinance.

11.1.10 Specialists and Experts

In addition to the design engineer, in complex projects additional specialists and consultants are called in, such as environmentalists etc.

11.1.11 Decisions on Site

The mutual decisions of the site supervisor and the contractor's representative are made in daily meetings regarding face observations and geotechnical interpretation of the System Behaviour and documented in "Required Support Sheets", which are signed by the client's and contractor's representative.

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Recommendations on the development process for Mined Tunnels

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Working Group 19
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The International Tunnelling and Underground Space Association/Association Internationale des Tunnels et de l'Espace Souterrain (ITA/AITES) publishes this report to, in accordance with its statutes, facilitate the exchange of information, in order: to encourage planning of the subsurface for the benefit of the public, environment and sustainable development to promote advances in planning, design, construction, maintenance and safety of tunnels and underground space, by bringing together information thereon and by studying questions related thereto. This report has been prepared by professionals with expertise within the actual subjects. The opinions and statements are based on sources believed to be reliable and in good faith. However, ITA/AITES accepts no responsibility or liability whatsoever with regard to the material published in this report. This material is: information of a general nature only which is not intended to address the specific circumstances of any particular individual or entity; not necessarily comprehensive, complete, accurate or up to date; This material is not professional or legal advice (if you need specific advice, you should always consult a suitably qualified professional).

Recommendations on the development process for Mined Tunnels

Working Group 14
Mechanized Tunnelling

Working Group 19
Conventional Tunnelling

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1 >> Glossary

This document has been elaborated by the members of the ITA Working Groups 14 (Mechanized Tunnelling) and 19 (Conventional Tunnelling). They represent various countries from three different continents.

The technical expressions used in this document take into account the ITA Glossary (https://www.ita-aites.org/en/component/seoglossary/1-main-glossary).

Nevertheless, most contractual terms are not part of the ITA Glossary. This document follows generally the design bid build procurement model (see also FIDIC Red book) [16].

The most important contractual terms will be defined additionally for this document.

Contractor :
Person or organisation appointed by the Owner as Contractor whose role is to build the project in accordance to the design and specifications of the Design Engineer and to the cost and time negotiated and agreed in the contract documents.

Design Engineer : Person or organisation appointed by the Owner responsible for the the elaboration of the design and the specifications of the project during all design stages.

Owner : Organisation, or individual, who commissions the activities necessary to implement and complete a project in order to satisfy their needs and the enters into contracts with the commissioned parties.

An Owner organisation can be categorized as follows:

1. Publicly or privately funded.
2. Level of knowledge and experience within the Owner organization in dealing with the construction industry and implementing building projects.
3. Owner acts as future operator or acts as project developer to pass the project on to others.
4. The degree of contribution that the Owner is making to the actual project management

Site Supervision : Owner's representative on site responsible for the construction management of the project during the execution stage.

Tunnelling Methods : Catalogue of construction methods for the excavation of underground structures, with a distinction between the mechanical drives (excavation by TBM) and conventional drives (excavation by drill and blast method or any other mechanical aid than TBM).

2 >> Summary

ITA's working groups on mechanized (WG 14) and on conventional tunnelling (WG 19) elaborated several documents regarding the specific tunnelling methods [1], [2], [8]. In many projects the ground conditions allow either conventional or mechanized tunnelling methods. Therefore, many Owner's organisations have to find an answer on the question which would be the most appropriate tunnelling method for their project.

Both working groups agreed during the WTC 2010 in Vancouver that recommendations on this topic shall be a joint work of both working groups. The answer on the question of the most appropriate tunnelling method depends on many factors for each individual project, not only on the ground conditions but also on many other factors as discussed herein this report. It also depends significantly on the knowledge gained during the project development and on other projects in the area. The complexity of the topic does not allow a simple approach.

The present document intends to highlight the influence of the main project requirements and the factors affecting the selection of the tunnelling method depending on the different project phases. This document does not include typical technical data, such as advance rates, penetrations rates depending on ground conditions, etc. Such aspects shall be treated in a future ITA-Report.

Each project is unique and requires independent project-specific assessment. However, these recommendations represent guidelines and suggestions for the project development with respect to the selection of the tunnelling method in general. The recommendations were developed on the "design – bid – build" procurement model. If other models, such as e.g. the "design – build" are chosen, the general approach will be the same, but with a different allocation of the responsibilities. The present report does not treat this topic in detail which shall be analysed in a future document. Also the list of typical documents is only a first collection of some examples. This list shall be developed in a next report of ITA.

These recommendations are intended to be used by Owner's representatives, tunnelling engineers (Design Engineers and Site Supervision), Contractors and Subcontractors.

3 >> Introduction

The increasing demands for infrastructure projects today require more underground construction in increasingly adverse ground conditions. It has been observed that in recent years' tunnels are being located in more challenging conditions, adverse tunnelling conditions, and remote locations. Concurrently, tunnelling methods shall be carefully considered in light of site conditions, geological setting, and end use objectives. The selection and implementation of the tunnelling methods is one of the key factors competing and conflicting in order to achieve all end-use objectives.

The selection process consists not only of the Contractor's final choice of equipment, but it is a process starting during early feasibility studies. Although at this early point the task may seem simplistic, the early feasibility studies limit or open the variety and choices of the means and methods of the tunnelling method during construction. As major infrastructure projects often have long preparation phases, (sometimes measured in decades), it is advisable to come back to the initial studies and question the early project decisions in light of technological developments and changes in project conditions.

In this process it is required to observe from the beginning, the different interests and task allocations of all involved parties. It is in the overall interest of all parties in this revolving process to select the tunnelling method which best fits the final purpose of the structure, permits safe construction, utilizing state-of-the-art methods and still achieving the most robust economical and sustainable solution. Figure 1 shows conceptually, the main parties involved in the selection of the tunnelling method.

3.1 INTENDED USE OF THE RECOMMENDATIONS

The aim of the working groups 14 and 19 with this report is to develop recommendations for Owners, Consultants and Contractors to promote the international understanding of the development of underground projects by unifying the terminology and by presenting an overview of a recommended structured approach for the project development.

The contents shall be valid for most parts of the world. Therefore, the recommendations highlight only the most important principles, but do not deal with the details, which are treated by many national codes, guidelines, and practices.

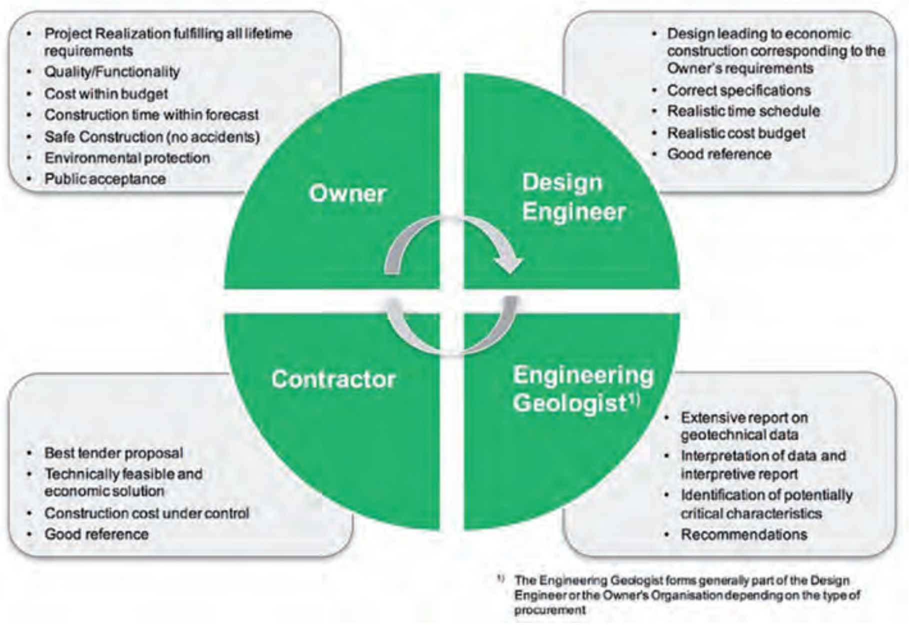

Figure 1: Parties involved in the selection process of the tunnelling method

(1) The Engineering Geologist forms generally part of the Design Engineer or the Owner's Organisation depending on the type of procurement

The report starts with a description of the main project requirements for an underground project independent from a specific project phases. In the following chapters, supplementary measures for the selection of the tunnelling method for each project phase specifically related to the individual project requirements are given.

Therefore, the specific recommendations in Chapters 4 to 7 shall always to be considered together with the general recommendations made in Chapter 3.

3.2 SUMMARY OF TUNNELLING METHODS

3.2.1 Mechanized Tunnelling

Mechanized Tunnelling in the context of this document utilizes Tunnel Boring Machines (TBM) and Shielded Machines. The excavation diameters for mechanized tunnelling range from approximately 400 mm for remote controlled utility tunnelling up to double-deck traffic tunnels with diameters beyond 17.5 m. Figures 2 and 3 show examples of tunnels constructed by mechanized tunnelling.

TBMs could be equipped with a full face cutter-head or with partial face excavation from within a shield.

Depending on the TBM design, mechanized tunnelling allows to maintain continuous active support onto the tunnel face during the excavation process if required such as the case for soft ground TBM. The tunnel face and excavation area can be completely isolated from the rear tunnel and working area, for example to maintain natural ground water levels, even higher than 10 bars, or to tunnel safely in contaminated or gassy ground.

Ground support can be installed simultaneously from within the advancing TBM. In hard rock the ground support can simply be rock bolting, with the possibility of applying sprayed concrete lining. Ground support by precast reinforced concrete segments build a watertight lining in both, hard rock excavations as well as in soft ground tunnelling. The segments are installed from within the TBM.

The production quality of the precast segments has advanced to high standards permitting its use as an integral part of the final tunnel lining. On most applications the precast segmental lining is the final lining without any additional structural liner. This is called single-pass lining.

The excavated material will be removed through the TBM, depending as well on the type of face support. In Slurry-TBMs the material is pumped from the TBM to the tunnel portal in pipes together with the face support medium, normally bentonite suspension, to a separation plant. Open face rock TBM or Earth Pressure Balance (EPB) TBMs can as well use rail-bound transport or continuous conveyor belts for mucking. The material supply to the TBM is either rail-bound or rubber-wheeled vehicles.

TBMs, customized for each project, are travelling factories with specifically designed work areas for each work sequence. This way the efficiency is high, but it requires trained personnel for the different positions. Table 1 provides most common mechanized equipment for rock or soft ground applications.

Full face tunnelling using any of the above listed equipment will produce a circular cross-section tunnel; with both curved and tangent alignments. However, recently and in limited applications square, rectangular, double and triple - O tunnel cross-sections have been successfully excavated.

Figure 2 : Top left: Lowering a TBM into the start shaft Lower left: TBM arrived at the portal with back-up still inside the tunnel © Babendererde Eng

Figure 3 : Top right: Pipe-jacking tunnel as water sewer Lower right: Backfilling the gaps aside of an invert gallery in a large tunnel parallel to tunnel excavation © Babendererde Engineers

3.2.2 Conventional Tunnelling

Conventional tunnelling in the context of these recommendations means the construction of underground openings of any shape with a cyclic construction process of:

- Excavation of the full or the partial face, by using the drill and blast methods or mechanical excavators, except by full face TBM
- Mucking excavated material from the face to the shaft or portal for disposal
- Placement of the primary support elements such as:
  - Steel ribs or lattice girders
  - Soil or rock bolts
  - Sprayed or cast in situ concrete, not reinforced or reinforced with wire mesh or fibres

Conventional tunnelling generally allows a high flexibility of the shape of the excavation (Fig. 4 right) and the possibility of partial face excavation if needed.

Conventional tunnelling is carried-out in a cyclic execution process of repeated steps of excavation followed by the application of relevant primary support, both of which depend on existing ground conditions and ground behaviour. An experienced team of tunnel workers (tunnellers), assisted by standard and/or special plant and equipment executes each individual cycle of tunnel construction.

Conventional tunnelling method encompasses the so called traditional Drill and Blast (D+B) and the so called New

FACE SUPPORT	FULL FACE EXCAVATION	PARTIAL FACE EXCAVATION
None or passive	Open Hard Rock TBM or Main Beam TBM	Digger shield
	Single Shield Hard Rock TBM	Auger or road header
	Double Shield Hard Rock TBM	
Active	Earth-Pressure Balanced TBM (EPB-TBM)	Digger shield with compressed air
	Slurry-TBMs	Auger or road header with compressed air
	Compressed Air Shields	
Combination	Dual- or Multimode-TBMs, combining for example hard rock excavation with EPB- and/or Slurry mode.	

Table 1. Most common equipment with or without active face support for hard rock or soft ground applications.

Austrian Tunnelling Method (NATM) or sometimes referred to as the Sequential Excavation Method (SEM) or the Sprayed Concrete Method (SCM).

The conventional tunnelling method using standard equipment allows access to the tunnel excavation face at almost any time and is very flexible and adaptable for situations that require a change in the structural support system. Instrumentation and monitoring of the behaviour of the ground during excavation is essential for successful tunnelling. Supplementary support system, often referred to as tool box, can be implemented as required. A standard set of equipment for the execution of a conventional tunnel drive in rock may consist of the following items:

- Drilling jumbo to drill holes for blasting, rock bolting, water and pressure relief, grouting, etc. (Figure 4 left)
- Road-header or excavator in cases where the ground is suitable for road-header excavation or blasting is not possible or economical

Figure 4 :
- Top: Drilling jumbo working in a conventional tunnel drive.
- Below: Tunnel bifurcation excavated by conventional tunnelling General description of the project development process © AlpTransit Gotthard Ltd.

- Lifting platform allowing the miners to reach each part of the tunnel crown and of the tunnel face
- Lifting equipment for steel sets or lattice girders
- Loader or excavator for loading excavated ground onto dump trucks
- Dump trucks for hauling excavated ground
- Set of sprayed concrete equipment for application of wet or dry sprayed concrete

3.3 General description of the project development process

Underground projects follow the same project development process as many other infrastructure projects. In many countries national codes or standard practices give clear definitions of the design and construction process and the related tasks to be taken by the Owner and its Consultant. Table 2 shows an example of the project development steps from the point of view of the ITA Working groups 14 & 19, as there is no international standard available for the definition of the Project Phases.

Owner's organizations shall be aware that the level of influence of the Owner's decisions regarding the means and methods of tunnelling method is most effective at the earliest phases of the project, whereas the consequences (on the final cost and time schedule) increase mainly after the completion of the final design and the starting of the tendering process (Fig. 5). Under certain circumstances, Contractors may opt to change the construction method proposed by the Owner if determined that the Contractor proposed method will save time or money. The assessment of the risks and consequences shall be properly documented and clearly stated. Owners and their Consultant's shall pay highest attention to the project definition and design phase in general but also regarding the topic of the selection of the most appropriate tunnelling method. However, it is recommended that Owners provide performance specifications of the means and methods of construction allowing the Contractor to select the proper equipment.

Whereas the alignment of an underground structure can be shifted easily in the design phase, such a decision becomes more difficult after starting the procedure for obtaining the environmental clearance and the construction permit and it will be nearly not feasible after the contract award. Costs for such a decision will increase very much if such a decision is taken in the late design phases or much later.

GENERAL PROJECT DEVELOPMENT PHASES	CONSULTANT'S TASKS	GOAL
1. Project concept and definition	0- Analysis of the needs 1- Basic design criteria Environmental Process	Purpose of the projects Design criteria, corridors Environmental process, approvals and permitting, right of way acquisition
2. Design	2- Conceptual (basic) design 3- Preliminary design 4- Final (detailed) design[1]	General layout, feasibility Cross sections Detailed design, construction permit, third party approvals, interfacing design, coordination and project integration
3. Preparation of the construction (tender phase)	5- Tender documents 6- Tender process	Draft contract documents Most economic offer
4. Construction	7- Construction documents 8- Site Supervision	Execution of the work
5. Completion/ Commissioning	9- Documentation	As built documentation and collecting construction experiences

Table 2. General project development phases and consultant's tasks

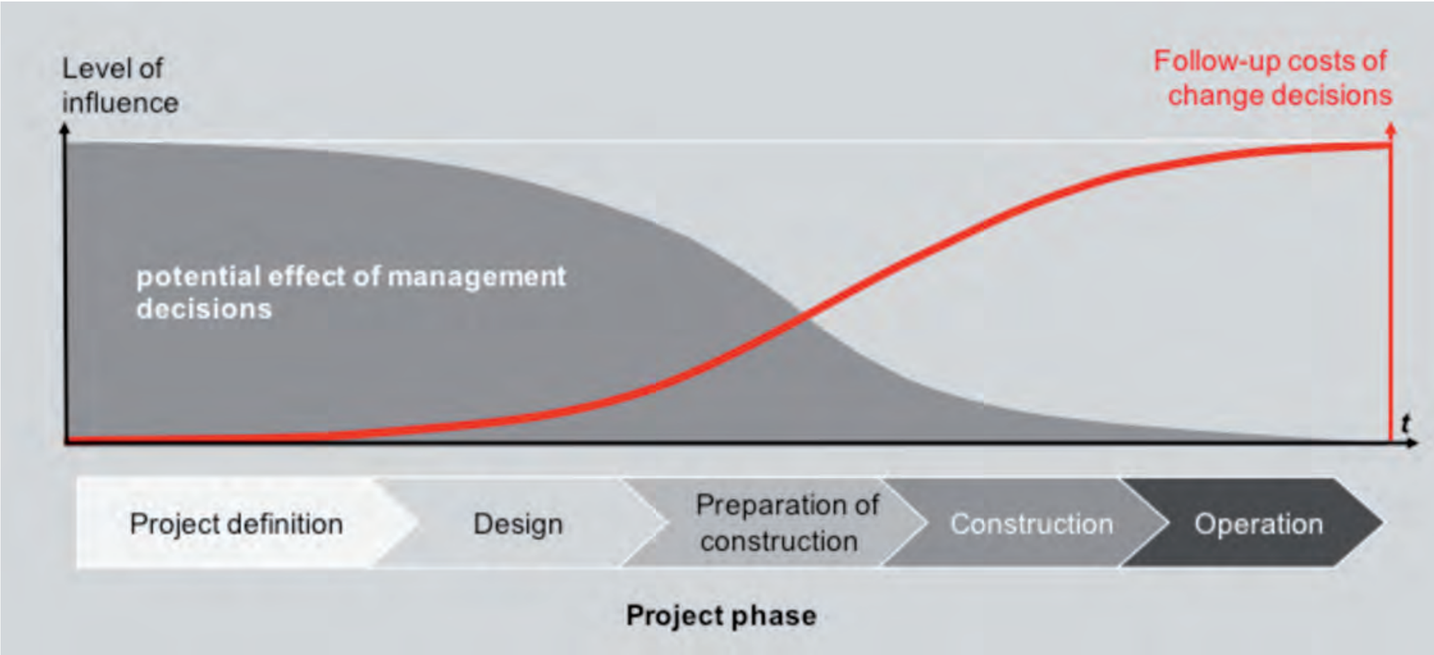

Figure 5 : Potential effects of management decisions and potential impact on costs

Regarding the topic of the selection of the tunnelling method, the costs will increase rapidly if the Owner asks for such a change after tendering the project.

Figure 5 shows that management decision can be taken during the earliest project phases without high follow-up costs. After receiving the construction permits and obtain required approvals and mainly after the contract award, the follow-up costs of management decisions increase significantly. Regarding the question of the selection of the tunnelling method, Figure 5 indicates that an unplanned change of the tunnelling method is very expensive and could lead to major cost increase and time delay after the award of the contract. The Owner's organisation shall define the most appropriate way to ensure the selection of the most appropriate tunnelling method preferably no later than during the phase of the preparation of the tendering documents as defined in Table 2. If obtaining the construction license depends on the tunnelling method, the selection of the method has already been done in the design phase (e.g. projects where separation plants are needed).

Alternatively, if the selection of the tunnelling method is not strongly influenced and either of the two methods is viable; Owners may issue the tender documents with two options allowing the Contractors to bid on both methods.

4 >> Description of the main project requirements

The main goal of the implementation of a tunnelling project is to meet its functionality of requirements within the commonly agreed upon level of quality, design life, and operational requirements. Other requirements are the realization of the project within the foreseen time limit and within the given cost target.

Owners shall be aware that the ground surrounding the excavation is the main supporting element and the stability of the tunnel depends on the factual ground behaviour in response to the excavation. The ground conditions often remain not completely known, and its behaviour not completely predicted even after extended ground investigation campaigns. Factual ground conditions may also change within a short distance as many experiences have shown. Owners shall be aware that risks related to ground conditions or ground behaviour are the responsibility of the Owner.

Other boundary conditions which have to be taken into consideration include:

- the Geology (ground conditions)
- Ground behaviour
- Ground water conditions
- Geometrical restrictions
- Location, Accessibility and Logistics
- Occupational health and safety
- Environmental conditions
- Nearby buildings and structures
- Noise and vibrations
- Public acceptance / Stakeholder interests
- Market conditions
- Experiences from comparable projects
- Organisation and processes
- Time schedule
- Length and cross section of the tunnel
- Contractor's preference
- Risk aspects
- Cost

All these requirements may have an influence on the selection of the tunnelling method and have to be considered during the different stages of the project development. The importance of a specific requirement may increase or decrease during the project development phases. For example, the geotechnical aspects are more critical during the conceptual and preliminary design phases while market conditions aspects are more critical during the tendering and construction phases.

Table 3 and the following section will give an indication how to deal with the different requirements in the different design phases.

4.1 GEOLOGY

The description of the geological, hydrogeological and geotechnical conditions is the basis for the interpretation of the ground conditions and its subdivision into different homogeneous zones as well as the definition of possible difficult and mixed ground conditions. A ground model (geological and geotechnical model, including shear and fault zones) is defined by the description of the ground conditions and the expected behaviour of the ground during tunnelling. The ground model must be the stable base for the development of the project in subsequent phases. The geotechnical model forms part of the ground model and bases on a thorough ground investigation and its evaluation. The geotechnical model is the base for the definition of the excavation method and required support to be established in the design documents and shall lead to the application of an excavation and support classes system.

When developing the ground model, a clear distinction between the description of the ground (factual data) and the Design Engineer's or Geologist's interpretation of the ground behaviour has to be made.

PROJECTS REQUIREMENTS	PROJECT DEFINITION PHASE	DESIGN PHASE		TENDER PHASE	CONSTRUCTION
Geology	set tunnel alignment	ground investigations	ground model	provifing all geol. docs (GDR, GDSR, GBR)	monitoring, report and documentation
Logistics	analyse accessibility	develop logistic concept		transfer boundary conditions to future contractor	contractor's responsability
Quality/functionality	requirements	quality level, general layout		definition of final quality/functionality	Owner : check of quality
Time Schedule	determine time restrictions	structured in detail		provide detailed time schedule	Owner : time management
Costs and financing	rough cost estimation	first cost calculation	financing secured	costs verification	Owner : cost control
Occupational health and safety		define level of work safety		requirements transfered to future contractor	Contractor : fulfill requirements
Environmental aspects	restrictions considered	define of protection		requirements transfered to future contractor	Contractor : fulfill requirements
Public acceptance	inform effected stakeholders	public discussion		includ public relations	public outreach program
Market conditions	estimate capacity	check availability		market force decides	
Experiences	lessons learned from former projects	experienced engineers, responsabilities		contractors experience	monitoring, report and documentation
Organisation and processes	established clear idea	construction permit		contract award	processes coordinated

Table 3. Project requirements and relevant general tasks for project development with respect to the tunnelling method

4 >> Description of the main project requirements

Factual data are:

- Results from field borings and laboratory testing
- Key engineering properties of the ground samples with distinction for the different excavation techniques
- Ground water conditions (incl. chemistry of the ground water)
- Flow rates
- (known) gassy conditions
- Overburden height
- Measured pollutants and contamination in the ground and groundwater
- Detected obstacles and known underground structures; existing foundations
- Presence of boulders in soft ground matrix
- Presence of shear zones, faults, discontinuities, etc.
- Measured in-situ stresses
- Observed and expected mixed ground conditions

Interpreted data are:

- Geological units (Fig. 6) and their interpreted geotechnical properties
- Description of anticipated ground behaviour
- Description of anticipated ground water (flow rate, presence of artesian conditions, saturated sand lenses, etc.)
- Definition of the hazard scenarios (including geological hazards)
- Relevant experiences in the same or similar geological units
- Baseline values

Geological, hydrogeological and geotechnical investigations shall be carried out at an appropriate level depending on the project phase.

The origin of all geological data shall be documented in a clear and comprehensive way. It shall be stated whether the information derives from project related investigations and tests, references to technical literature, information in existing geological reports, empirical values, estimates or assumptions.

The accuracy of the descriptions or the relevant uncertainties shall be specified. Known gaps in the results presented shall be pointed out.

The type of investigation and the measurement methods shall be described. If possible, standardised methods shall be employed in the determination of the geotechnical properties of soil and rock using laboratory and field tests.

4.2 GEOMETRICAL RESTRICTIONS

Geometrical restrictions have a strong influence on the selection of the tunnelling method.

The largest diameter driven by a TBM is presently around 17.5 meters corresponding to an excavated area of 240 square meters. Apart from a few rather special cases TBM's excavate generally circular openings only.

Larger openings and openings with not circular geometry are usually constructed using the conventional tunnelling method.

Whereas conventional tunnelling can follow any curved design, tightly curved alignments with a radius of less than 15 dtunnel with lining and 10 dtunnel without lining pose a challenge to TBM's with long back-up installations.

The maximum length of a tunnel drive depends on the restrictions of logistics (supply chain) and the requirements of occupational health and safety (ventilation, rescue time). Both methods are suitable in this case. However, for short tunnels, the economical and time schedule requirements often favour the conventional tunnelling methods.

Both tunnelling methods are also applicable for inclined and vertical shafts. Although,

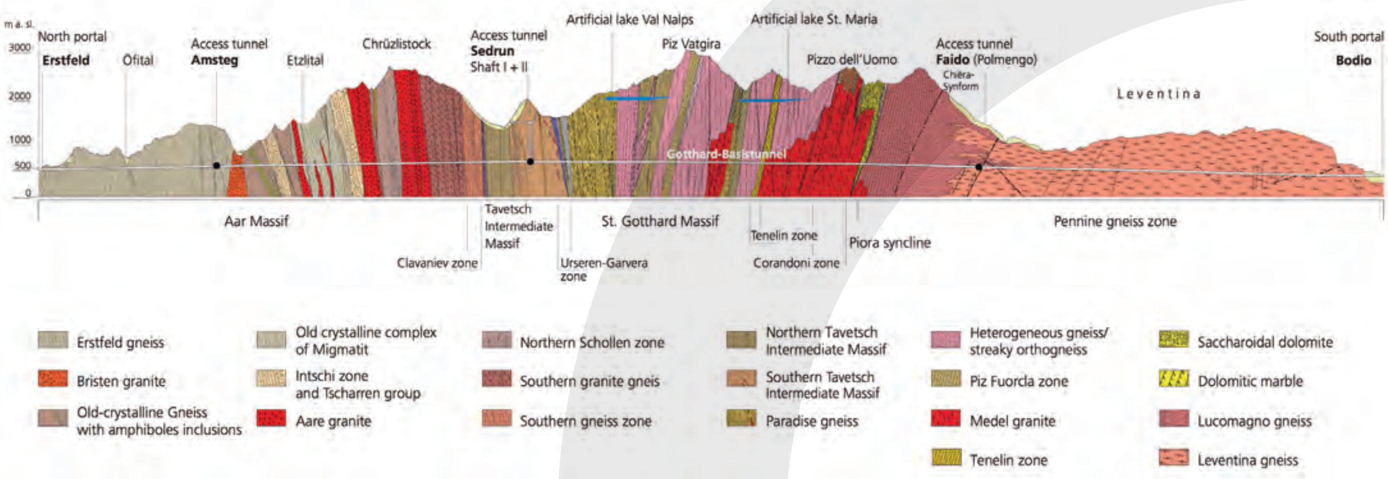

Figure 6 : Example of a geological longitudinal profile is part of the ground model © ATG

there are limitations on the size of vertical and inclined shafts using mechanized excavation.

Many projects consist in a composition of longer linear structures (tunnels) and shorter structures with large, not circular cross sections (caverns). Both tunnelling methods may be used therefore in the same project. Fig. 7 shows such an example.

4.3 LOGISTICS

In addition to the ground conditions, the local logistical conditions define additional restrictive requirements which may influence the selection of tunnelling method of a project. The following topics have to be considered:

- Accessibility
- Availability and capacity of energy (power) and water supply
- Potential disposal areas
- Potential areas for site installations (e.g. area for a segment factory (Fig. 8)) and assembling areas for TBM's above or below ground
- Muck separation plant
- Availability of area for separation plant in case of slurry TBM
- Transportation requirements

Conventional tunnelling uses generally a standard set of equipment. The standard equipment is generally smaller than a TBM. Also the level of electric power consumption is generally lower for conventional drives. Conventional tunnelling is therefore more convenient for projects with a restricted accessibility or a limited power supply.

Figure 8 :Stored precast concrete segments ready for supply to the tunnelling work for a water supply project. The logistics and supply of this type of tunnel support are extensive and needs to be considered early in the tunnel planning phases. © Daetwyler

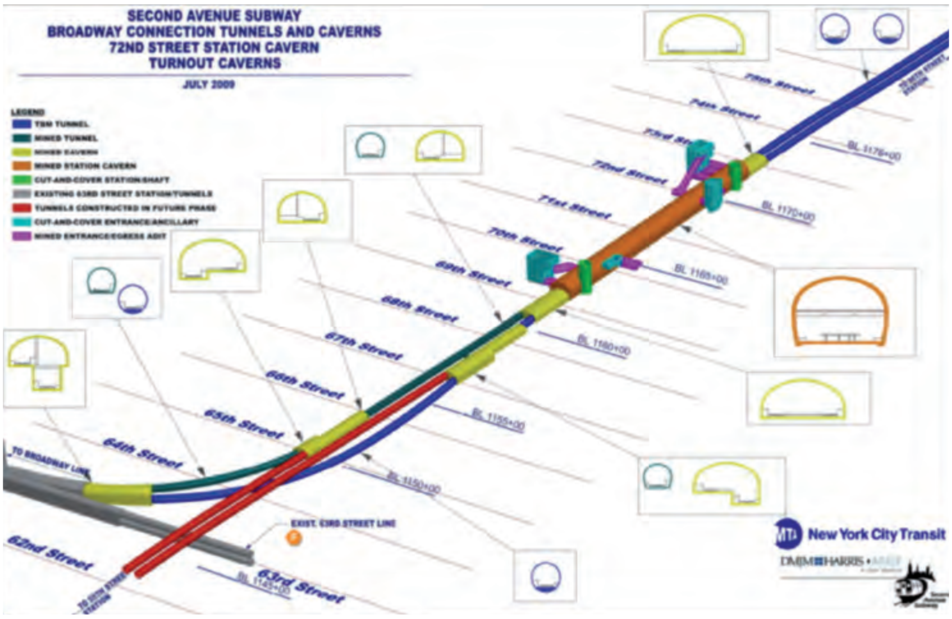

Figure 7 : Example of a project including TBM bored tunnels, caverns and tunnel enlargements, shafts in soil and rock conditions were built using the conventional tunnelling method. (Overall site plan for the Second Ave. Subway, 72nd Street Station and Tunnels Project for the MTA in New York City, USA).

4.4 QUALITY / FUNCTIONALITY

Each project must fulfil the functionality requirements of its future use (Fig. 9) during its design life. These include the regular operation, maintenance requirements, and the operational requirements in the case of extraordinary events (e.g. natural disasters or accidents) during its operation.

The intended operational requirements define the internal cross sections and the internal geometrical requirements, whereas the ground conditions and the structural durability define the dimensions of the lining and therefore the excavated (outer) diameter. Expandability of the project (e.g. second tube for traffic single line traffic tunnels) shall also be considered in many cases during the planning phases.

The quality level of the construction shall be selected according to the expected design life of the facility and taking into considerations the costs for operation and maintenance. For example, a mine access tunnel life span may be 10 to 15 years, while the life span of a road tunnel is a 100 to 150 years. The quality requirements and the predefined design life shall be established early in the project basic design criteria during the project definition phase and preferably shall remain unchanged. A late change of the quality level will lead to major consequences in later project phases and during the entire project life cycle. The quality level has a major influence on the cost of the project.

Quality and functionality must be achieved regardless to the selected tunnelling method.

Figure 9 : Functionality and required design life must be defined in the basic design criteria © Raimond Spekking/de.wikipedia.org

4.5 TIME SCHEDULE

The duration of the project is also a key factor tor the total project cost. The time schedule indicates whether and how the target schedule can be achieved.

The overall time schedule of a project shall include not only the design and construction processes, but the time required for the following activities:

- Site investigations (geotechnical and environmental)
- Archaeological investigations
- Proceedings for the construction permit
- Land acquisition
- Negotiation of the funding commitments
- Environmental process and approvals
- Agreements with other agencies affected by the construction
- Coordination with third party stakeholders and the public
- Procurement and project delivery method (i.e. design-bid-build; design-build, public-private partnership, etc.)
- Utility and traffic relocations
- Construction access points and logistics
- Construction activities, including
  - Mobilisation and set up time
  - TBM and power delivery
  - Excavation and lining
  - Finishing
  - Testing and commissioning
  - Time contingencies

The construction time depends on the tunnelling method, due to different mobilisation times and generally different daily advance rates for both methods. Not only the excavation cycle determines the overall advance rate, but also the logistics of the entire supply chain and the type of maintenance requirement of the equipment are key factors, which must be considered, when calculating the overall advance rate (Fig.10). Furthermore, tunnels being linear structures, the availability of multiple access points and headings would influence the time schedule for excavation and lining.

TBM drives are generally faster for long tunnel drives in homogeneous ground conditions and therefore often more economic than conventional drives.

For projects with special boundary conditions, logistical issues or with a certain geological setting, the construction of a short tunnel using a TBM or of a long tunnel using conventional tunnelling can be more economical or less risky as several examples have shown.

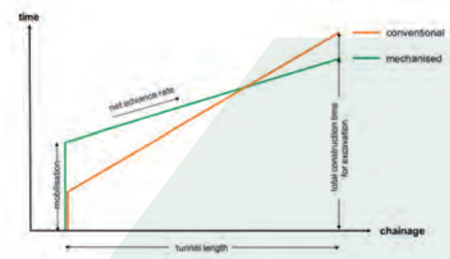

Figure 10 : key factors for the calculation of the construction time for the excavation

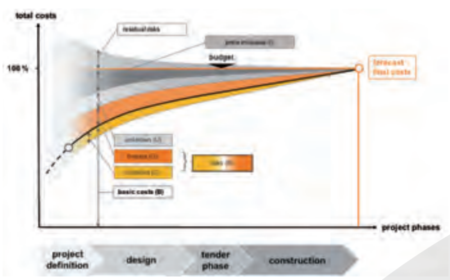

Figure 11 : General cost development during design and construction of a project [14]

4.6 COSTS AND FINANCING

Costs of a tunnelling project depend mainly on the required quality level of the final construction, on the construction schedule (including all aspects of the ground conditions, logistics etc.), or risk factors, and on the market conditions.

Cost objectives and the funding limits are often critical requirements for the execution of a project. An absolute cost transparency is therefore a must during all phases of the project.

According to the well-known experience that no construction is risk free, it is of highest importance that not only the basic costs are calculated. Also the costs for risks, unknown conditions and the future price escalation have to be included in order to get a reliable forecast of the final costs (cf. Fig. 11), a stable budget and to minimise the risk of a budget overrun.

Each design step has its own level of cost evaluation using the appropriate methods (see Table 4). Proper contingencies comparable with the level of the design development shall be included.

During the project definition phase a cost framework is established. The cost framework is defined by the general data of the project (length, volume) multiplied by specific cost values which are based on the experience from completed projects under comparable boundary conditions. The tunnelling method

PROJECT PHASES	PROJECT DEFINITION	DESIGN			TENDER PHASE	CONSTRUCTION
Design phases	Basic design criteria	conceptual design	preliminary design	final design	tender design	construction drawings
Project knowledge	not consolidated	planning	planning	planning	planning / contract	contractually
Level of cost evaluation	cost framework	pre-consolidated	consolidated	consolidated	consolidated	consolidated
Method for cost evaluation	Characteristic values	intermediate	preliminary cost estimate	final	verification of the final	contract

Table 4. Design steps and corresponding level and methods for the cost evaluation

is at this early stage of the project often of secondary influence, but shall be considered as a parameter in the database of specific experience values.

The intermediate cost estimate in the phase of the conceptual design is still not based on a consolidated project knowledge. It is generally calculated on specific costs on the main construction elements. The specific costs for the excavation shall take the various tunnelling methods into account.

The preliminary and the final cost estimates are based on a single, consolidated project. A detailed calculation of the basic costs, based on quantities material costs, labour costs, equipment costs, cost of consumables, indirect costs, costs of logistics, overhead cost and anticipated profit shall be included. The construction cost shall reflect the selected tunnelling methods.

Risk management is the base for the definition of additional costs for potential risks. A surcharge for unforeseeable aspects shall be added as also the costs for the price increase within the period of the project design and execution, if the final costs at the project end are required. Risk management plan shall be established including a risk register to allocate mitigation measures during design and/or construction. The cost of the mitigation measures shall be included. Residual risks shall be priced and a suitable contingency be established and included in the project overall budget.

The procurement model and the payment method may have an influence on the estimated final costs, due to the fact that procurement models with payment methods with asymmetric risk allocations generally lead to higher costs due to the fact, that higher risk contingencies are often included by the Contractor or the Owner (Fig. 12).

Furthermore, projects that are delivered using public-private partnership, build-operate-transfer or other similar arrangements, the cost of funding the project shall also be included.

As financial risks may become crucial for the success of a project an independent review of risk analysis and the budgets by experienced experts is highly recommended after each project phase.

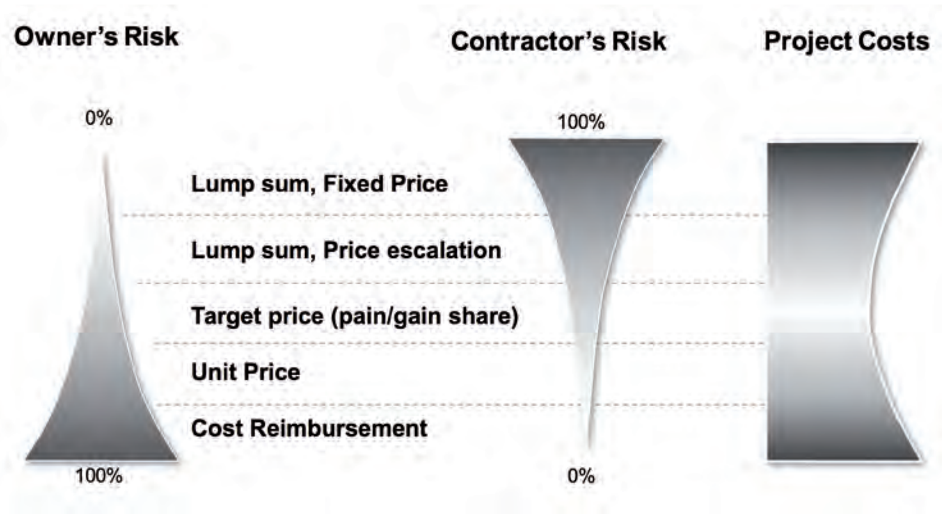

Figure 12 : Total costs in function of the payment method (for underground construction)

The Owner shall also consider the lifecycle costs including the costs for maintenance and operation. The analysis of lifecycle costs may have an influence on the selection of the tunnelling method.

Early and stable funding sources and a financially sound and technical competent Contractor help to achieve the financial goals of a project.

4.7 OCCUPATIONAL HEALTH AND SAFETY

Each worker has the right to leave the site after his working shift as healthy and safe as he started his work. Health and safety requirements are therefore of highest importance for underground construction.

The general layout (accesses, escape ways, etc.), the selection of the construction materials and the availability and the quality of the working space define the general level of work safety already in the early design phases. Occupational health and safety requirements in conjunction with the geology and other factors may impact the selection of the tunnelling method.

Important aspects to be considered are:

- Working place conditions
- Occurrence of gas
- Fire hazards
- Water inflows (high pressure, hot water)
- Ground water table (e.g. compressed air environment)
- Equipment selection
- Proximity to other nearby structures
- Availability of rescue teams
- TBM intervention requirements

Many international and national regulations define the requirements on health and safety. It is recommended to follow ITA's "Guidelines for good occupational health and safety practice in tunnel construction" [3] already in the earliest design phases.

Up to now no internationally recognized studies are available, which show significant differences on the level of occupational health and safety related to the tunnelling method.

Regardless of method of construction, occupational health and safety measures shall be implemented consistent with the selected tunnelling method.

4.8 ENVIRONMENTAL ASPECTS

Environmental aspects are critical in order to make an underground project feasible.

The following topics have to be taken into consideration

- Consideration of nature reserves
- Consideration of historical preservation
- Consideration ground water protection zones
- Investigation on the occurrence of contaminated ground and groundwater
- Concept for re-use of muck and muck disposal
- Protection of neighbouring buildings and structures
- Minimising vibrations
- Minimising surface deformations
- Minimising dust
- Minimising noise
- Prevention of odours
- Prevention of lighting
- Prevention of toxic substances
- Minimising impact on aquifers
- Wastewater treatment
- Slurry treatment
- Ground treatment according to weather seasons
- Use of biodegradable liquids

Many international and national regulations define the requirements on environmental aspects. It is recommended in the earliest design phases to follow the checklist of appendix A in ITA's report on "Underground works and the environment" [4].

Tab. 4 shows a list of environmental topics directly related to the tunnelling method

As TBM drives produce generally lower vibrations and less noise impact than a drill a blast drive, environmental aspects may be decisive for the selection of the tunnelling method in certain cases, mainly in densely populated urban areas with shallow overburden.

4.9 PUBLIC ACCEPTANCE

Many infrastructure projects encounter objection by the public. This is often due to lack of understanding the project benefits, the impact on the community and the environment, or the financing aspects. A lack of public acceptance may complicate the realisation of a project, delay it or even result in cancelling the project.

It is therefore of highest importance to secure the public support of a project from the earliest phases by early engagement of the public and the project stakeholders and continue throughout the project phases.

The following elements may help to gain the public acceptance:

- Clear communication of the needs and benefits of the project
- Early and clear communication of the project risks
- Minimising the impacts on the environment and on third party assets
- Professional stakeholder management (involve affected stakeholders in a direct cooperation or by continuous information)

Public acceptance is generally driven by environmental aspects (noise, dust, vibrations), impact during construction (traffic, impact on businesses, utilities, etc.) and economical aspects but not directly by the selection of the tunnelling method. However, the impacts of the tunnelling method on the environmental aspects, time schedule and costs are important for public acceptance. The public acceptance is often influenced by experiences from similar other projects.

REQUIREMENT	MECHANIZED	CONVENTIONAL
Dust emissions	X (open TBM only)	x
Diesel emissions	(x)	x
Noise reduction	-	x
Vibrations	x	x
Pollution of muck	-	x
- Nitrite	x	x
- Hydrocarbons	x	-
- Conditioners		
Pollution of slurries	-	x
- Nitrite	x	x
- Hydrocarbons	x	-
- Conditioners		

Legend :

X impact to the environment
(x) impact to the environment may occur, depending on secondary installations

- not relevant

4.10 MARKET CONDITIONS

The local market conditions have to be considered in the selection of the tunnelling method of an underground project, regarding the following aspects:

- Local labour skills and availability
- Local industry experience and preference
- Local Owner's experience and preference
- Availability of suppliers
- Tax liabilities
- Material and labour costs
- Trade barriers
- Union and labour laws
- Local occupational health and safety requirements

Market conditions are related to the local boundary conditions. In some countries the experience with TBMs is rather small, such an implementation of this equipment would initially ask for more international specialists to initiate a TBM operation and maintenance which often they continue throughout the constriction in expertise and advisory capacity. Conventional tunnelling works with standard equipment and is generally applicable in all markets.

4.11 EXPERIENCES

Experience is of highest importance in underground construction. Personal experiences of the Owner's decision makers and their consultants may facilitate the decision making of selecting the tunnelling method. Comparison with other projects can give helpful information.

When carrying out comparative studies it is highly recommended to consider also the boundary conditions of the comparable projects in order to understand the decisions taken.

Wrong conclusions may be taken if the selection process is not fully vetted and all issues are not fully addressed for the project specifics.

It is important to recognise that experiences cannot replace the regular engineering process by the Design Engineer or the advancement in the technologies of both mechanized excavation and conventional tunnelling.

There is a world-wide broad experience on conventional and on mechanized tunnelling available to assist in regions with less experience.

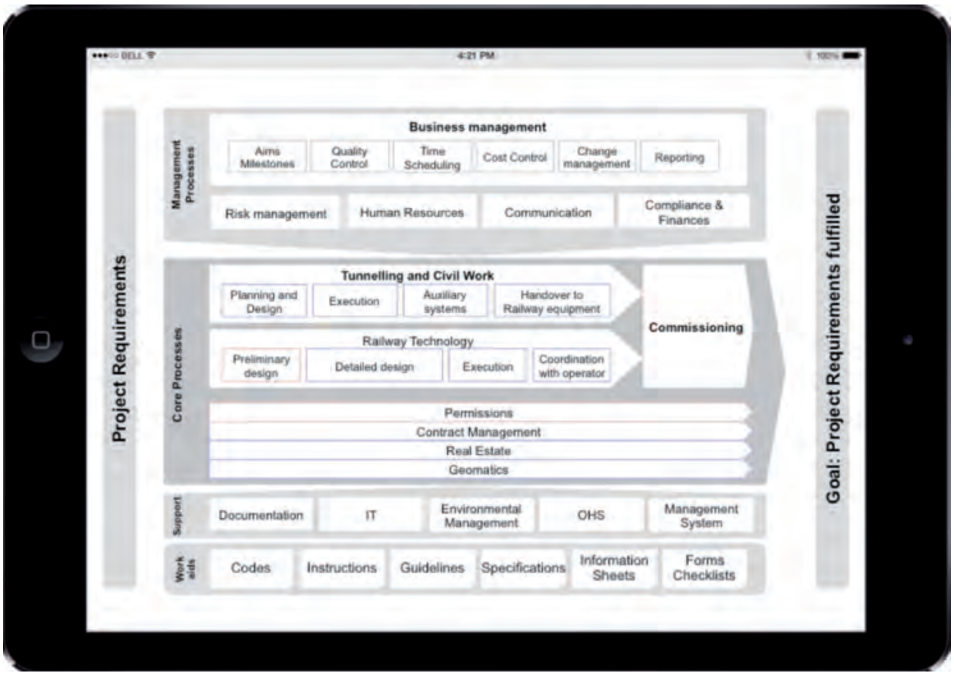

Figure 13 : Example of a process portal for a railway tunnel project on a tablet computer

4.12 ORGANISATION AND PROCESSES

The realisation of a project is a sequence of many processes. Each project needs a clear process map (Fig. 13) with a clear allocation of the responsibility for:

- The core processes (design, tendering, construction)
- The management processes (financial funding; cost control, scheduling, risk management; environmental management; health and safety management; management of change requests, stakeholder management, procurement model, project insurance, etc.)
- The support processes (legal and code compliance, real estate, human resources, controlling, reporting, IT-support, etc.)

The general processes are not directly related to the tunnelling method, whereas the time required for individual process steps may vary significantly from one tunnelling method to the other.

The organisational structure is generally not depending on the selection of the tunnelling method. However, the resources may be different from one tunnelling method to the other.

It is highly recommended that the project management plan or handbook reflects the processes required for the selection of the tunnelling method.

4.13 RISK MANAGEMENT

Underground construction is clearly different from any other type of construction because of its inherent nature: uncertainties in the ground conditions, unforeseen conditions, dependency on the means and methods, and the high construction risk associated with this type of construction.

Therefore, the recognition and the assessment of potential hazards as well as the planning of appropriate mitigation measures are fundamental to the design of underground structures.

Hazard identification and the management of risk to ensure their reduction to a level 'as low as reasonably practicable' (ALARP) shall be integral considerations in the planning, design, procurement and construction of Tunnel Works. So far as it is reasonably practicable, risk shall be reduced through appropriate design and construction procedures in any case.

Responsibility for risk management shall be explicitly allocated to relevant parties to a contract so that they are addressed adequately and appropriately in the planning and management of a project and that appropriate financial allowances can be made.

The use of a formalised Risk Management procedure, such as ISO 31000 (Fig. 14), shall be employed as a mean of documenting formally the identification, evaluation and allocation of risks [15]. Risk Management shall start at the the initial stage of the project definition and shall be treated as a continuous cyclic process during the entire period of the project design and construction.

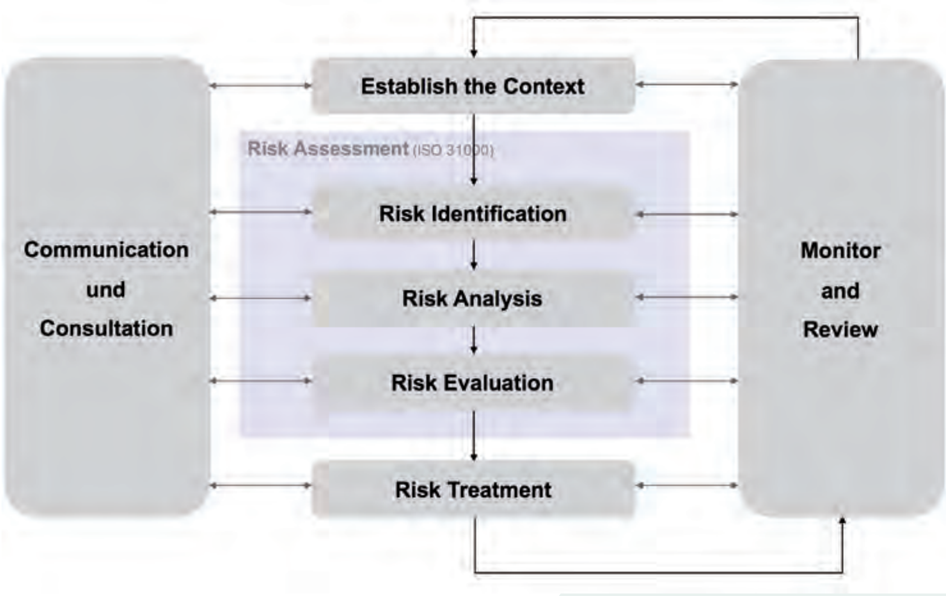

Figure 14: Risk Management process according to ISO 31000

The specific hazards shall be considered for each part of the project with the related tunnelling method, whereas the general hazards may be considered generally for each contract. The qualitative risk assessment shall include (independently from the tunnelling method):

- Hazard identification
- Classification of the identified hazards, assessment and evaluation the risks
- Identification of risk mitigation measures
- Details of the risks in the project risk register indicating risk class and risk mitigation measures for each hazard.

It is recommended to follow ITA's "Guidelines for tunnelling risk management" [5].

In the present document, the term "hazards" means an event that has the potential to impact on matters relating to a project, which could give rise to consequences associated with:

a) Health and safety

b) The environment

c) The design

d) The design schedule

e) The costs for the design

f) The execution of the project

g) The construction schedule

h) The costs associated with construction

ii)Third parties and existing facilities including buildings, bridges, tunnels, roads, surface and subsurface railways, pavements, waterways, flood protection works, surface and subsurface utilities and all other structures/infrastructure that can be affected by the execution of the works.

jj) The reputation of a project and the involved organisations

It is important to identify the potential hazards in a structured process. The following suggestion for the grouping of the the potential hazards is proposed in ITA's "Guidelines for tunnelling risk management" [5].

General hazards:

1. Contractual disputes
2. Insolvency and institutional problems
3. Authorities interference
4. Third party interference
5. Labour disputes.

Specific hazards:

6. Accidental occurrences
7. Unforeseen adverse conditions
8. Inadequate designs, specifications and programmes
9. Failure of major equipment, and
10. Substandard, slow or out-of-tolerance works.

5 >> PROJECT DEFINITION PHASE

5.1 GEOLOGY

The exact alignment of the future project is often not exactly known in the phase of the conceptual design rather various corridors are usually being considered. The project is developed at this stage within the boundaries of predefined corridors. In order to reduce risks, it is of high importance to know the zones of unfavourable ground conditions within the design corridors at this early stage (see example Fig. 15).

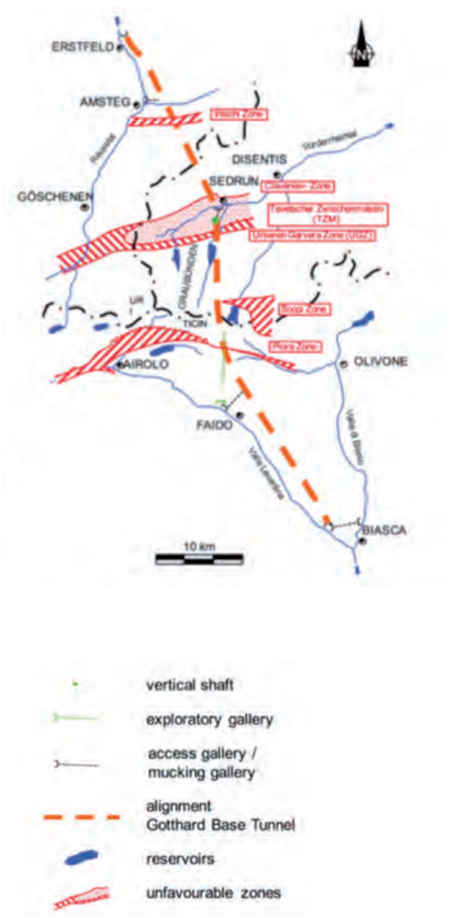

Figure 15 : Alignment of the Gotthard Base Tunnel (Switzerland) in relation to unfavourable ground conditions

First ground investigations shall be done. Commonly used methods at this phase are:

- Analysis of existing geological records (e. g. for structures already built in the same or similar geological formations)
- Historical records of adjoining projects
- Geological maps
- Technical literature
- Field mapping
- Remote sensing
- Limited exploratory boring

Usually the Design Engineer tries to find an alignment of the project, where the unfavourable zones will be crossed in the shortest possible distance while meeting the project functional requirements. For example, unfavourable zones for urban tunnelling include known manmade or natural underground obstacles or limitations in the right of way. Avoiding crossing active faults in seismic area, or difficult ground conditions are other examples.

Difficult geologic and hydro geologic conditions can be dealt with ground improvement methods. These consist of the various forms of grouting such as permeation grouting, jet grouting, compaction grouting, compensation grouting or drainage and ground freezing to name the most common methods. With improved ground, tunnelling conditions become more favourable and are available for both mechanized and conventional tunnelling.

In urban tunnelling where the alignment conditions may be shallow and the ground friable, ground improvement may allow for conventional tunnelling within tolerable surface deformation limits. Ground improvement in combination with the various pre-support methods in conventional tunnelling including for example pipe arch canopy methods will lead to a robust design and thereby enhance management of risk associated with characteristics of ground strength, stability and deformations.

5.2 LOGISTICS

Accessibility, transportation, access, potential laydown areas, areas for muck deposits and disposal, etc. shall be analysed in this phase. Under certain circumstances, these conditions may be decisive on the selection of the tunnelling method at this initial stage of the project.

5.3 QUALITY / FUNCTIONALITY

At this stage the Owner shall decide on the functionality (e.g. design speed, number of trains running through a tunnel, allowed breaks of operation for maintenance, etc.) of the project and the required quality level (e.g. life time). It is important to define these parameters early and maintain them throughout the various design phases.

Although generally the functionality and quality requirements do not directly affect the selection of the tunnelling method, certain functional or quality requirements could impact the selection of the tunnelling method. For example, the functional requirements in a undergroud railway station may favour using conventional tunnelling in a system executed by TBM (cf. Fig. 7)

5.4 TIME SCHEDULE

Due to the lack of information at this phase, the time schedule cannot be evaluated in detail.

However, it is important to start assessing the time schedule at the early stages taking into consideration the two tunnelling methods. Also for the time schedule a certain range of uncertainty must be communicated and assumptions shall be clearly indicated. Linear schedule consisting of time-distance-diagrams are useful tools for linear structures, such as tunnels.

The time schedule will be different according to the tunnelling method and the boundary conditions. In many projects both tunnelling methods can fulfil the time restrictions of the project at this design phase and therefore, shall be assessed carefully to identify certain milestones that can favour one method versus another.

5.5 COSTS AND FINANCING

During the project definition stage no consolidated information on the project is available.

Therefore, no detailed bottom-up cost estimate can be calculated; however, cost estimates shall be prepared for both tunnelling options using historical data and unit prices. Costs can be estimated only very roughly based on the experience from costs of comparable projects.

Adequate contingencies for risks and the unknown have to be added.

The range of uncertainty and the assumptions for each tunnelling method of the cost estimate shall be documented and communicated.

5.6 OCCUPATIONAL HEALTH AND SAFETY

All requirements of the local legislation have to be fulfilled by both tunnelling methods. The impact from possible polluted areas, gas etc. shall be considered in this phase.

5.7 ENVIRONMENTAL ASPECTS

All environmental restrictions have to be considered already in this early project phase, as they may be decisive for the alignment of the underground structure and the selection of the tunnelling method (see Section 3.8). Environmental aspects may be decisive on the selection of the tunnelling method at the project definition stage, such as e.g. noise protection, protection against vibrations.

5.8 PUBLIC ACCEPTANCE

Comprehensive stakeholder management is difficult to carry out in the project definition phase as there does not yet exist an exactly defined project. Nevertheless, the project requirements, the risks of the project and the main mitigation measures shall be communicated in an appropriate way. Affected stakeholders shall be involved in the project at this phase in order to make them participants of the project future development process.

Issues related to noise, dust, disturbance, traffic, etc. shall be communicated as they relate to the tunnelling methods.

5.9 MARKET CONDITIONS

The capacity of the market shall be estimated in this phase as it may have an important impact the future decision on the selection of the tunnelling method. The market conditions usually vary with time; therefore, this issue shall be re-assessed at every phase of the project.

5.10 EXPERIENCES

Experiences from similar projects shall be collected and interpreted. In the project definition phase, the design and the lessons learned during the construction from other projects shall rather be analysed as they relate to the specific requirements and issues of the current project.

It is important to know the specific boundary conditions and project requirements of similar projects in comparison of the current project in order to understand the decisions taken in other projects and how they relate to the current project. Other conditions or requirements may lead to different technical solutions for the selection of the tunnelling method.

5.11 ORGANISATION AND PROCESSES

At the end of the project definition phase a clear idea about the project organization and the processes shall be established. The continuous risk management process must be implemented at the end of this phase, independent from the tunnelling method. The risk management shall address the two potential tunnelling methods.

The Owner's organisation shall take the decision on the procurement model, as there are:

- **the design-bid-build - model (DBB)**
  This model follows the approach of a design and construction by different contractual partners of the Owner.
  The Owner commissions a Consultant (Design Engineer) with the preparation of the project documents, mainly the contractual documents, consisting of drawings, detailed specifications and further contractual documents such as bill of quantities, technical reports etc. The Contractors submit their offers on the basis of the tender documents prepared by the Owner's Engineer. The award of contract by the Owner will be given to the Contractor with the economically most advantageous bid (including price and quality).
- **the design-build - model (DB)**
  This procurement model follows the approach of a combined order for the detailed design and the construction.
  The Owner develops a conceptual (basic) design for his project and tenders the design and construction of his project in a single contract. The Owner signs the contract with a single partner who acts as a general Contractor for the design and the construction. Usually specialized Contractors with the ability to organise the design and construction work act as a provider. The engineering-procurement-construction model EPC is a particular expression of the design-build model with limited influence of the Owner during the construction phase (turn-key contract).
- **the design-build-operate-maintain - model (DBOM)**
  This model follows also the approach of a single contract for the design and the construction of a project. The Owner follows the design-build procurement model. In relation to the design, the DBOM model goes still one step further. The Contractor will also ensure the future operation and the maintenance during a predefined period.
- **the build-operate-transfer – Model (BOT)**
  The BOT model is the procurement model with the highest integration of the Contractor in the project implementation. The BOT- agreement governs the design, construction, operation and maintenance as well as the financing of the project. The Owner issues a long-term concession to a project company in order to construct and operate the infrastructure. The infrastructure is passed back to the Owner after the expiry of the contractually agreed concession period. The BOT-model is often used for purely private projects or for projects based on public and private partnership financing (PPP - Model).

The risk policy of the Owner, the expected integration of the Contractor in the project and the financial capabilities of the Owner are the main criteria for the selection of the procurement model. The tunnelling method is of secondary importance in relation to the decision on the procurement model.

ITA's General Report on Conventional Tunnelling Method [2] gives a brief overview on the design procedures in underground construction in general and specifically for conventional tunnelling, whereas ITA's recommendation and guideline for tunnel boring machines (TBMs) [6] gives general information on the selection of the appropriate TBM.

As shown in Table 2, the design phase includes conceptual, preliminary, and final design phases. It is recommended that the selection of the tunnelling method be selected as early as possible, preferably at the end of the conceptual design, if clear differentiators can be identified. However, if the selection cannot be clearly made early in the design phase, the two methods shall be advanced through the preliminary design and if needed through the final design. Sometimes, it may not be possible to have a clear decision of the preferred method in the design phase and both methods are equally applicable, then the Owner may tender the contract with both methods allowing the selected Contractor to choose his preferred method. Obviously, all technical and environmental aspects shall be completely vetted for both methods.

6.1 GEOLOGY

The assessment of the ground conditions in the design phases is essential for the project definition and the construction methodology. The geological investigations are the Owner's responsibility. The investigations shall be planned and supervised by experienced engineering Geologists in close cooperation of both, the Design Engineer and the Owner.

Detailed ground investigations shall be started at the beginning of the design phase, when the general horizontal and vertical alignments of the future project are determined.

Nevertheless, also the determination of the alignment requires already a certain level of ground investigations (cf. 4.1).

The following well-known investigation methods are mainly employed to investigate the site conditions:

- Analysis of existing geological records, desk study (e. g. for structures already built in the same or similar geological formations)
- Engineering geological field mapping
- Exploratory drillings, galleries or shafts
- Field tests
- Laboratory tests
- Remote sensing
- Exploratory adits and galleries (pilot tunnels)
- Geophysical investigations

Based on this information a ground model (geological and geotechnical model) is established as the basis for the development of the future project. The ground model shows all factual data and the interpretation of the boundaries of the various strata. Ground behaviour in the various geological zones are determined in geotechnical interpretive report and/or baseline report by the Geologist and the Design Engineer.

As long as the ground conditions do not exclude one tunnelling method, the ground model and the geological/geotechnical reports shall describe the ground behaviour (incl. hazard scenarios) for both, mechanised and conventional tunnelling. The anticipated ground behaviour for mechanised tunnelling and/or for conventional tunnelling has a major influence on the selection of the tunnelling method.

As applicable the ground model implements the selected ground improvement methods and displays those for the various sections of the alignment. Ground classes and support classes for conventional tunnelling take the effects of ground improvement into account.

6.2 LOGISTICS

The boundary conditions on logistics have to be studied in detail in the design phase.

Whenever possible the Design Engineer shall develop logistic concepts (accessibility, transportation, laydown area, TBM assembly, installation areas, power supply, water supply, ventilation systems, etc.), which allow the application of mechanized or conventional tunnelling.

If compelling reasons of logistics exclude one or the other method, these reasons have to be clearly documented or provisions shall be made to overcome the difficulties of the logistics of one of the two methods. Cost of accommodating the logistics shall be taken into considerations.

6.3 QUALITY / FUNCTIONALITY

The required design life of the underground infrastructure defines the quality level needed.

Underground structures for transportation or water conveyance have often a required design life of 100 to 150 years.

The criterion of the functionality describes the restrictions of the future operation of the infrastructure as e.g. the required operation time and the allowed maximum time for maintenance and repair.

The quality/functionality criterion has a big influence on the general layout of an underground structure (e.g. double track tunnel vs. two single track tunnels for railway systems), the standard profiles (e.g. single lined tunnel vs. double lined tunnel) and therefore also influence the selection of the tunnelling methods.

6.4 TIME SCHEDULE

A time schedule is elaborated in each step of the design phase showing the overall design and construction time as well as the critical path for each of the two tunnelling methods. The time schedule is structured following the project breakdown structure and shows the details according to the requirements of each design stage.

It is recommended to show and to communicate the range of the forecast of the construction time for each tunnelling method as the result of the risk analysis, taking into account the uncertainties of the ground conditions.

The total construction time may become decisive for the selection of the tunnelling method based on the preliminary design.

6.5 COSTS AND FINANCING

The costs can be calculated for the first time on the base of a consolidated planning during the design phase. The accuracy of the estimate is directly related to the design level (preliminary design, final design).

Costs are usually calculated based on the main construction elements during the conceptual and preliminary design phase using bottom up approach by calculating the material quantities, labour requirements, productivity rates, equipment usage, cost of consumables, soft costs, profit, and suitable contingencies based on the risk profile. During the final design the costs are calculated based the detailed tasks of the construction and unit prices on the level of working positions.

Not only the basic cost for construction but also charges for planning, land acquisition, third party cost, etc. shall be considered.

Adequate contingencies for risks and the unknown have to be added also during the design phase.

The range of uncertainty of the cost estimate must be communicated.

Stable financing shall be established preferably at the end of the design phase defining the funding sources, the cash flow, and secured commitment for completion of the project.

Without a stable financing the tendering shall not be started.

Costs and financing can be decisive on the selection of the tunnelling method at this phase from the Owner's point of view. Nevertheless, it shall be highlighted that a tender process with all options might produce quite surprising results as the potential Contractors may evaluate risks differently than the Design Engineer.

6.6 OCCUPATIONAL HEALTH AND SAFETY

The level of work safety is defined in the design phase by the conceptual design (layout), the construction procedures, by the selection of the quality of the construction materials and by the definition of the required health and safety standards.

Both tunnelling methods have to fulfil the required national or international OHS-standards.

6.7 ENVIRONMENTAL ASPECTS

Similar to the aspects of safety at work, the aspects of environmental protection shall be defined within the design phase and shall be assessed for both tunnelling methods. The sustainability aspects of the two tunnelling methods shall be evaluated. Decisions shall be taken such as the reuse of the excavated materials for gravel production in order to reduce the need of the use of natural, alluvial resources and the standard of environmental protection during the construction phase.

It is recommended to follow the checklist of key topics to consider when managing an underground or tunnel project as published in the ITA report No. 3, "Underground Works and the Environment [4]". The main categories of the checklist are as follows:

- Management and Organisation Considerations
- Architectural and Landscaping Considerations
- Water Issues
- Air Issues
- Ground Contamination
- Noise and Vibrations
- Natural Biotopes
- Natural Resources

Both tunnelling methods shall fulfil the required environmental standards. Based on the selected alignment, the conceptual design of the project is refined and an Environmental Impact Study is performed taking into consideration the tunnelling methods, showing the impact of the project on the environment but also the proposed mitigation measures. The proposed mitigation measures will have an impact on the cost and time schedule.

6.8 PUBLIC ACCEPTANCE

Public discussions shall be initiated as early as possible to obtain the public and local authorities and elected officials support. It is intensified during the end of the design phase and especially during the legal proceedings for the construction permit and start of actual construction works. It shall also continue through the construction process to maintain the public support.

Environmental, construction impact, political and financial aspects are often the main subjects of discussion with various points of views depending on the stakeholders.

Compromises are often found before the initiation of the legal process to obtain the construction permit if long lasting legal processes or construction interruption is to be avoided. The early implementation of project-related public outreach panels, representing the interests of the various stakeholders is highly recommended. The lack of public acceptance may hinder the realization of underground structures.

Figure 16 : Open site event attract all generations (© AlpTransit Gotthard Ltd.)

Once under construction, underground constructions attract the interest of many people (Fig. 16), who are generally fascinated when they have the opportunity to visit the often unknown world of underground construction. Open minded relations to the different stakeholders may help to get the acceptance of the majority of affected people.

6.9 MARKET CONDITIONS

The Owner shall check, whether the market applicable to the selected design is able to support the selected tunnelling method. The Owner shall prepare the design for a TBM-drive and a conventional drive if both solutions are equivalent and the market is able to deliver both solutions. The Owner may tender both methods and allow the Contractors to choose their preferred method. However, if this approach is to be undertaken, all issues shall be vetted out thoroughly from the technical aspects as well as environmental issues and public acceptance.

6.10 EXPERIENCES

Experienced tunnel engineers shall be responsible for the design of underground projects.

Specific experience related to the tunnelling method is required. It is recommended to the Owner to carry out a design check of the project after each design phase by independent, experienced design checkers (expert design checking). The independent design checking engineers (Design Checkers) shall be highly experienced with the selected tunnelling methods and could be assigned from foreign countries if needed.

6.11 PROCESSES

The construction permit shall be obtained according to the local requirements of the project area. As long as the Owner has no mandatory reasons to prefer one or the other method, he shall also ask for a construction permit for both methods (e.g. rig area for segment factory, management of the muck, explosive handling or noise emissions) as long as the local legislation allows such a procedure.

7 >> Preparation for construction (tender phase)

The tender phase is generally crucial for the selection of the tunnelling method. It is recommended to follow the various ITA recommendations during this phase, mainly the ITA

Contractual Framework Checklist for Subsurface Construction Contracts [7] and the Guidelines on contractual aspects of conventional tunnelling [8]. At this stage, if the Design Engineer was able to determine the preferred tunnelling method, the tender documents shall be prepared in accordance with the selected method. Otherwise, if no clear preferred method can be identified, the Owner may opt to tender both methods leaving the selection of the tunnelling method to the winning Contractor. In this case, the tender documents shall address issues related to both methods.

7.1 GEOLOGY

The Owner transfers his knowledge of the ground conditions to the future Contractor in the tender phase. The tender design documents shall contain among other documents [1] the following documents related to the ground conditions:

- a summary of the results of geological and geotechnical investigations, the Owner's interpretation of the results and all raw data from the exploration programme for the bidders' own evaluation.
- a description of the ground and the associated key parameters
- a description of the possible hazards, the relevant influencing factors, the risk analyses performed, and the underlying geotechnical model
- a description and anticipated performance of any improved ground and reasoning for the selection of the specific ground improvement methods (dewatering, grouting, ground freezing)
- a description of any additional methods for the use of controlling surface, subsurface and structure (mainly buildings and utilities) deformations including specialty tunnel presupport methods, compensation grouting, and underpinning
- the specification of excavation and support, relevant scenarios considered, analyses applied, and results
- a baseline construction plan
- detailed specifications concerning the baseline construction plan (including measures to be determined on site if any)
- the determination of excavation and support classes, their distribution along the alignment
- baseline geotechnical and interpretive reports

The baseline construction plan in the tender design documents describes the expected ground conditions (geological model with distribution of ground types in the longitudinal section), the excavation and support types (round length, excavation sequence, overexcavation, invert distance, support quality and quantity, ground improvements, etc.) as well as zones, where specific construction requirements have to be observed. The baseline construction plan also has to contain clear statements describing which measures cannot be modified during construction, as well as the criteria and the actions for possible modifications and adjustments during construction (e.g. adaptation of the excavation sequence, the support types or round lengths in conventional tunnelling). Experience has shown that full disclosure of geotechnical information would reduce the risk to both the Owner and the Contractor and thus the project costs. Therefore, it is important for Owners to invest in a comprehensive geotechnical program during the early design phases, independent from the type of procurement.

The information on the ground conditions shall be included in the contract documents. The intent of the disclosure of geotechnical information is to share and allocate construction risks between the Owner and the Contractor properly.

A geotechnical data report contains all the raw data, including boring logs, records of measurements, and field and laboratory tests and their results. It is recommended that the Geotechnical Data Report be made a contract document in order to provide the potential

bidders with the same information that the Design Engineer used in the design.

In an interpretive geotechnical report, the Design Engineer's interpretation of the data, anticipated ground behaviour, and the identification of the conditions which affect the design and which may impact on construction would be shown. The interpretive report shall be provided to the potential bidders. The contractual status of the interpretative geotechnical report depends on the procurement model (contractual document in the case of DBB, for information in DB-contracts).

A separate geotechnical baseline report establishes a baseline on the quantitative values for selected conditions anticipated to have great impact on construction. These values are established through technical interpretation of the data and financial considerations of risk allocation and sharing between the Owner and the Contractor. The advantages of this report are ease of administration of contractual clauses, unambiguous determination of entitlement,

clear basis of Contractor's bid, and clear allocation of risk between the Owner and the Contractor. If baseline values are defined optimally, this can result in minimising contingency of the bidders while limiting the Owner's risk to a reasonable level.

The tender documents have to show the geological and geotechnical data on the same level for both tunnelling methods if both tunnelling methods are equally feasible and if the Owner allows both methods.

7.2 LOGISTICS

The boundary conditions and prior agreements reached on logistics shall be transferred to the future Contractor in the tender documents.

If compelling reasons (e.g. restriction in the construction permit) exclude one or the other method, these reasons have to be documented in the tender documents in order to exclude Contractor's alternatives.

The Contractor has to prove his ability to organise his supply chain in such a way, that he is able to reach his offered performance. The Contractor's ability to fulfil the offered contractual performance shall be an award criterion.

7.3 QUALITY/FUNCTIONALITY

The Owner defines the requirements of final quality/functionality, the target values and the required quality control system in the tender documents.

Quality/Functionality is not related to the tunnelling method at this stage, but the more the Owner departs from the design process (for design-build contract or PPP procurement models) the more detailed the performance specifications of the final product must be defined at the time of tender.

The Contractor shall prove his ability to fulfil the required quality standards, the target values and the required control system with his offer.

The Contractor's ability to fulfil the required quality standards shall be an award criterion.

7.4 TIME SCHEDULE

The Contractor calculates his contractual advance rates according to the Owner's information on the ground conditions (see 6.1) and his working cycle. The excavation rate makes part of the entire performance offered by Contractor to meet the time schedule. The Contractor's ability to fulfil the offered contractual performance and to reach the milestones fixed by the Owner shall be an award criterion (see 6.2). However, advance rates, and the working cycles are part of the Contractor's means and methods and shall be solely his responsibilities.

7.5 COSTS AND FINANCING

Costs can be verified at stage of the final design by pricing of the bill of quantities from experiences of the Owner or his Design Engineer. This calculation creates the Owner's benchmark in the tender process. If the award is based on a lump sum price, the Owner shall request the cost breakdown and the quantities to verify that all issues have been included and that the cost breakdown structure is properly structured to meet the Owner's goals and quality standards.

Adequate contingencies for risks and the unknown have to be added also at this phase of the project. Based on the contractual structure, contingencies could be controlled by the Owner or the Contractor or a combination manner in which a structured formula for access the set aside contingency.

The range of uncertainty of the cost estimate shall be also communicated to the sponsor or the funding agency at this stage of the project.

The financing of the project shall be fixed at this stage of the project. Tendering without a stable financing is not recommended.

7.6 OCCUPATIONAL HEALTH AND SAFETY

The Owner's requirements on occupational health and safety are transferred to the future Contractor with the tender documents. The Owner has to define the required standards, the target values and the required control system.

It is recommended to require the Contractor to provide the occupational health and safety plan in his offer and measures in the bill of quantities [10]. In addition, if special requirements by Owner are needed, they shall be included in the tender documents.

The Contractor shall also prove his ability to fulfil the required standards, the target values and the required control system in his offer.

Occupational health and safety is not related to the tunnelling method at this stage.

7.7 ENVIRONMENTAL ASPECTS

The Owner's requirements on environmental aspects and commitments made during the design phase shall be transferred to the future Contractor with the tender documents. The Contractor shall prove his ability to fulfil the required standards, the target values and the required control system in his offer.

Environmental aspects shall be an award criterion and may decide on the tunnelling method at this stage.

7.8 PUBLIC ACCEPTANCE

Measures for public relations during construction shall be included in the tender documents (facilities for visitor centres, information points, open site visits) shall be included in the tender documents regardless of the tunnelling method.

7.9 MARKET CONDITIONS

The market forces decide on the future tunnelling method during this phase. The Owner shall tender or at least allow offers for both methods as long as no compelling reasons favour one of the two methods in advance.

If both methods are of equal ability and no one method is favoured over the other, then the tender documents shall describe both methods in an equivalent level.

7.10 EXPERIENCES

If both tunnelling methods are technically feasible, experience with the tunnelling method offered by the Contractor shall be considered in the award process. The best experiences may become decisive. An experienced contractor with experienced work force is required for a successful construction of underground structures. The Contractor's experience (and his staff) shall be an award criterion.

7.11 PROCESSES

Costs can become the decisive criterion on the selection of the tunnelling method if both methods are technically feasible. The most economic or best value offer (best combination of quality and price) shall get the contract award. Quality in this context means Contractor's measures to ensure the completion of the project milestones, the type and quality of the site organisation, measures to ensure the project functionality, type of the quality assurance, mitigation measure for environmental protection, risk management and mitigation measures

etc. (see 6.2 ff.).

8.1 GEOLOGY

The primary support measures for conventional tunnelling and tunnel drives with open TBMs are chosen on site out of the provisions of the detailed (final) design after the thorough recognition of the ground conditions. It is advisable that the recognition and the relevant assessment of the ground conditions are carried out by experienced Geologists, the Contractor's and the Owner's representative (in the case of DBB procurement).

It shall be noted that traditionally, the ground conditions and the anticipated ground behaviour during construction is the responsibility of the Owner; the Owner owns the ground.

In this regard, if the actual ground conditions are different than anticipated requiring additional measures or changes in the construction method, the Owner shall be responsible and the Contractor shall be compensated for additional costs or time delay in accordance with the contractual conditions.

The ground conditions are one of the key factors for the daily advance rate and shall be taken into consideration from the design through the construction phases.

In the case of unforeseen ground conditions (Fig. 17), supplementary construction measures shall be applied. Conventional tunnelling allows generally more flexible reaction on changed ground conditions, as the excavated cross section can be changed and the tunnel face is normally accessible in the case of necessity.

Figure 17 : Unforeseen ground conditions due to rock burst phenomena© ATG

TBMs again must be designed to tackle the worst expected ground conditions. Recent progress in technology application provided the mechanised excavation method with increased flexibility and efficiency to be able to handle different ground conditions, difficult ground conditions, and mixed face ground conditions. Still, in case of unforeseen worse ground conditions conventional tunnelling is often used as a supplementary measure for TBM drives in the case of difficult ground conditions (using by-passes or auxiliary shafts).

Only in very rare cases the tunnelling method has been switched totally.

8.2 LOGISTICS

The Contractor is responsible for the logistics on site (Fig. 18), regardless the tunnelling method selected. TBM drives, due to their often high advance rates, will cause a comparable higher demand on logistics for transportation, whereas conventional tunnelling has high requirements on the logistics of the various steps in each round (drilling, blasting, mucking, primary support).

Figure 18 : Rig area of a major tunnel project - the heart of logistics© ATG

8.3 QUALITY/FUNCTIONALITY

The excavation is the prerequisite for the placement of the final lining and therefore the achievement of the lifetime requirements of the underground structure.

There are no indications on a generally different level of quality/functionality in relation to the tunnelling method. However, over-excavation associated with conventional tunnelling would often require filling the over-excavation with concrete or sprayed concrete which may impact (negatively or positively) the long term performance of the facility.

8.4 TIME SCHEDULE

Time management is of crucial importance for the success of the project.

Many contracts follow the principle that the ground belongs to the Owner. Accordingly, the Owner is responsible for time schedule delays if the ground conditions deviate from the contractual conditions.

On the other hand, the Contractor is responsible for the achievement of the contractually agreed performances as long as the ground conditions remain within the contractually defined conditions.

There are no indications on generally different development of the time schedules in relation to the tunnelling method. However, the time schedule and meeting Owner defined milestones will be different for the different tunnelling methods.

8.5 COSTS AND FINANCING

The cost changes during construction is mainly driven by the following parameters:

- Changes of the project requirements (e.g. higher standard of safety, environmental protection or compromises with stakeholders)
- Change orders from the Owner
- Ground conditions outside the contractually agreed limits
- Unexpected changes in the market
- Progress rates slower than planned

Changes of the project requirements and change orders require a decision of the Owner's organisation. The cost changes due to these factors can be influenced by the Owner.

Changed ground conditions outside the contractual limits and unexpected changes in the market remain outside the influence of the Owner. However, it is the Owner's responsibilities for the ground conditions, while it is the Contractor's responsibilities for changes in the market conditions such as unavailability of locally qualified workers, or changes in cost of energy or fuel, etc.

8.6 OCCUPATIONAL HEALTH AND SAFETY

The requirements of occupational health and safety (example Fig. 19) have to be fulfilled each day independently of the selected tunnelling method. There are no indications for a systematically different level of the occupational health and safety standards in relation to the tunnelling method, though the conditions within the TBM back-ups are more factory-like and fully designed workplaces at every work position while in the conventional tunnelling the workers are more exposed to the ground at the tunnel face.

Figure 19 : Modern refuge chamber© ATG

The national standards regarding occupational health and safety shall be fulfilled in any case.

ITA Working group 5 has published several documents on the actual state of the art in the occupational health and safety. It is highly recommended to apply ITA's reports such as:

- Safe working in tunnelling [9]
- Guidelines for good occupational health and safety practice in tunnel construction [10]
- Guidance on the safe use of temporary ventilation ducting in tunnels [11]
- Guidelines for good working practice in high pressure compressed air [12]
- Guidelines for the provision of refuge chambers in tunnels under construction [13]

8.7 ENVIRONMENTAL ASPECTS

The environmental requirements (Fig. 20) shall be fulfilled each day independently from the selected tunnelling method. Nitrite and rests of explosives are the main issues for conventional tunnelling. Conditioners and hydrocarbons are the main items for TBM drives.

There are no indications for a systematically different level in the fulfilment of the environmental requirements in relation to the tunnelling method.

Figure 20 : Use of particle filters is part of the concept for environmental protection (© AlpTransit Gotthard Ltd)

8.8 PUBLIC ACCEPTANCE

Tunnel construction generally attracts high public interest independently from the tunnelling method. Public acceptance can be achieved with organized site visits (public days of the "open site" (Fig. 21)), visitor centres, information points, webpages etc.

8.9 MARKET CONDITIONS

Market conditions are relevant for the Contractor in this phase (suppliers, workers, engineers) and depend on the local conditions and the capabilities of the resources for the tunnelling method. The selection of the tunnelling method shall take into consideration the market condition at the time of the selection and the future trend of the market conditions such as competing projects or potential changes in supply chains.

Figure 21 : Stakeholder management with the youngest in UK © A3 Hindhead Tunnel

8.10 EXPERIENCES

The experiences for future projects are gained with each underground project under construction. Monitoring, reporting and documentation are of highest importance during the construction phase. TBM data can be collected and evaluated by sophisticated monitoring systems and used for improvement of the technology.

Conventional tunnelling data can also be collected for further analysis. For example, similar systems as on TBMs exist also for modern drilling jumbos.

The Owner shall organize the evaluation strategy of the collected data during the tender phase independent from the selected tunnelling method. There is generally no difference in gaining further experiences in relation to selection of the tunnelling method.

8.11 ORGANISATION AND PROCESSES

Both tunnelling methods require highly sophisticated processes on the Owner's and the Contractor's side which shall be coordinated in a project specific quality management system. The requirements on processes and organisation are needed regardless to the tunnelling method selected.

9 >> Brief conclusion

The selection of the tunnelling method depends on the fulfilment of many requirements. The various requirements shall be analysed according to their relevance in each design phase.

Each project shall be evaluated on a case by case basis taking into considerations the project specific conditions and evaluation criteria.

It is preferred that the selection process of the tunnelling method be made during the design phases; however, often there is no obvious favourable method for the specific project. In this case it is recommended that the bidders be allowed to bid either of the two methods. If this approach is selected, the owner's engineer shall develop the tender documents allowing both methods and providing equal relevant information to allow the bidders to make informed decision on the selection of the tunnelling method.

Generally, there is no quick solution for the decision on the selection of the tunnelling method. As shown in the earlier chapters of this document, the Owner can leave this decision to the market conditions, as long as he has no compelling reasons to prefer one or the other method. There are two options:

a. The Owner tenders both methods to the same level of information in the tender documents

b. The Owner tenders only his preferred method but allows Contractor's alternatives for the second method

In both cases the tender documents have to contain all information related to the selection of the tunnelling method on the same level for both methods. Tab. 3 shows the various tasks which shall be considered in order to select the most suitable tunnelling method in relation to the main project requirements.

10 >> References

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[2] General Report on Conventional Tunnelling Method (Report of ITA WG 19), ITA Report No. 002; ITA-AITES, 2009

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[5] Guidelines for tunnelling risk management, International Tunnelling Association, Working Group N°. 2; Tunnelling and Underground Space Technology 19 (2004)

[6] The ITA Contractual Framework Checklist for Subsurface Construction Contracts, (Report of ITA WG 3), ITA-AITES, 2011

[7] The ITA Contractual Framework Checklist for Subsurface Construction Contracts, ITA Report No. 006, ITA-AITES, 2011

[8] Guidelines on contractual aspects of conventional tunnelling; ITA Report No. 013; ITA-AITES, 2013

[9] Safe working in tunnelling", ITA booklet, ITA-AITES, 2012

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ITA Report No. 001, ITA-AITES, 2008

[11] Guidance on the safe use of temporary ventilation ducting in tunnels,

ITA Report No. 008, ITA-AITES, 2011

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[13] Guidelines for the provision of refuge chambers in tunnels under construction, ITA Report No. 014, ITA-AITES, 2014

[14] Final report of the Federal commission for the reformation of major projects, German Federal Ministry of Transportation, 2015

[15] A Code of Practice for Tunnel Works, ITIG/ITA-AITES, 2012

[16] Conditions of Contract for Construction for building and Engineering Works designed by the Employer (Red Book), FIDIC, 1999

11 >> List of typical and exceptional projects

This report contains contributions by the various Members of Working Group 14 and Working Group 19 over the period 2013 – 2015. The animators Lars Babenderde (WG 14) and Heinz Ehrbar (WG 19) coordinated the work. Alexandre Gomes was the Tutor of WG 19 and Rick Lovat was the tutor of WG 14.

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Switzerland	ANAGNOSTOU, Georg	Swiss Federal Institute of Technology
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11 >> List of typical and exceptional projects

CATEGORY	ID	PROJECT name	PROJECT section	PROJECT purpose	DIMENSION excavated diameter [m]	DIMENSION excavated cross-section [m2]	DIMENSION cross-section final tunnel [m2]	DIMENSION lenght [km]	CHARACTERISTICS water	CHARACTERISTICS geology	CHARACTERISTICS other	YEAR OF COMPLETION	TUNNELING METHOD tendered	TUNNELING METHOD executed	COUNTRY
typical	1	Wienerwald Tunnel		Railway	10.7		48	2 + 11		rock		2012	Conv & TBM	Conv & TBM	Austria
typical	2	Lainzer Tunnel		Railway	- 13 m	80 to 140	75	12.8		rock		2012	Conv	Conv	Austria
typical	3	Unteres Intall		Railway	13.0					rock		2012	Conv & TBM	Conv & TBM	Austria
typical	4	Koraim Tunnel	Lot KAT 1	Railway		82	43	2.0		rock		2022	Conv	Conv	Austria
typical	4	Koraim Tunnel	Lot KAT 2 TBM	Railway	9.9	78	43	17.2	yes	hard rock		2022	TBM	TBM	Austria
typical	4	Koraim Tunnel	Lot KAT 2 Conv	Railway		82	43	2.1		rock		2022	Conv	Conv	Austria
typical	4	Koraim Tunnel	Lot KAT 3 TBM	Railway	9.9	78	43	10.5	yes	hard rock		2022	TBM	TBM	Austria
typical	4	Koraim Tunnel	Lot KAT 3 Conv	Railway			43	0.7		rock		2022	Conv	Conv	Austria
exceptional	5	Semmering Base Tunnel		Railway			43	19 + 8	yes	rock		2025	Conv & TBM	Conv & TBM	Austria
typical	7	Albvorland Tunnel		Railway	11.3	100	58	8.2		rock	karst	2021	Conv	TBM	Germany
typical	8	Bossler Tunnel		Railway	11.4	102	58	5 + 3		rock	karst	2021	Conv & TBM	Conv & TBM	Germany
typical	9	Steinbül Tunnel		Railway	11.3	100	58			rock	karst	2021	Conv	Conv	Germany
typical	10	Filder Tunnel		Railway	10.8	92	58	9.0	minor	rock	swelling	2021	Conv & TBM	Conv & TBM	Germany
typical	11	Albabstiegl Tunnel		Railway	11.3	100	58	5.9							Germany
exceptional	12	Herrentunnel		Road	11.2	99	n.a.	2 x 0.9	3,5 bar	softground		2005	PPP (free)	TBM	Germany
exceptional	13	Lötschberg Base Tunnel	Lot Steg / Raron	Railway	9.4	69	47	10,2		hard rock		2007	Conv & TBM	Conv & TBM	Switzerland
exceptional	14	Lötschberg Base Tunnel	Lot Ferden	Railway		65 to 69	47	7.4	110 bar	hard rock	natural asbestos	2007	Conv	Conv	Switzerland
exceptional	15	Lötschberg Base Tunnel	Lot Mitholz	Railway		65 to 69	47	17.0	70 bar	hard rock	karst	2007	Conv	Conv	Switzerland
exceptional	16	Gotthard Base Tunnel	Lot Erstfeld	Railway	9.5	72	41	7.8	40 bar	hard rock		2016	TBM	TBM	Switzerland
exceptional	17	Gotthard Base Tunnel	Lot Amsteg	Railway	9.5	72	41	11.3	100 to 200 bar (initial)	hard rock		2016	Conv & TBM	TBM	Switzerland
exceptional	18	Gotthard Base Tunnel	Lot Sedrun	Railway	9.5 to12	85 (35 to 320)	41	8.6	100 to 200 bar (initial)	soft & hard rock	squeezing	2016	Conv	Conv	Switzerland
exceptional	19	Gotthard Base Tunnel	Lot Faido	Railway	9.4	69 (17 to 328)	41	13.4	100 to 200 bar (initial)	hard rock	squeezing	2016	Conv & TBM	Conv & TBM	Switzerland
exceptional	20	Gotthard Base Tunnel	Lot Bodio	Railway	8.9		41	16.0	minor	hard rock		2016	TBM	TBM	Switzerland
typical	21	Ceneri Base Tunnel	Vigana	Railway		90 to 350	41	0.8		softground/ rock		2020	Conv	Conv	Switzerland
typical	22	Ceneri Base Tunnel	Sigirino	Railway		48 to 87	41	14.1		rock		2020	Conv & TBM	Conv	Switzerland
typical	23	Ceneri Base Tunnel	Vezia	Railway		81	41	0.3		rock		2020	Conv	Conv	Switzerland
exceptional	24	Bypass Tunnel Flims	Flimsterstein	Road		90 to 120	70	2.9 + 0.5	200 to 700 Vs	rock	karst	2009	Conv	Conv	Switzerland
typical	25	Cross City Line Zurich	Weinberg Tunnel	Railway	11.3	100	65	4.8		rock	river undercrossing	2014	TBM	TBM	Switzerland
typical	26	Bypass Tunnel Kueblis		Road		99 to 120	70	3.4		rock		2016	Conv	Conv	Switzerland
typical	27	Bypass Tunnel Saas		Road		80 to 110	70	2.6		rock		2011	Conv	Conv	Switzerland
typical	28	Bypass Tunnel Roveredo	Tunnel San Fedele	Road		100 to 158	70	2.1 + 2.5		rock	softground in portal zone	2016	Conv & TBM	Conv & TBM	Switzerland
typical	29	TRunnel Visp		Road						rock		2019	Conv	Conv	Switzerland
exceptional	30	HEPP Machu Pichu	Tailrace River Crossing	Water	3.2			2 x 0.120	5 bar	softground		2000	TBM	TBM	Peru
exceptional	31	Tunnel Weighbridge	Watertunnel	Water	3.2			0.7	2 bar	rock	fractured	2002	TBM	TBM	Jersey Isld
exceptional	32	Lake Mead Intake N°3		Water	7.8			4.8	13 bar	various		2015	TBM	TBM	USA
exceptional	33	Tuen Mun to Chek Lap Kok	Junction section East	Road	17.6			0.8	5 bar	softground		20xx	TBM	TBM	Hong-Kong
exceptional	34	Alimieti Madhava Reddy Project		Water	10.0			43.5	to 300 MPa	hard rock		20xx	TBM	TBM	India

typical

exceptional

This list will be extended in future reports.

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Workshop on NATM & TBM Tunnelling incl. Risk Management

1 - How to deal with uncertainties in tunnelling?

6 – 8th February 2018, New Delhi, India

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founded 2007, 12 Employees

Cost and Risk Management:

- Risk Management
- Cost Estimation, Cost Validation
- Project Cost Control
- Tunnelling, Ground Engineering, Infrastructure
- Software Development
- Research & Development

RIAAT
Risk Administration and Analysis Tool

Extensive consulting experience for major infrastructure projects in Austria, Germany, Switzerland, North and South America.

Projects

Koralm Base Tunnel

Source: http://www.koralmtunnel.eu

With a total length of 32.8 km and a maximum cover of 1,250 m the base tunnel will traverse the Koralpe mountain range and will connect the Austrian states of Styria and Carinthia.

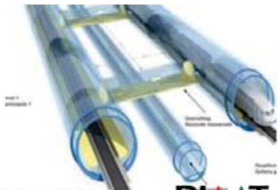
Services:	Probabilistic risk assessment, Moderation of the process during planning and construction stage
Project costs:	approx. $ 2.1 Billion

RIAAT

Brenner Base Tunnel

The Brenner Base Tunnel is the main element of the new Brenner railway from Munich to Verona. At 64 km, it is the longest underground railway connection in the world, a pioneering work of engineering and it will markedly improve passenger travel and freight transport through the heart of Europe.

Services:	Support and validation probabilistic risk assessment
Project costs:	approx. $ 12 Billion



Source: http://www.bbt-se.com/projekt/bbt

RIAAT

Subway New York: Canarsie Tunnel

New York City Transit

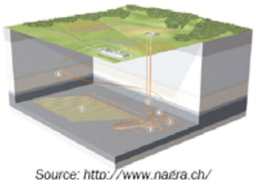
Flooding caused by Superstorm Sandy inundated the Canarsie Tunnel with seven million gallons of salt water. The rehabilitation includes upgrading of the Canarsie Tunnel facilities from 1st Avenue Station in Manhattan to Bedford Avenue Station in Brooklyn and three substations.

Service: Risk assessment, identifying and quantifying risks for project cost and schedule, quantify potential reduction in risk through mitigation.

Source: New York Times

RIAAT

NAGRA - Swiss National Cooperative for the Disposal of Radioactive Waste



Source: http://www.nagra.ch/

Safe long-term disposal of radioactive waste in deep geological repositories is a challenging task that NAGRA has committed to implementing in the interests of man and the environment.

Services: Probabilistic cost estimation and risk analysis, software development, process development, staff training

nagra.

RIAAT

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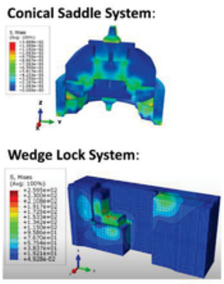
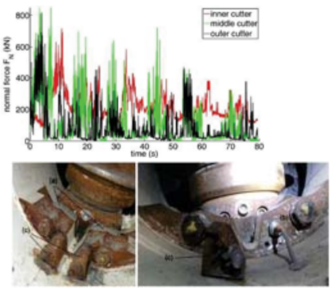
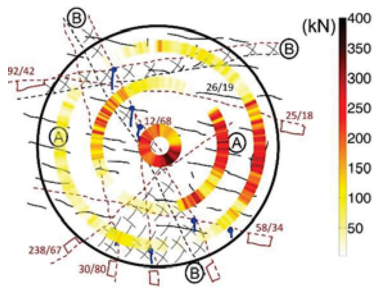
2014 – 2016: Construction Manager at Züblin Ground Engineering

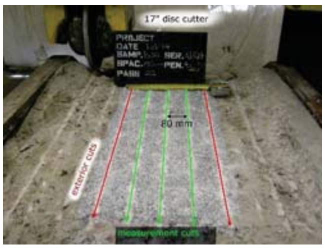
2017 – today: Senior Expert for Cost and Risk Management at RiskConsult

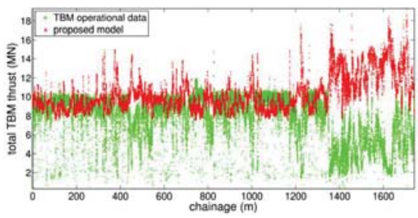
Research – TBM:











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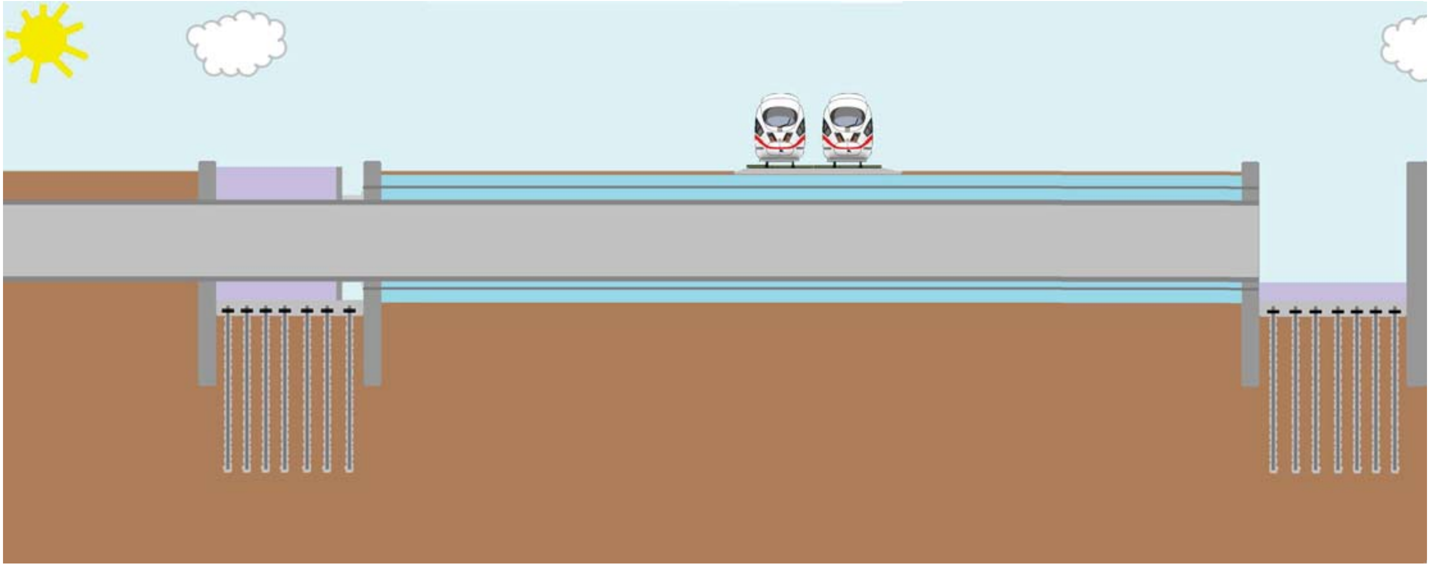
Construction Management – Major Risks:



There is no Tunnelling Project without risk!

- Major delays
- Major monetary losses as a result of delay
- No personal damage / injuries!

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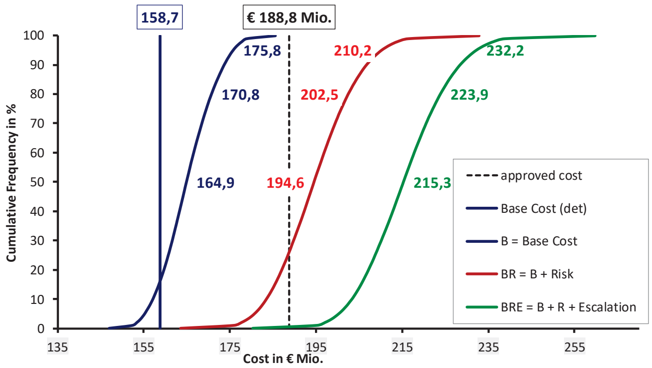
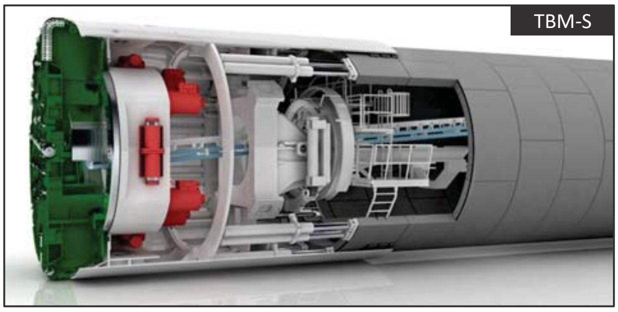
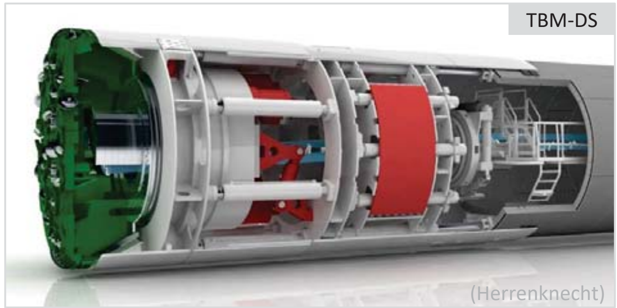
2017 – today: Senior Expert for Cost and Risk Management at RiskConsult

Cost and Risk Management:

- Transparent & robust budgeting
- Comparison of Alternatives





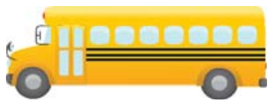


What is Risk Management?

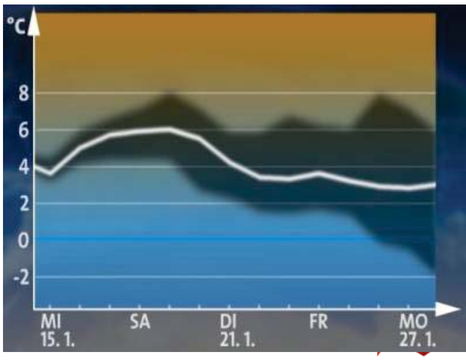
What is Risk Management?

„Risk Management“ can mean a lot of things!

- When do I have to leave the house to catch the bus?



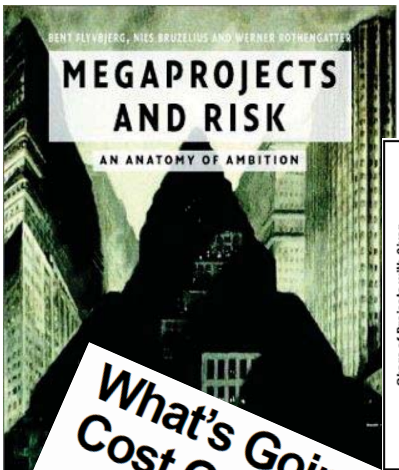
- What is the chance of rain? Should I bring an umbrella?



(ARD)

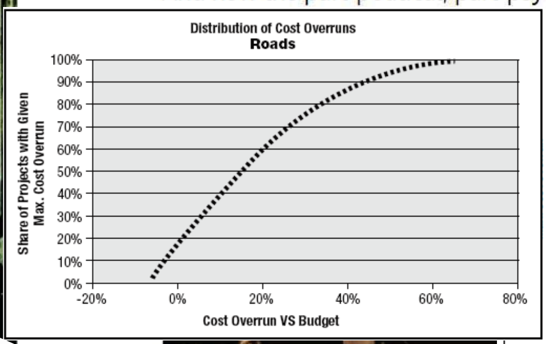
Cost Overrun / Time Overrun

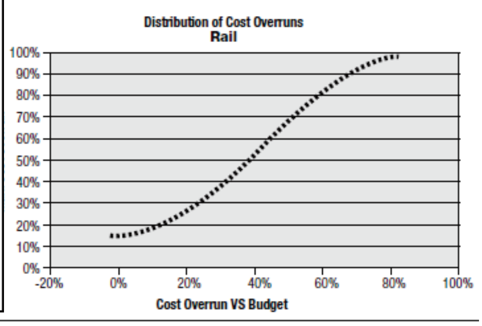
Bent Flyvbjerg

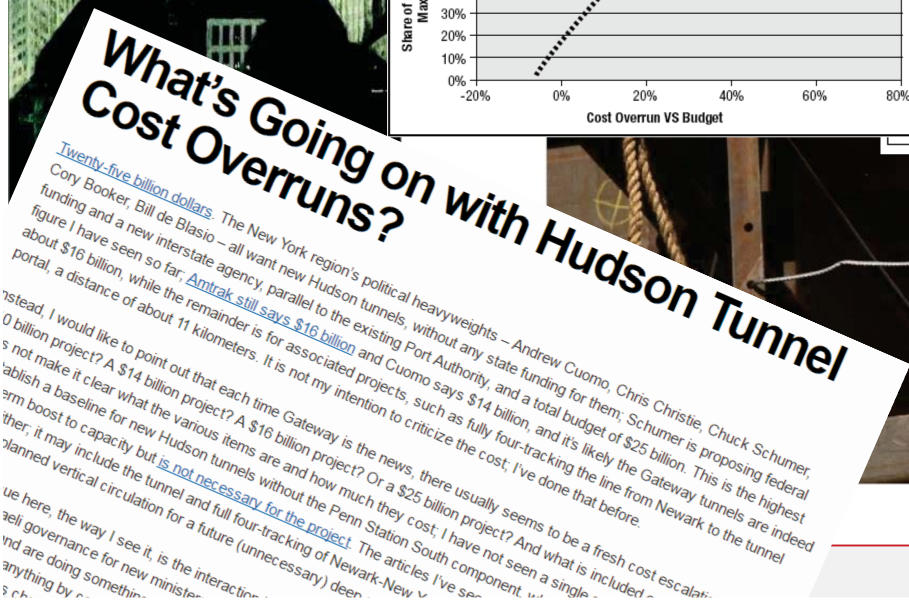


Why Mega-Projects Always End Up Costing More Than Expected

And how the part-political, part-psychological problem can be avoided.







What's Going on with Hudson Tunnel Cost Overruns?

Twenty-five billion dollars. The New York region's political heavyweights – Andrew Cuomo, Chris Christie, Chuck Schumer, Cory Booker, Bill de Blasio – all want new Hudson tunnels, without any state funding for them; Schumer is proposing federal funding and a new interstate agency, parallel to the existing Port Authority, and a total budget of $25 billion. This is the highest figure I have seen so far; Amtrak still says $16 billion and Cuomo says $14 billion, and it's likely the Gateway tunnels are indeed about $16 billion, while the remainder is for associated projects, such as fully four-tracking the line from Newark to the tunnel portal, a distance of about 11 kilometers. It is not my intention to criticize the cost; I've done that before.

nstead, I would like to point out that each time Gateway is the news, there usually seems to be a fresh cost escalati... 0 billion project? A $14 billion project? A $16 billion project? Or a $25 billion project? And what is included ... s not make it clear what the various items are and how much they cost; I have not seen a single ... ablish a baseline for new Hudson tunnels without the Penn Station South component, ... erm boost to capacity but is not necessary for the project. The articles I've se... ther; it may include the tunnel and full four-tracking of Newark-New Y... planned vertical circulation for a future (unnecessary) deep...

ue here, the way I see it, is the interaction ... eli governance for new minister... nd are doing somethin... anything by c...

What is Risk Management?

Risk Management means to us:

- Transparent cost, transparent schedule
- Robust budgeting
- Promoting an open risk culture where Risk Management is a team effort
- RM-Process as part of project management: State of the art, hands on, Integration of Cost, Opportunities, Threats and Schedule in one process

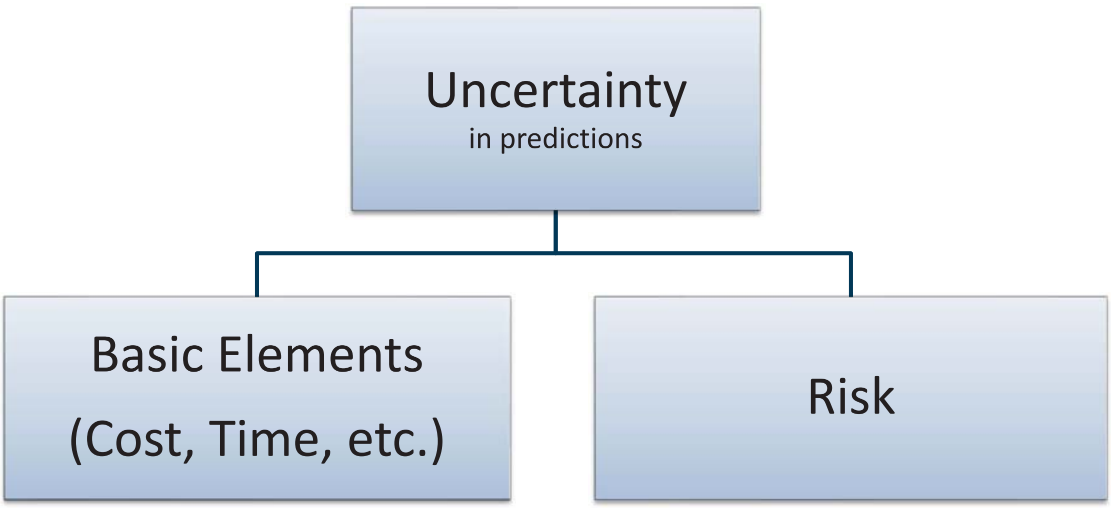
	Owner	Contractor
Project	✓	(✓)
Organisation	(✓)	(✓)

Owner's Strategies

- A risk-based approach gives a better understanding during design of potential costs and mitigation strategies which help manage the design to meet available budget
- Risk definition and characterization allows better contract documents with a more equitable sharing of risks
- Sharing of risk registers with contractors can "level the playing field" – more realistic bids with less "contingency"
- Owner's definition of specific risks can clarify who owns the risk as reflected in the owner's risk management plan
- Owner's definition of specific risks can help avoid "unanticipated" events that can lead to disputes, claims and litigation.

Risk-based cost estimating for construction allows:

- A better understanding of potential cost to inform the contractor's bidding strategy re potential profitability
  - Whether to bid
  - What level to bid
  - What potential profit/loss may be possible
- A better understanding of potential risks will allow:
  - Understanding who "owns" each risk
  - More specific risk management plans in construction
  - More specific risk mitigation and claims avoidance procedures



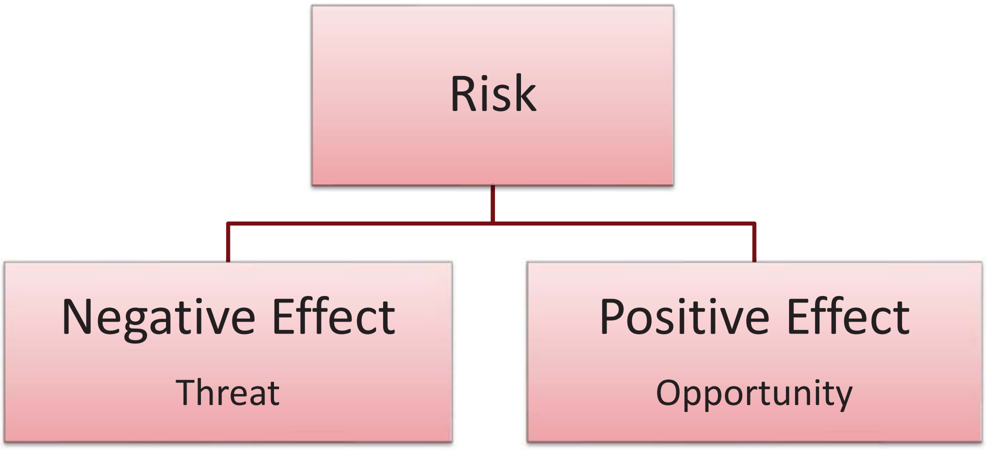
→ Will always occur (e.g. elements in a cost estimation)

→ Exact quantity, price or time is uncertain

→ Probability of occurence (might or might not occur)

→ Consequences (cost, time, etc.) are uncertain

Risk – Threats and Opportunities



Risk definition by ISO 31000:

Risk is the effect of uncertainty on objectives

NOTE: An effect is a deviation from the expected – positive and/or negative → THREATS & OPPORTUNITIES

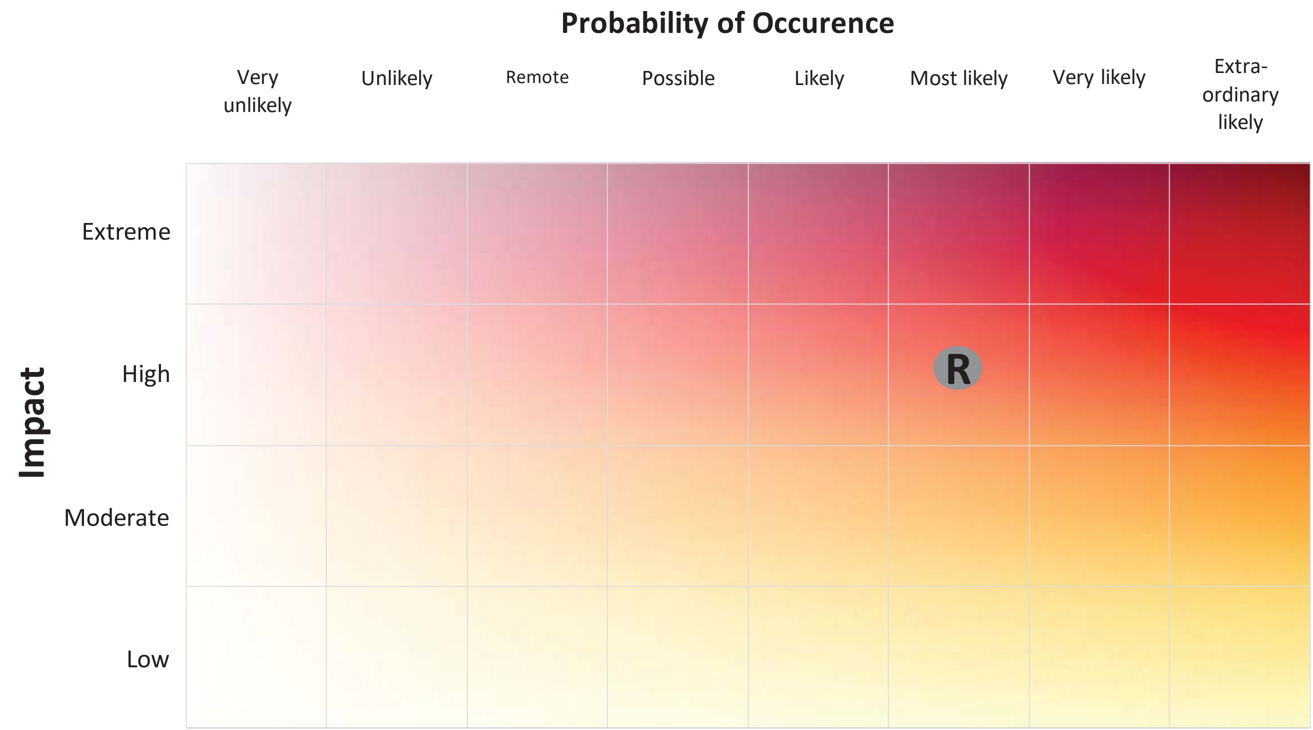
Qualitative

&

Semi-quantitative Approaches

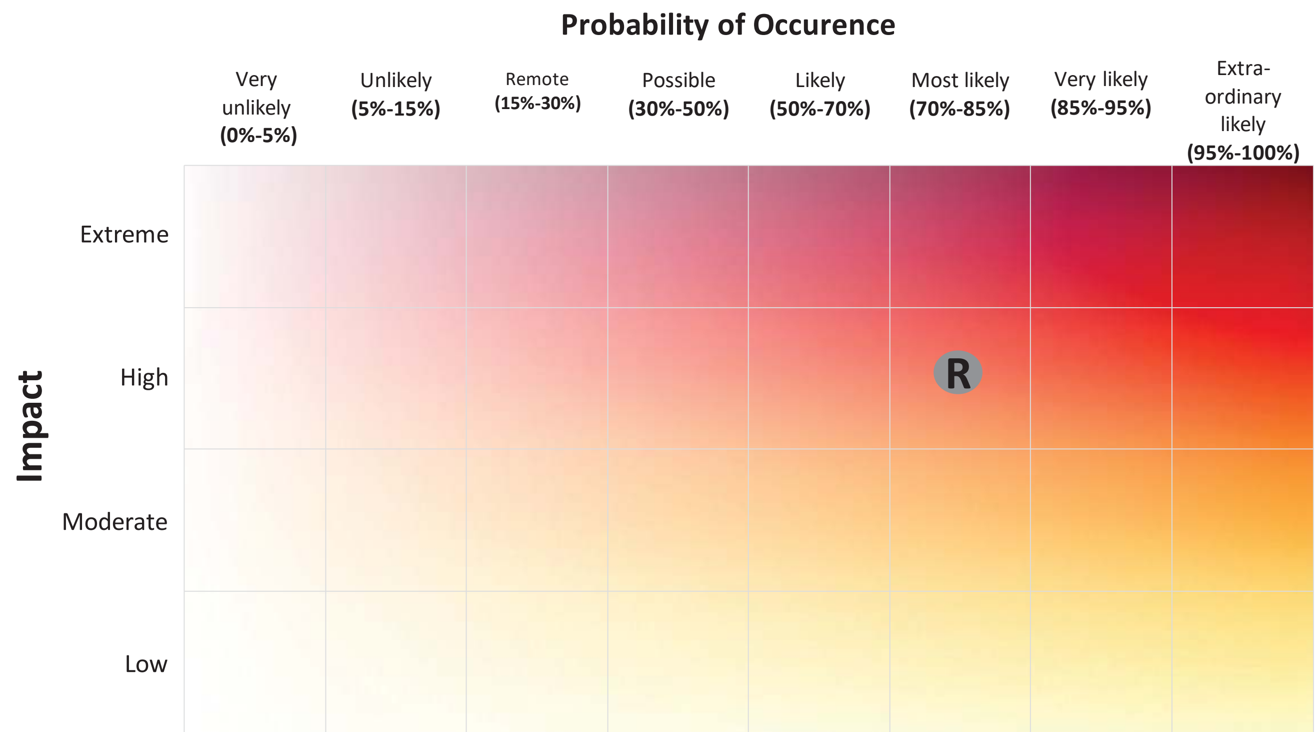
Qualitative Approach

Heat map „100% qualitative“

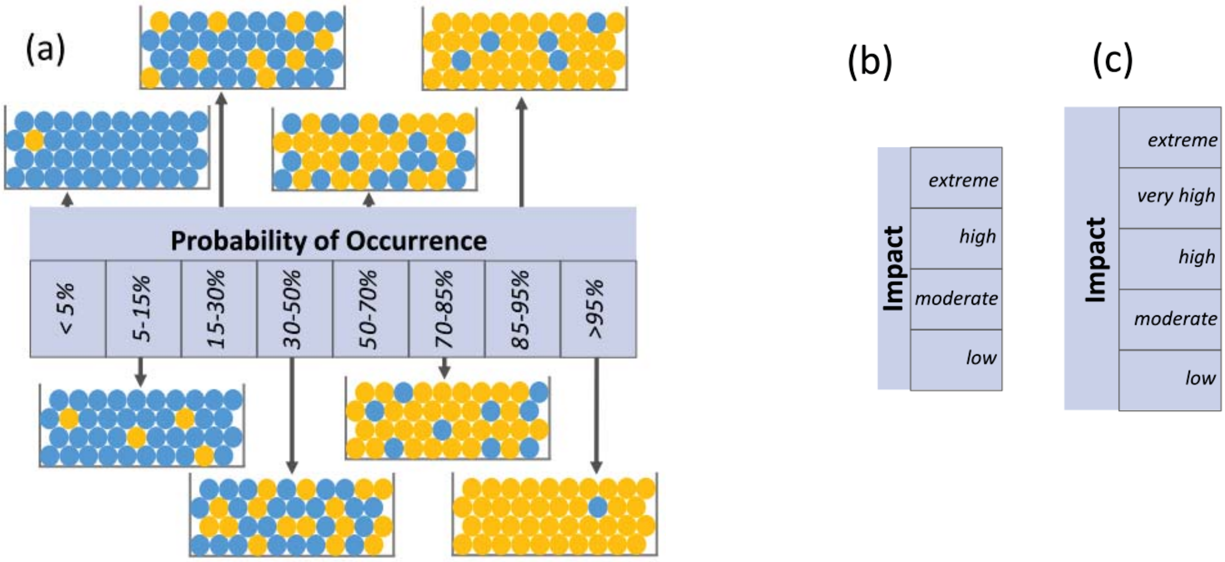


Qualitative Approach

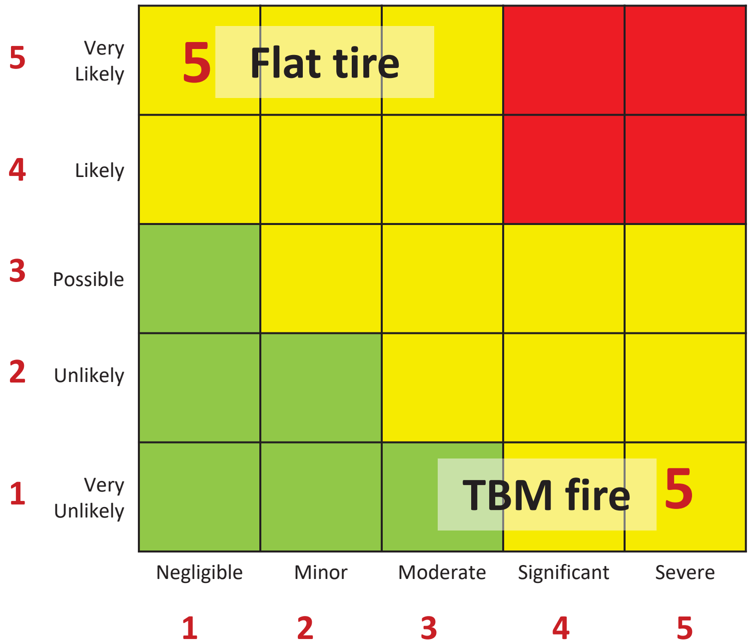
Heat map including Quantification of Probability of Occurence



Qualitative Approach



Semi-Quantitative Approach



- Probability and Impact are indepent
- Semi-quantitative approach combines the independent variables
- High Probability / Low-Impact scenarios = Low probability / high impact scenarios
- **Oversimplification! Be cautious**

Example semi-quantitative calculation:

Tire damage mine dumper:	5 x 1 = 5
TBM fire:	1 x 5 = 5
Accident with 10 casualties:	1 x 5 = 5

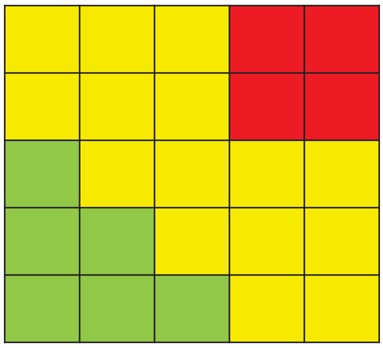
Excursus: Colors

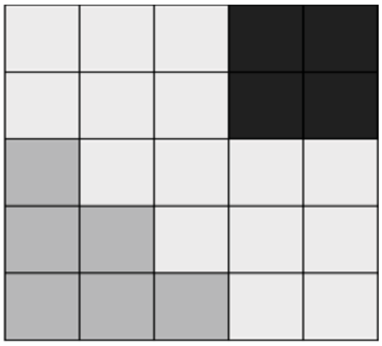
1) Green – yellow – red is firmly established

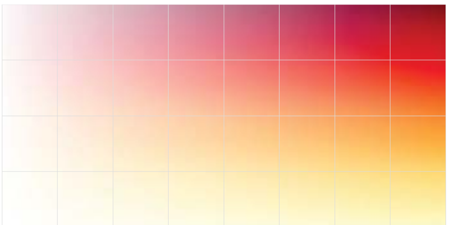
2) g-y-r: no continous increase of color intensity

3) Mostly, we are not interested in „green risks“

4) Alternative (below) offers independency of probability and impact as well as continuous coloring







Quantitative Approach

Comparison of 3 quantitative Approaches

1. **Deterministic:**
   Aggregated unit quantities multiplied by unit prices.
   (Often with some degree of conservatism built in)

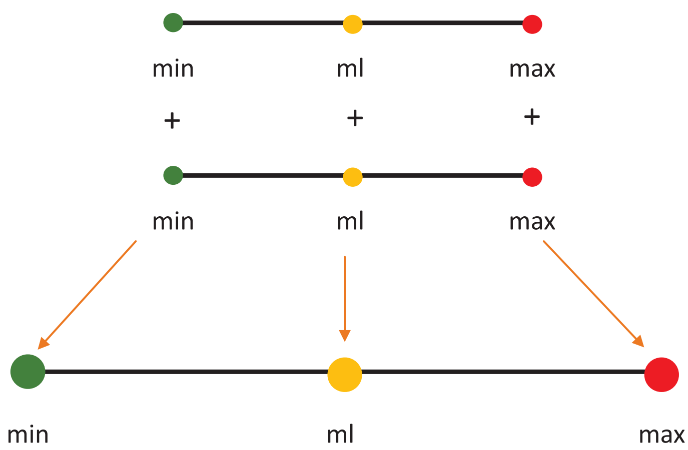
2. **Bandwidth:**
   Range approach with minimum, most likely, and maximum cost.
   The total cost is obtained by simply adding these parameters for all line items.

3. **Probabilistic:**
   Range approach which characterizes cost information with probability distributions

Bandwidth (Method 2) versus Probabilistic (Method 4) Approach: Basics

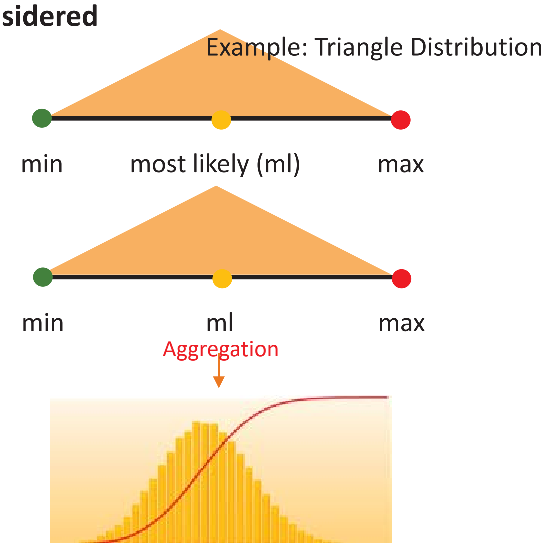
Bandwidth Approach

Input:
3-Point-Estimate
Process:
Simply adding up the minimum, most likely and maximum values from each item
→ **Suggests that the extreme scenarios will have the same occurrence rate as scenarios around the most likely value.**
→ **This will lead to scenarios which will not occur in reality**



Probabilistic Approach

Input:
3-Point-Estimate modelling a distribution density
Process:
Simulation (e.g. Monte Carlo Simulation) to cover most of real risk combinations
→ **Will lead to a realistic result where best and worst case scenarios are adequately considered**



Bandwidth (Method 2) versus Probabilistic (Method 4) Approach: E.g. Rolling 20 Dice

Input: One Die

→ Same probability of every value between 1 and 6

→ Same input for both methods

→ Simple 2-Point-Estimate

Rolling 20 dice – Consider this to be 20 risks in a project

Bandwidth Approach

Result

→ Bandwidth from 20 to 120

→ Same probability for every scenario

Many more combinations than rolling 1 die

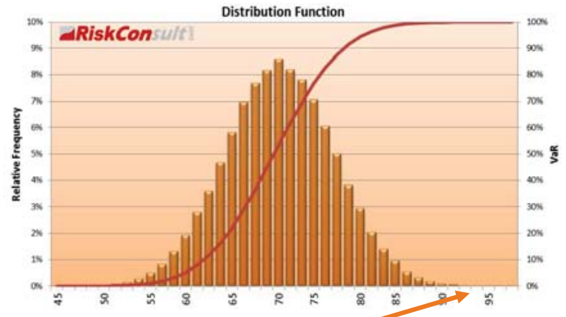
→ 120 (only one possible combination) is equally rated as e.g. 70 (many possible combinations)

→ No probability information

→ Not applicable for cost prediction

Probabilistic Approach

Result (Reality)



Maximum around **95** instead of **120**.
120 will not occur even using 100’000 iterations

→ Same for minimum

→ The most likely scenario will be around **70**

Quantitative Approaches - Comparison

Cost Item	Quantity Distribution	Quantity min	Quantity ml	Quantity max	Quantity unit	Unit Price [USD] Distribution	Unit Price min	Unit Price ml	Unit Price max	Price [USD] ml
Shotcrete 10 cm - Top Heading	Triangular	13.83	**15.37**	17.68	m²	Triangular	9.696	**12.12**	15.756	186.28
Steel Mesh AQ50, outer layer- Top Heading	Triangular	13.83	**15.37**	16.91	m²	Triangular	0.976	**1.22**	1.586	18.75
Swellex 3.0 m - Top Heading	Triangular	1.73	**1.82**	2.00	pc	Triangular	20.712	**25.89**	33.657	47.12
Shotcrete 5 cm - Bench	Triangular	5.18	**5.76**	6.62	m²	Triangular	5.992	**7.49**	9.737	43.14
Swellex 3.0 m - Bench	Triangular	0.43	**0.45**	0.50	pc	Triangular	20.712	**25.89**	33.657	11.65
										306.95

1. Deterministic Approach

Most likely quantity x most likely price

306.95 USD

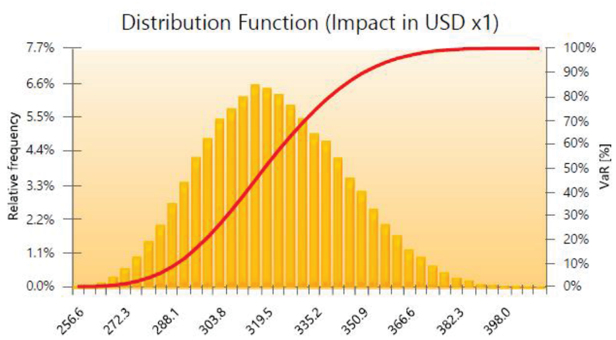
2. Bandwidth Approach

$\sum CostItem(\min Q * \min P)$ **223.36 USD**

$\sum CostItem(mlQ * mlP)$ **306.95 USD**

$\sum CostItem(\max Q * \max P)$ **453.86 USD**

4. Probabilistic Approach



P5: **286,00 USD**

P50: **321,10 USD**

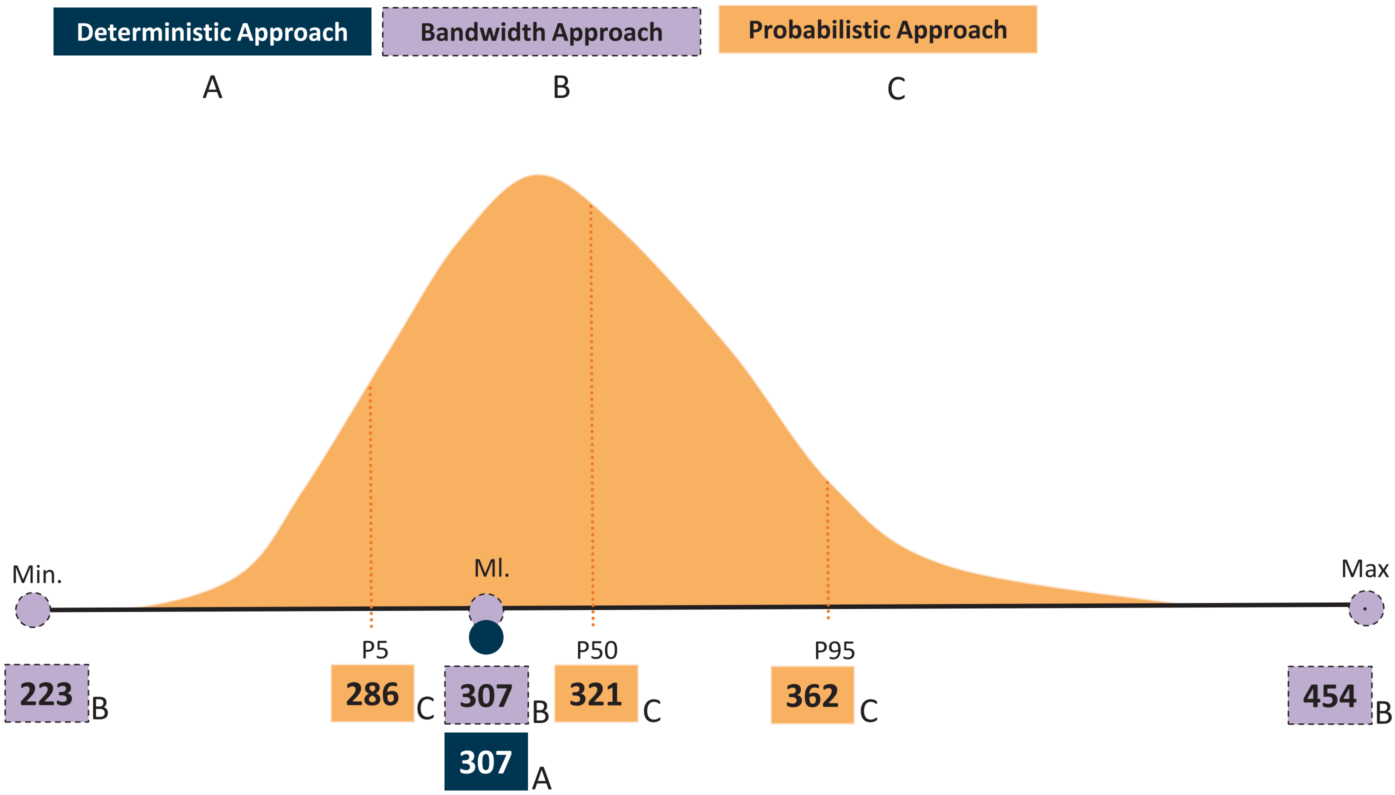
P95: **362,47**

Extreme values (100.000 iterations):

P0: 250,66 USD

P100: 413,58 USD

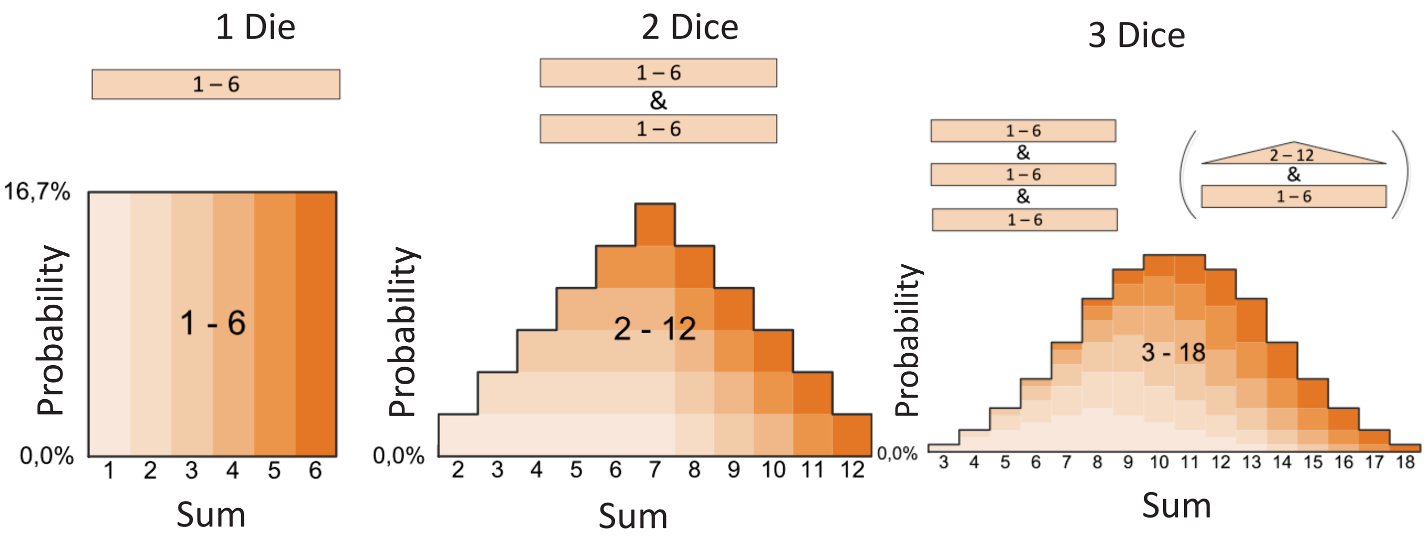
Quantitative Approaches - Comparison



Quantitative Approaches - Comparison

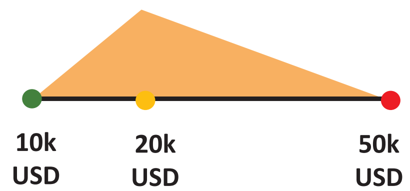
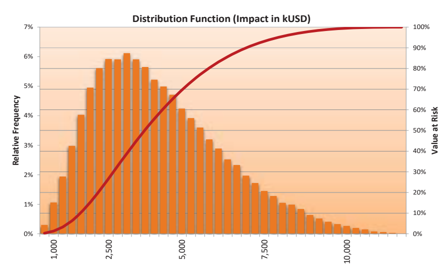
Approach	Pro	Con
1. Deterministic	**One single figure** Well-known & accepted Quick Can be performed "manually"	**No probability information** for single value **No VaR** information More often than not **on the unsafe side** (high, unknown probability of cost overruns)
2. Bandwidth	**Three values** (minimum, most likely and maximum) in a range Quick Can be performed "manually"	**No probability information** for range values **No VaR information** More often than not **on the unsafe side** (high, unknown probability of cost overruns) Range **maximum and minimum very unlikely**
4. Probabilistic	**Full probability information**	Needs **probabilistic thinking & understanding** Needs (a little bit) more time Needs **software support**

Rolling the Dice



Combinations	1,1	1,2 2,1	1,3 2,2 3,1	1,4 2,3 3,2 4,1	1,5 2,4 3,3 4,2 5,1	1,6 2,5 3,4 4,3 5,2 6,1	2,6 3,5 4,4 5,3 6,2	3,6 4,5 5,4 6,3	4,6 5,5 6,4	5,6 6,5	6,6
Results	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Probability	1/36	2/36	3/36	4/36	5/36	6/36	5/36	4/36	3/36	2/36	1/36
	2,8%	5,6%	8,3%	11,1%	13,9%	16,7%	13,9%	11,1%	8,3%	5,6%	2,8%

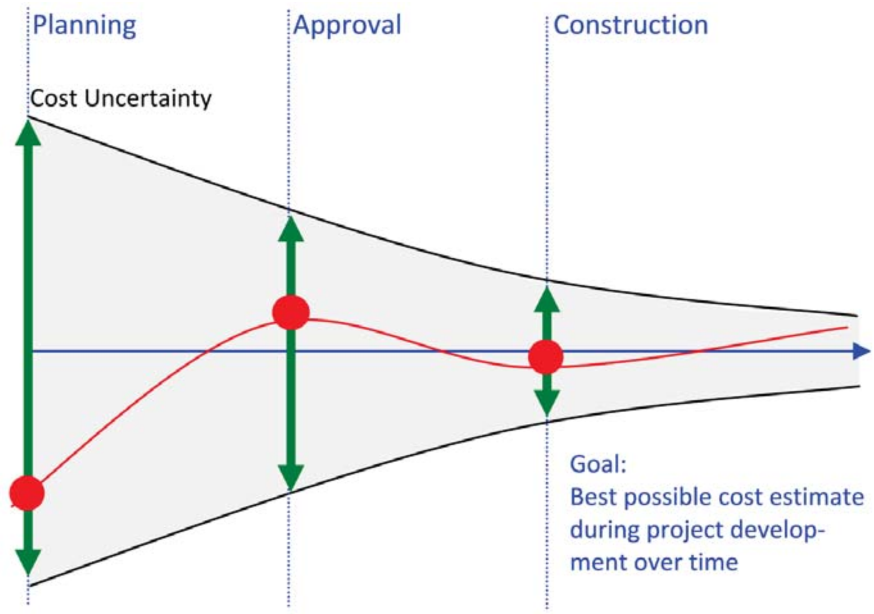
Comparisons of Deterministic and Probabilistic Approach

	Deterministic Approach	Probabilistic Approach
Input Single risk	**Single number:** probability of occurrence times impact **50 % x 20k USD = 10k USD** → **Uncertainty not considered**	**Distribution:** probability of occurrence and several values for the impact (e.g., minimum, most likely, and maximum) **50 % &**  → **Considers uncertainty**
Result Overall risk potential	A **simple mathematical addition** gives the aggregated consequence for all risks. This results is an **expected consequence** for the aggregated risks. $R_{total} = \sum p_i * I_i$	Simulation methods produce a probability distribution based on thousands of realistic scenarios. 

Comparisons of Deterministic and Probabilistic Approach

Deterministic approach:
– single figure (sharply defined):
- **Determined (no range)**
- **Has high uncertainty**
- **Appears accurate but is not!**

Probabilistic approach:
–bandwidth represents the range of potential values
- **Uses ranges**
- **Degree of certainty changes according to project progress**

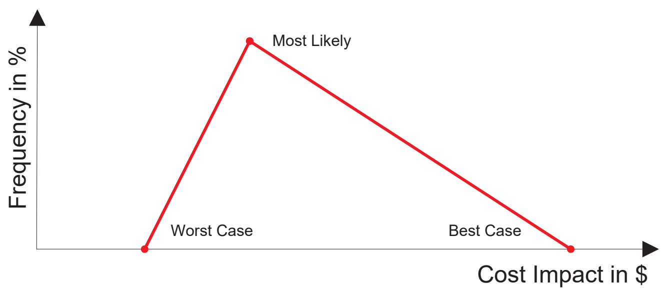


Assessment of Single Risks

Risk Assessment
- Probability of occurence (%) or number of events (Frequency, Poisson distribution)
- Impact (cost and time)

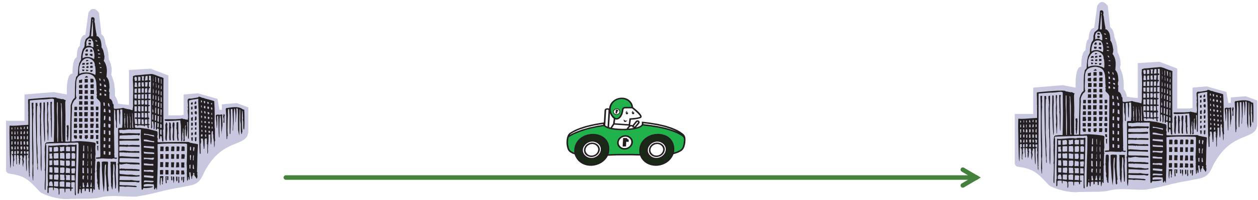
3-Point Estimate
- Reality can be described much better with bandwidths than with single numbers
- Triangle function is easy to understand
- Complex modeling is possible at any point in the process

Example triangle distribution: easy to determine, flexible (skewness, etc.)



- 3-Point-Estimate (min, expected value, max)
- Integration of Skewness
- No extra parameters without direct meaning

Example: Basic Driving Time from New York City to Boston

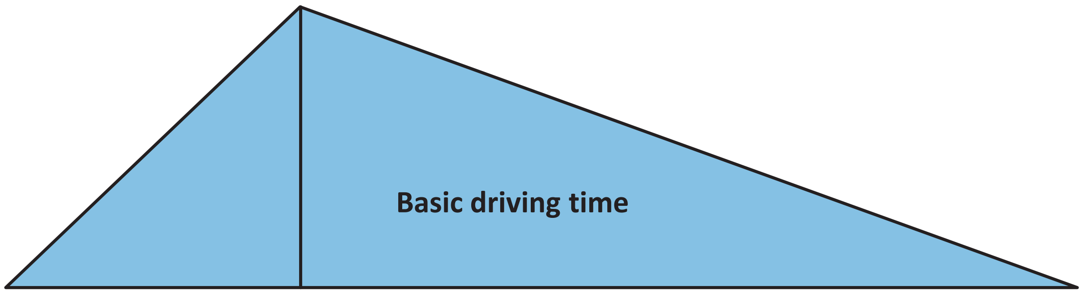


Vienna

Munich

Estimation of the basic driving time from Vienna to Munich

Premise: Normal traffic and weather conditions

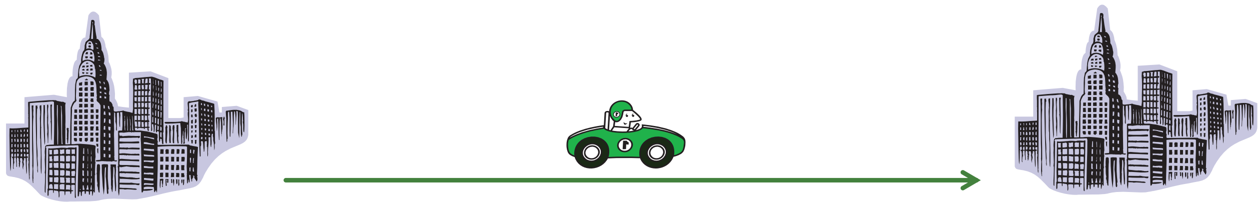


Best case: 3,5 h

Most likely: 4,0 h

Worst case: 5,0 h

Example: Add a Risk – Bad Weather

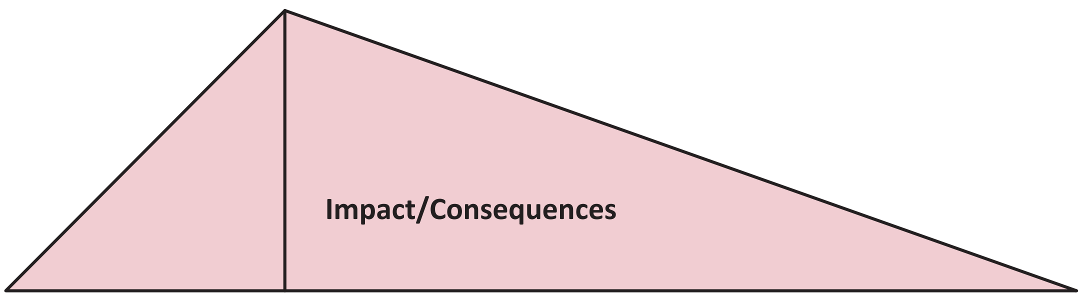


Vienna

Munich

Risk: Bad weather in January

- → Snow and icy roads
- → Scenario has a probability of occurrence – can occur but does not have to
- → Estimated probability: **45 %**
- → Additional time is needed (impact if risk does occur)



Best case: 0,5 h

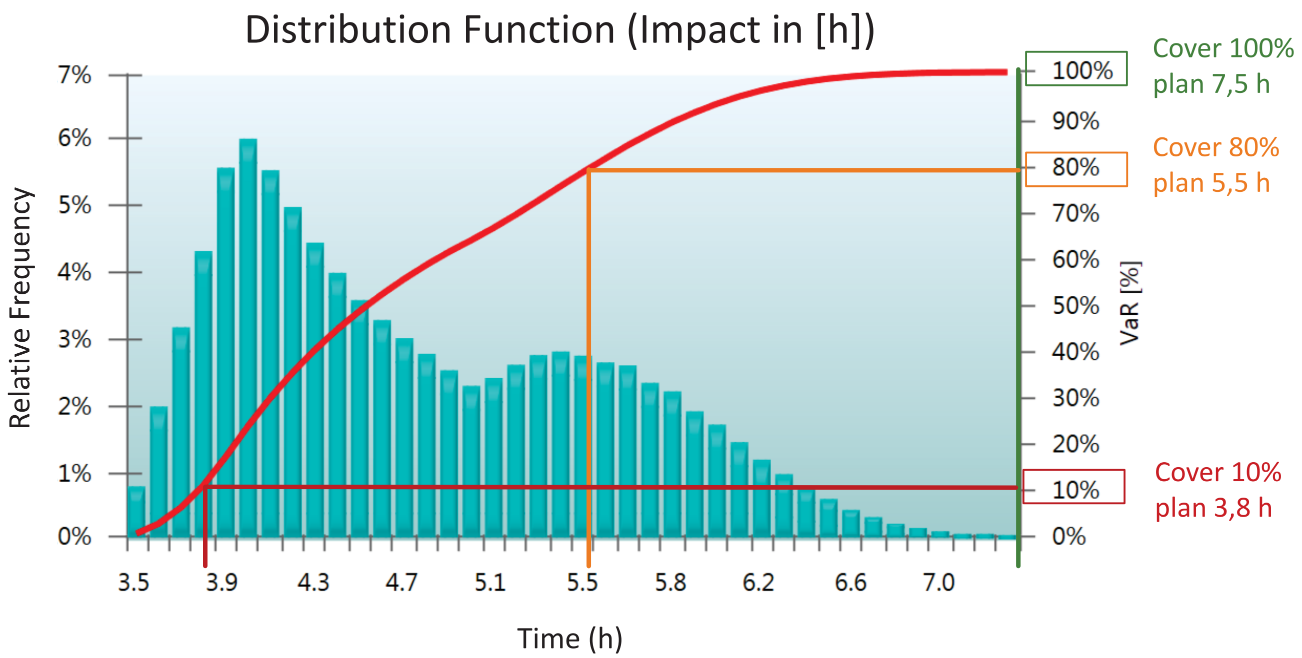
Most likely: 1,0 h

Worst case: 2,5 h

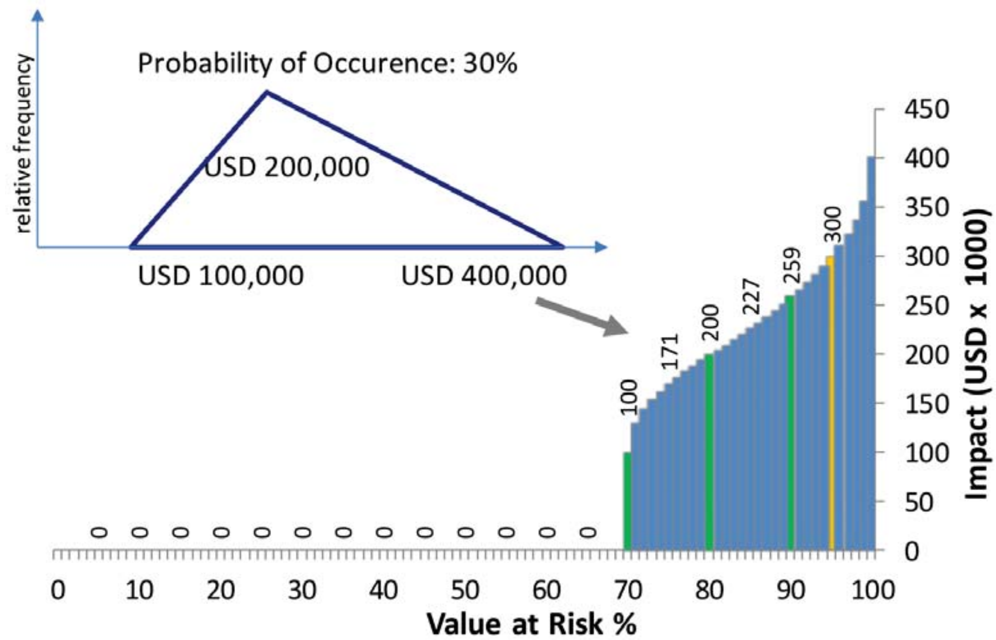
Example: Result – Plan your Trip

Now it is up to you as your own risk manager:

→ How important is your appointment in Munich?
→ Can you afford being late?
→ Cover the risk of being too late → start earlier or not?



Example - Risk



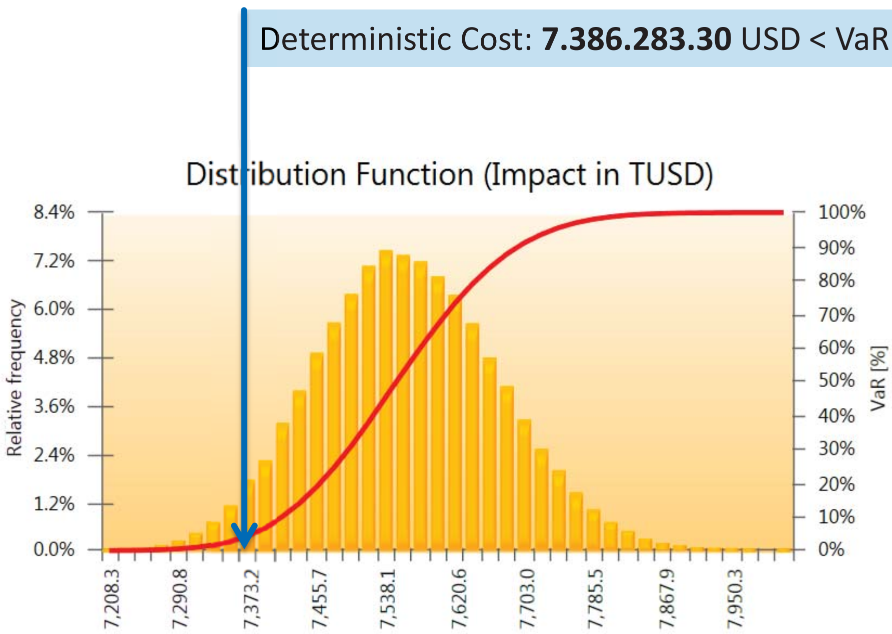
Deterministic Result: 30% x 200,000 = 60,000 USD

Example – Cost estimate concrete works

Description	Quantity					Unit Price				Item Price
	Dist.	Min	ML	Max	Unit	Dist.	Min	ML	Max	USD
Concrete works										**7,386,283.30**
Concrete Tower Floor	Triangle	210.700	**215.000**	221.450	m³	Triangle	101.85	**105.00**	115.50	**22,575.00**
Reinforcement Tower Floor	Triangle	51,049.200	**53,736.000**	59,109.600	kg	Triangle	1.04	**1.15**	1.32	**61,796.40**
Concrete Newsroom	Triangle	78.400	**80.000**	84.000	m³	Triangle	94.50	**105.00**	115.50	**8,400.00**
Reinforcement Newsroom	Triangle	19,150.100	**20,158.000**	22,173.800	kg	Triangle	1.04	**1.15**	1.23	**23,181.70**
Concrete Basement	Triangle	77.126	**78.700**	82.635	m³	Triangle	101.85	**105.00**	115.50	**8,263.50**
Reinforcement Basement	Triangle	18,696.950	**19,681.000**	21,649.100	kg	Triangle	1.12	**1.15**	1.26	**22,633.15**
Concrete Walls	Triangle	5,355.700	**5,465.000**	5,738.250	m³	Triangle	346.70	**361.15**	390.04	**1,973,684.75**
Reinforcement Walls	Triangle	519,206.350	**546,533.000**	601,186.300	kg	Triangle	1.10	**1.15**	1.23	**628,512.95**
Concrete Slabs	Triangle	9,122.820	**9,309.000**	9,774.450	m³	Triangle	220.80	**230.00**	248.40	**2,141,070.00**
Reinforcement Slabs	Triangle	1,072,502.500	**1,128,950.000**	1,241,845.000	kg	Triangle	1.10	**1.15**	1.23	**1,298,292.50**
Concrete Base Slab	Triangle	3,608.360	**3,682.000**	3,866.100	m³	Triangle	220.80	**230.00**	248.40	**846,860.00**
Reinforcement Base Slab	Triangle	289,967.550	**305,229.000**	335,751.900	kg	Triangle	1.10	**1.15**	1.23	**351,013.35**

Deterministic Value below VaR 5

Deterministic Cost: **7.386.283.30** USD < VaR 5



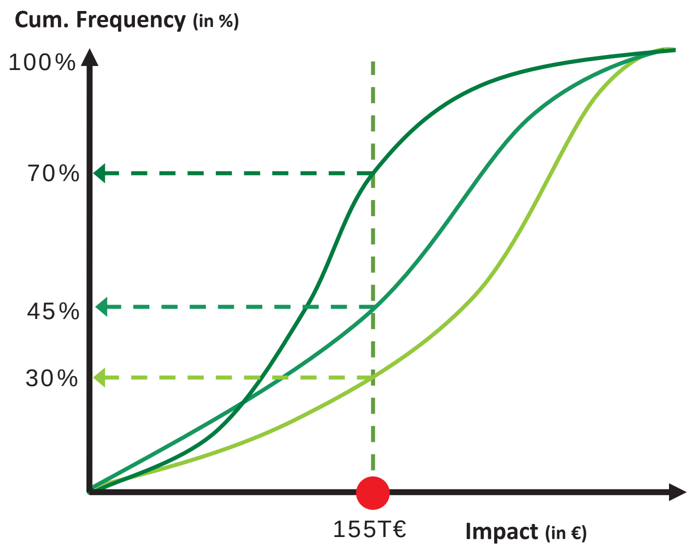
Cost in USD

det.	7,386,283.30	
VaR5	7,393,916	100.1 %
VaR10	7,429,348	100.6 %
VaR20	7,473,807	101.2 %
VaR30	7,507,054	101.6 %
VaR40	7,535,144	102.0 %
VaR50	7,562,386	102.4 %
VaR60	7,590,037	102.8 %
VaR70	7,619,675	103.2 %
VaR80	7,655,080	103.6 %
VaR90	7,703,938	104.3 %
VaR95	7,745,234	104.9 %

Example Deterministic Risk Rating

Risk	Prob	Impact	P x I
Risk 1	80%	10 T€	8 T€
Risk 2	33%	270 T€	90 T€
Risk 3	25%	28 T€	7 T€
Risk 4	5%	1.000 T€	50 T€
		Σ:	155 T€

Standard Risk Rating:
Risk = P x Impact



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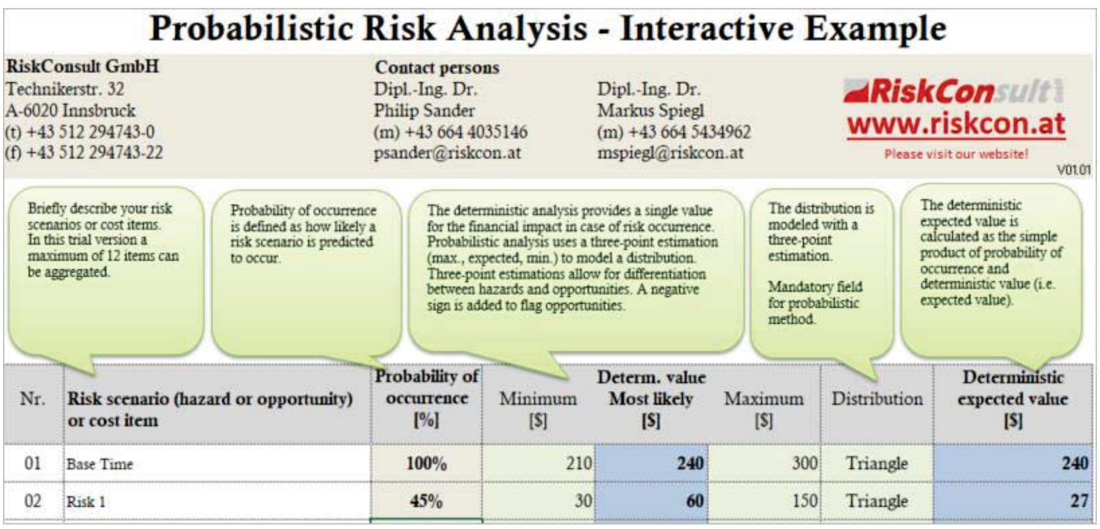
What is the robustness of our Risk Contingency?

Live Demonstration

Monte Carlo Simulation - Tool


Probabilistic Risk Analysis - Interactive Example

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RiskConsult
www.riskcon.at
Please visit our website!
V01.01

Briefly describe your risk scenarios or cost items. In this trial version a maximum of 12 items can be aggregated.

Probability of occurrence is defined as how likely a risk scenario is predicted to occur.

The deterministic analysis provides a single value for the financial impact in case of risk occurrence. Probabilistic analysis uses a three-point estimation (max., expected, min.) to model a distribution. Three-point estimations allow for differentiation between hazards and opportunities. A negative sign is added to flag opportunities.

The distribution is modeled with a three-point estimation. Mandatory field for probabilistic method.

The deterministic expected value is calculated as the simple product of probability of occurrence and deterministic value (i.e. expected value).

Nr.	Risk scenario (hazard or opportunity) or cost item	Probability of occurrence [%]	Minimum [$]	Determ. value Most likely [$]	Maximum [$]	Distribution	Deterministic expected value [$]
01	Base Time	100%	210	240	300	Triangle	240
02	Risk 1	45%	30	60	150	Triangle	27

Workshop on NATM & TBM Tunnelling incl. Risk Management

1 - How to deal with uncertainties in tunnelling?

6 – 8th February 2018, New Delhi, India

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Workshop on NATM & TBM Tunnelling incl. Risk Management

2 - Risk Management – Standards and Guidelines

6 – 8th February 2018, New Delhi, India

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RiskConsult GmbH www.riskcon.at

Standards & Guidelines

There are numerous Risk Management Standards and Guidelines:

- Generic
- Specific for certain applications / industries

We will look at:

1) **ISO 31000**: Risk Management – Principles and Guidelines
2) **ISO/IEC 31010**: Risk Management – Risk Assessment Techniques
3) **ITA** Guidelines for Tunnelling Risk Management
4) **OGG** Guideline for the Cost Determination for Transportation Infrastructure Projects

ISO 31000

Risk Management

Principles and Guidelines

Introduction

Organizations of all types and sizes face internal and external factors and influences that make it uncertain whether and when they will achieve their objectives. The effect this uncertainty has on an organization's objectives is “risk”.

When implemented and maintained in accordance with this International Standard, the management of risk enables an organization to, for example:

— increase the likelihood of achieving objectives;

— encourage proactive management;

— be aware of the need to identify and treat risk throughout the organization;

— improve the identification of opportunities and threats;

— comply with relevant legal and regulatory requirements and international norms;

— improve mandatory and voluntary reporting;

— improve governance;

— improve stakeholder confidence and trust;

Risk Management - ISO 31000

— establish a reliable basis for decision making and planning;

— improve controls;

— effectively allocate and use resources for risk treatment;

— improve operational effectiveness and efficiency;

— enhance health and safety performance, as well as environmental protection;

— improve loss prevention and incident management;

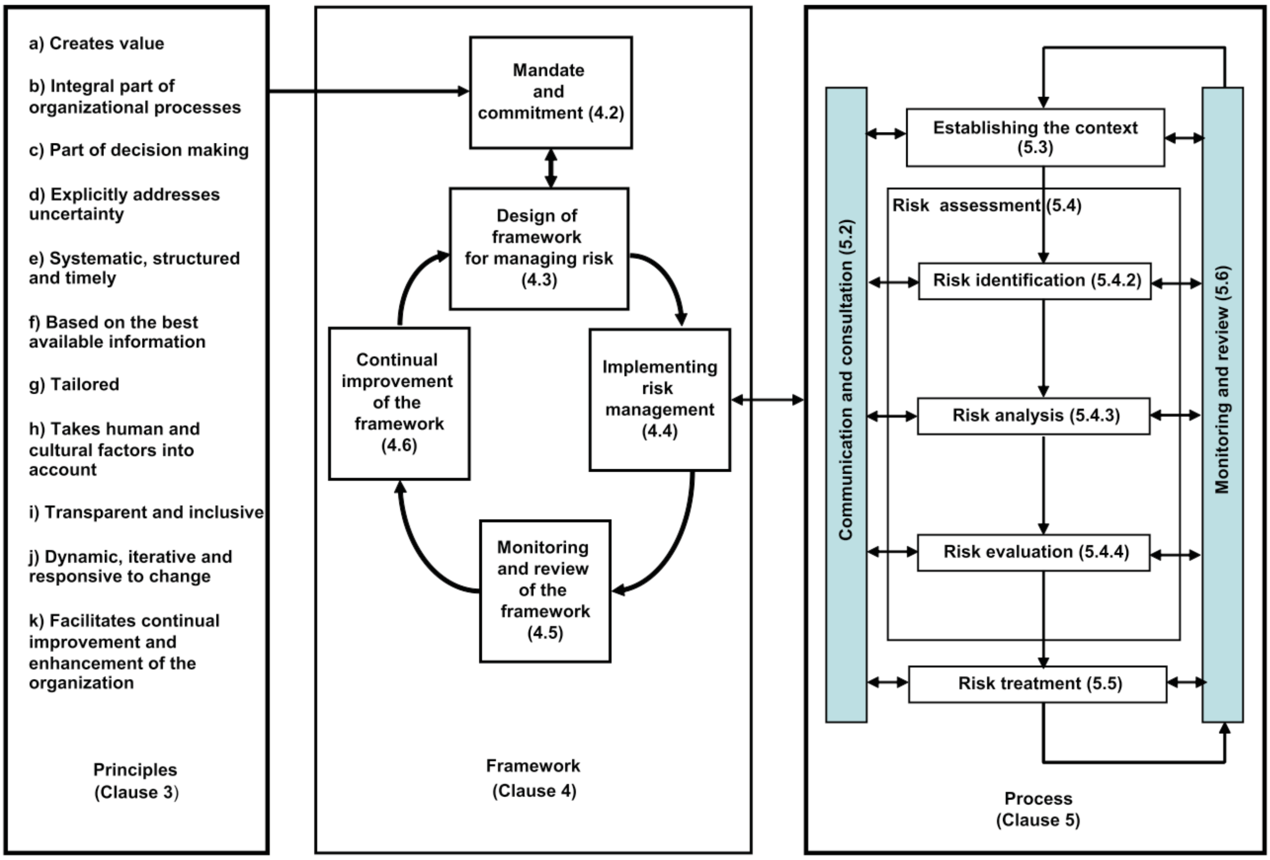
— minimize losses;

— improve organizational learning; and

— improve organizational resilience.

RM Principles, Framework, Process

Comply with Principles! Establish Framework Integrate RM Process into Project Management



Definition of „Risk“ – ISO 31000

effect of uncertainty on objectives

NOTE 1 An effect is a deviation from the expected — positive and/or negative.

NOTE 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).

NOTE 3 Risk is often characterized by reference to potential **events** (2.17) and **consequences** (2.18), or a combination of these.

NOTE 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated **likelihood** (2.19) of occurrence.

NOTE 5 Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.

Definition of „Risk“ – other standards

British Standard **BS 6079-1&2 (2002/2000):**
Project management. Principles and guidelines for the management of projects

„combination of the probability or frequency of occurrence of a defined threat or opportunity and the magnitude of the consequence of the occurrence“

ISO/IEC 16085 (2004):
Systems and software engineering -- Life cycle processes -- Risk management

„The likelihood of an event, hazard, threat, or situation occurring and its undesirable consequences; a potential problem.“

European Standard **DIN EN 62198 (2002)/(2001):**
Managing Risks in Projects

„Combination of the probability of an event occurring and its consequences on project objectives“

Risk: Scenario Development – Sources, Causes, Risk Scenarios

System Limits → Sources of Threats & Opportunities → Causes → Risk Scenario

- Current status of a system
- Definition of content and limits
- Base for Risk Analysis

- Source of specific events or circumstances (causes).
- Where do these causes/triggers come from?
- One source can be the origin of multiple causes

- Causes that might lead to an interaction with our objective
- Basis which leads to development of Risk Scenarios
- One risk scenario can be triggered by multiple causes

- Concrete description of a Risk (Assumption of relationship between causes, sequence of events and developments)
- Consequences on an objective can be positive or negative
- Uncertainty can be estimated using probability information.

Sample of Street Intersection Environment – Leading to Risks

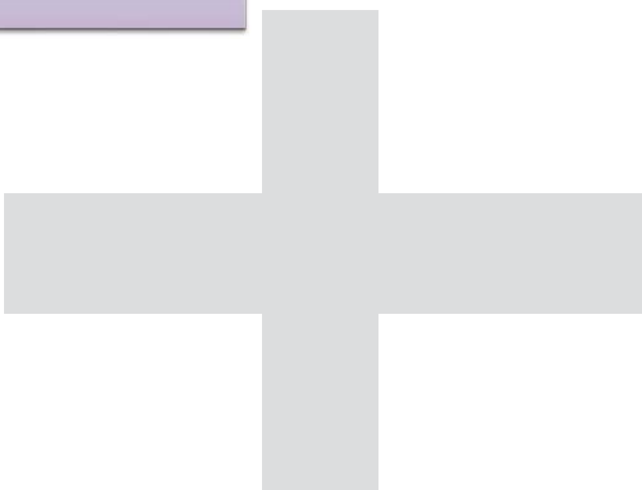
System Limits → Sources of Threats & Opportunities → Causes → Risk Scenario

System Limits
- Standard street junction
- Car Traffic
- City

Sources of Threats & Opportunities
- **Human Decisions**
- **Technology**
- **Environment**

Causes
- Can´t brake
- Doesn´t want to brake
- No clear view
- Condition of Pavement (Rain, Oil, Holes, etc.)
- Limit of Senses (Age, Alcohol, Drugs, Tireness, etc.)

Risk Scenario
- Potential for a Car Crash / Accident



Mitigation Measures:
→ Driving License / Experience
→ Traffic Lights and Signs - condition the environment for decisons
→ Eliminate Crossing/Junction (Change of System)

ISO/IEC 31010

Risk Management

Risk Assessment Techniques

ISO/IEC 31010

While ISO 31000 is a generic standard, ISO/IEC 31010 offers a variety of methods and tools to support ISO 31000 and put Risk Management into practice.

RM Techniques (31 in total):

- Brainstorming
- Structured or semi-structured interviews
- Delphi method
- Fault Tree Analysis
- Event Tree Analysis
- Monte Carlo Simulation
- Consequence/Probability Matrix → Risk Matrix
- …

6-3-5 Brainwriting

ISO 31010 offers different methods for Risk identification. A very good method (not mentioned in ISO 31010) is **6-3-5 Brainwriting:**

- 6 Participants (or 6 groups) supervised by a moderator
- Think of 3 risks and write them down within 5 minutes.
- Hand over your results to the next participant who will have another 5 minutes to add 3 risks.
- 6 rounds, 18 risks in each round: 108 risks

6-3-5	Risk 1	Risk 2	Risk 3
Participant 1			
Participant 2			
Participant 3			
Participant 4			
Participant 5			
Participant 6			

Event Tree Analysis

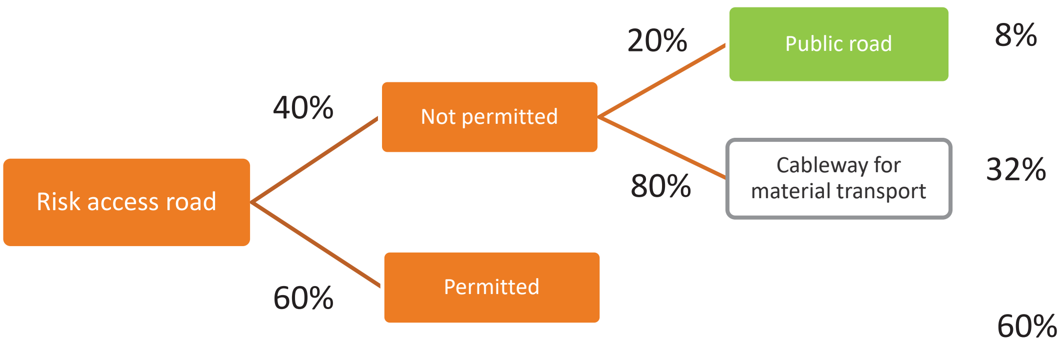
Scenario:

- We need an access road to the construction site of a reservoir of a hydro-electric power plant.
- 40% risk that the access road will not be permitted (environmental aspects). In this case (no permission), there are two alternatives:

1. Use of existing public road to the reservoir.
   estimated probability for permission: 20%
2. No permission for public road: new Cableway for material transport
   most expensive scenario (80%)

The scenario will be modeled by an event tree.

Event Tree Analysis

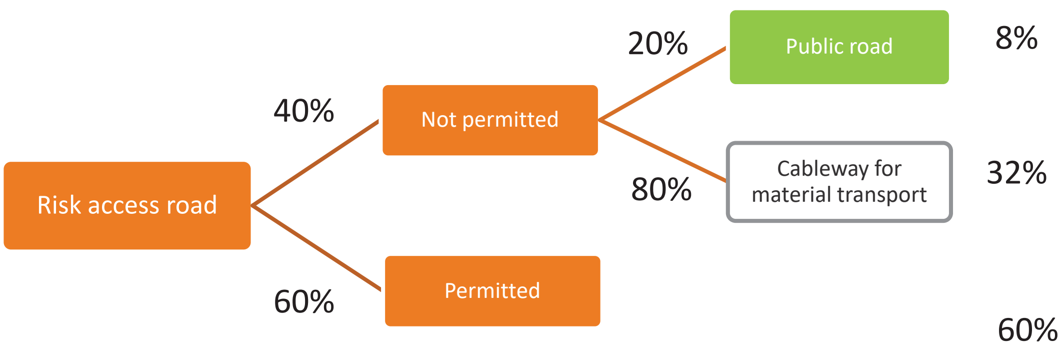


The cost of the access road is estimated at 1,000,000.
If there will be no permission the costs for the access road are saved in a first step.

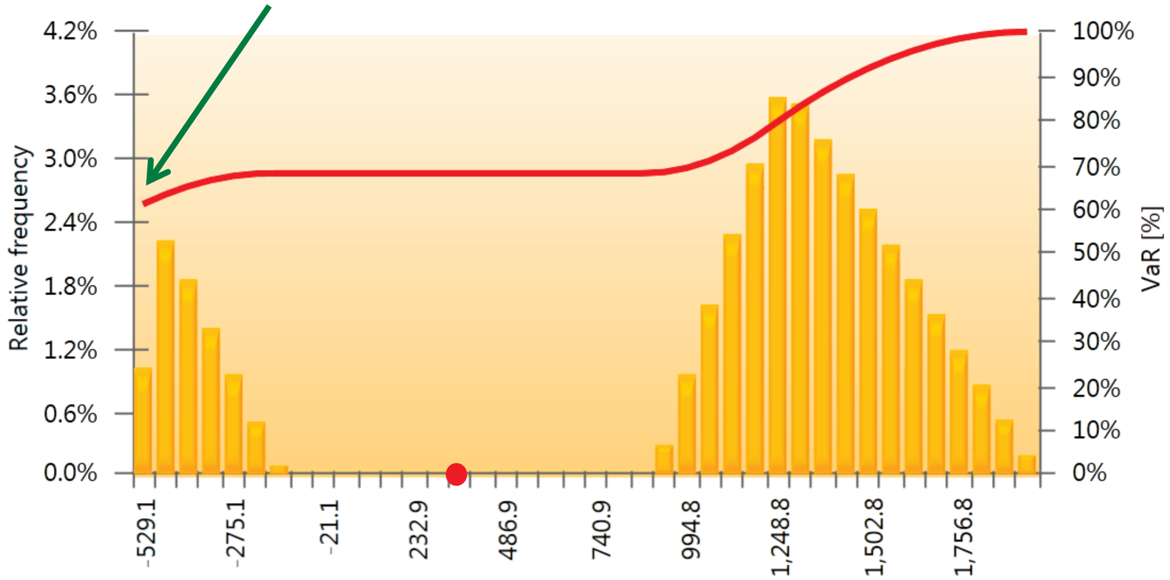
		triangle		
		min	ml	max
Omitted access road	8%	-1,000,000	-1,000,000	-1,000,000
Extension of public road		467,500	550,000	880,000
Omitted access road	32%	-1,000,000	-1,000,000	-1,000,000
Cableway for material transport		1,912,500	2,250,000	2,925,000

Live Demonstration – Event Tree Analysis

RIAAT
Risk Administration and Analysis Tool



After simulation the result is a probability distribution that displays the overall risk potential. There is a probability of 60% that the risk will not occur (see red distribution function).



8% x (-1,000,000 + 550,000) + 32% x (-1,000,000 + 2,250,000) + 60% x 0
= -36,000 + 400,000 + 0

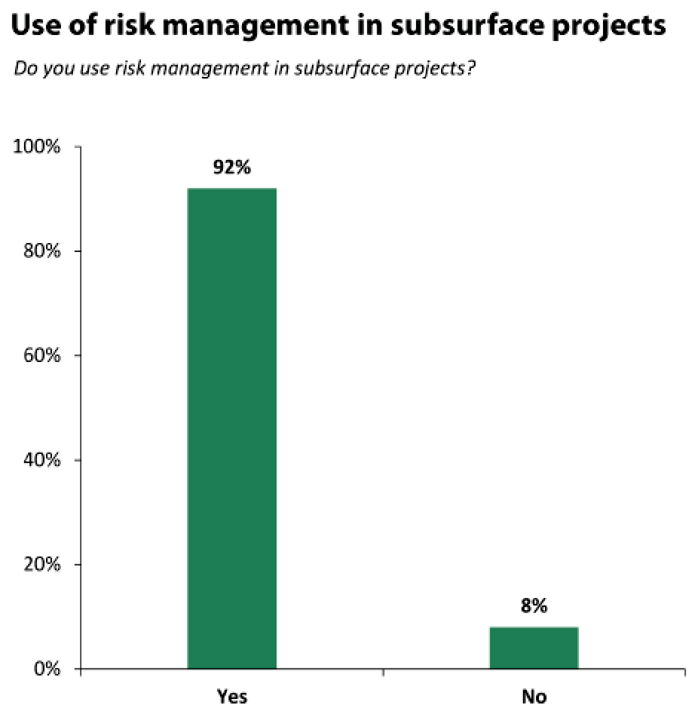
364,000 won‘t occur in reality

ITA – International Tunnelling Association

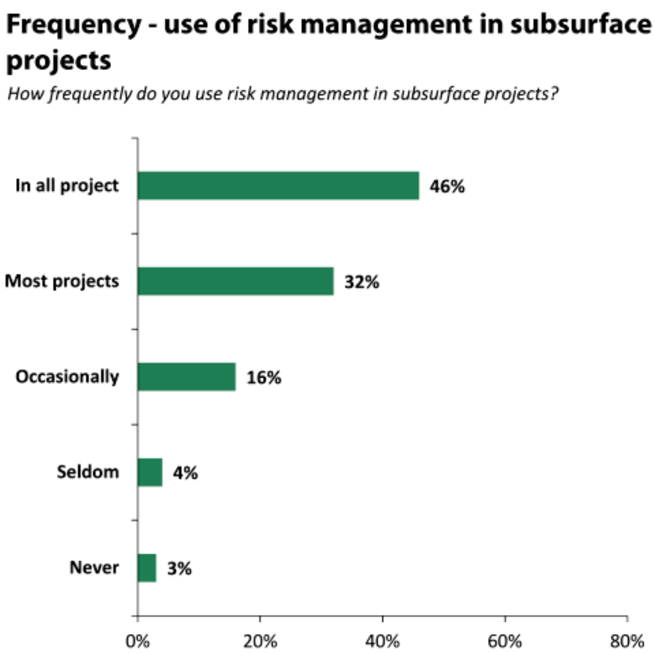
Guidelines for Tunnelling Risk Management

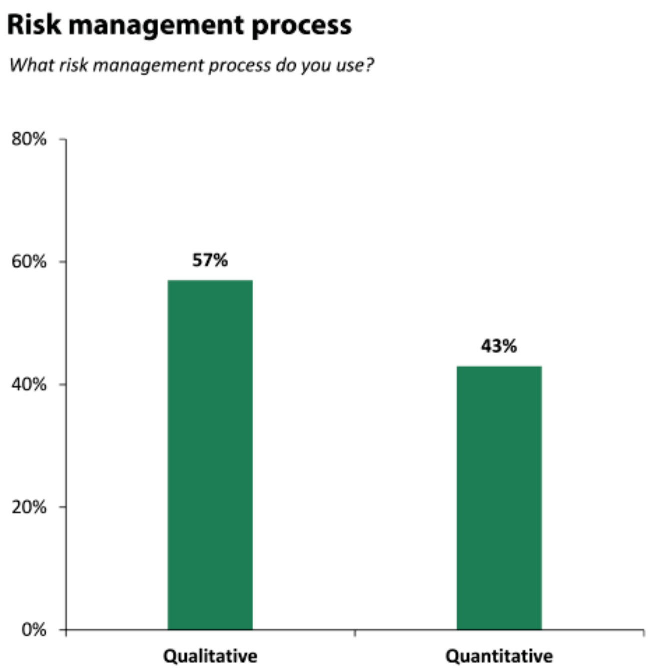
ITA Survey – Practice of Risk Management in Tunnelling

- Published by ITA Working Group 2
- Survey carried out April – June 2017



ITA Survey – Practice of Risk Management in Tunnelling

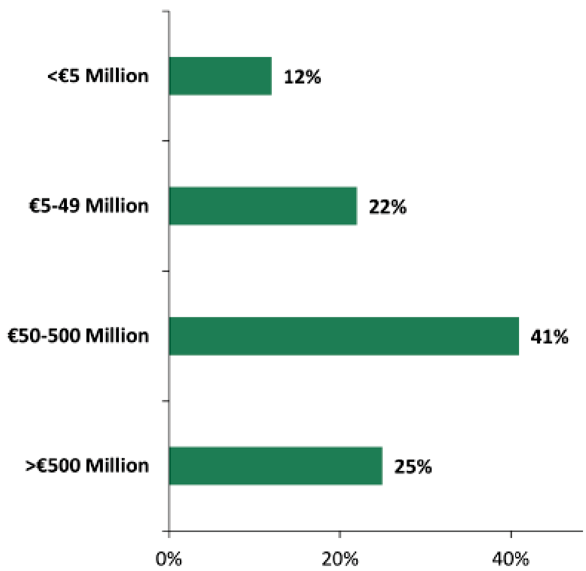




ITA Survey – Practice of Risk Management in Tunnelling

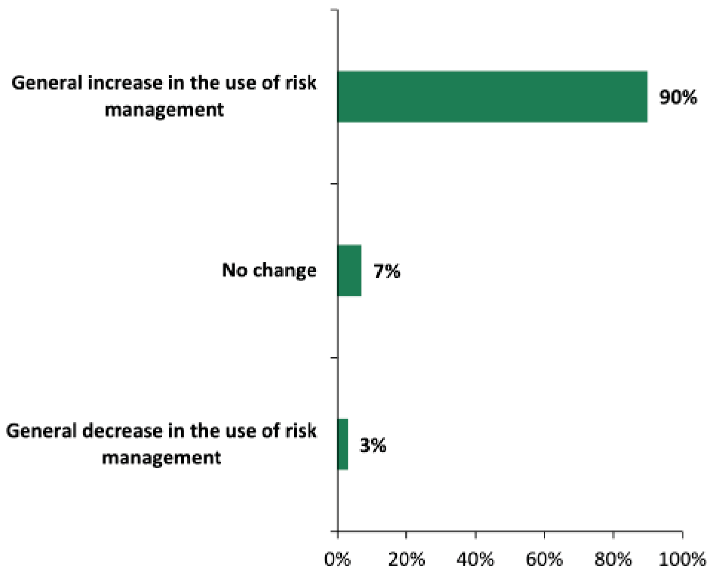
Size of projects mostly worked with

What size are the project you mostly work with?



Increase/Decrease in use of risk management

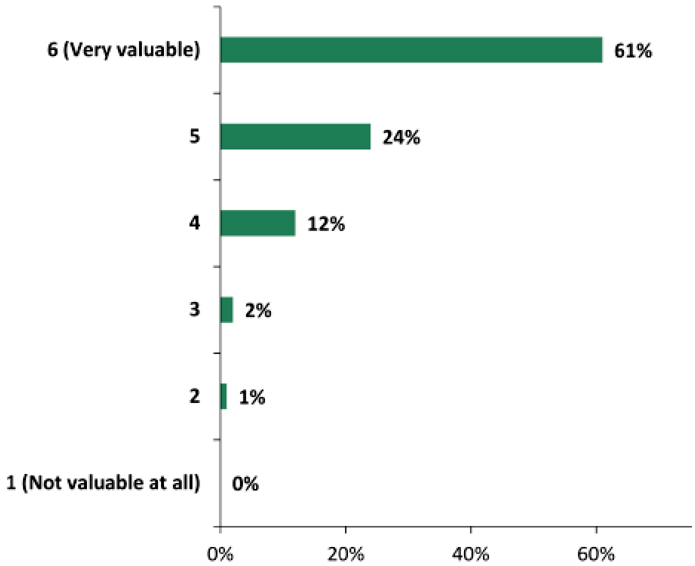
Is risk management becoming more prominent in the last decade?



ITA Survey – Practice of Risk Management in Tunnelling

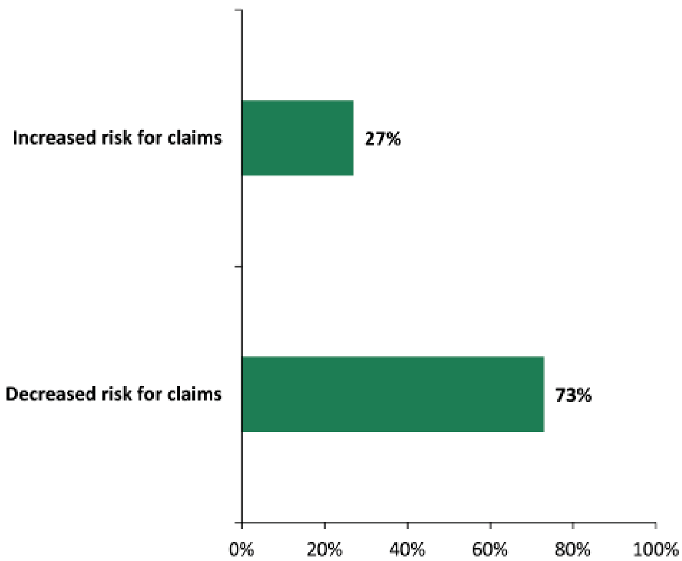
Value of risk management for projects in underground space

In your opinion, how valuable is risk management for projects in underground space?



Effects of risk management on claims

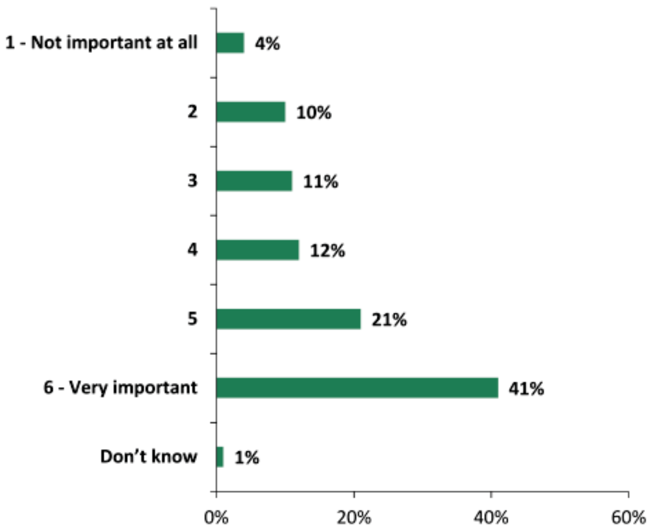
When applying the existing risk management methods, how do you think it affects the following aspects of a project? - Claims



ITA Survey – Practice of Risk Management in Tunnelling

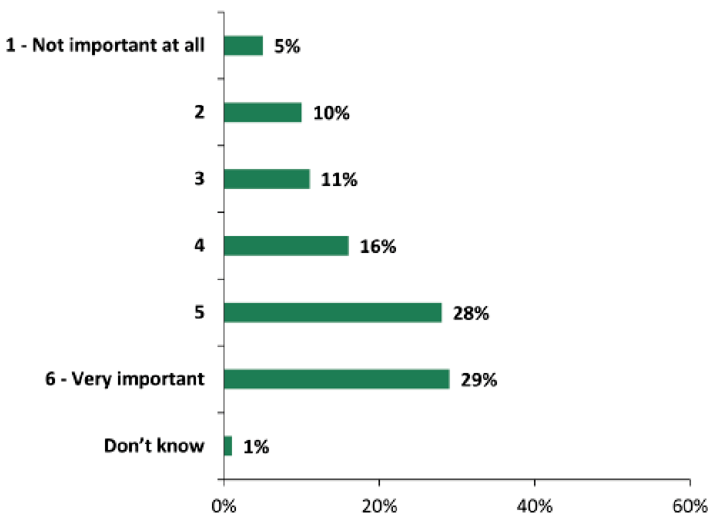
Effects of risk management on reducing costs

How important do you find risk management to be in a project, in terms of affecting the following aspect in a positive way? - Reducing cost



Effects of risk management on reducing time

How important do you find risk management to be in a project, in terms of affecting the following aspect in a positive way? - Reducing time



ITA Guidelines for tunnelling risk management

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Tunnelling and Underground Space Technology incorporating Trenchless Technology Research

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ITA/AITES Accredited Material

Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2 ☆

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Abstract

These guidelines, prepared by Working Group 2 (Research) of the International Tunnelling Association, are prepared in order to give guidance to all those who have the job of preparing the overall scheme for the identification and management of risks in tunnelling and underground projects. The guidelines provide owners and consultants with what is modern-day industry practice for risk assessment, and describes the stages of risk management throughout the entire project implementation from concept to start of operation.

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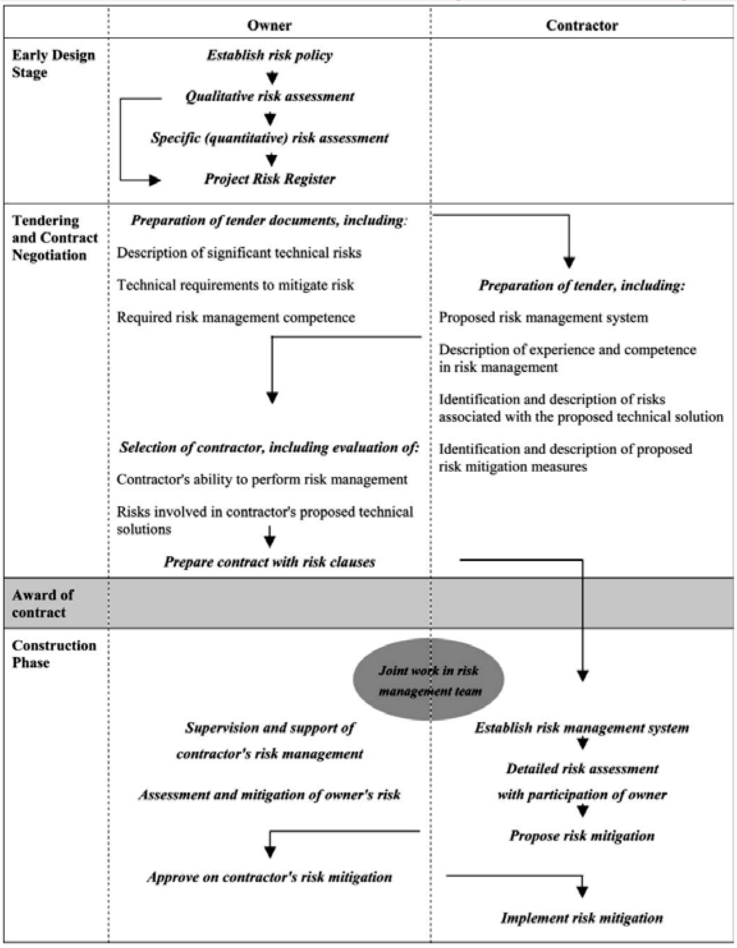
ITA Guidelines for tunnelling risk management



ITA Guidelines for tunnelling risk management

Table 1
Frequency of occurrence (in the construction period)

Frequency class	Interval	Central value	Descriptive frequency class
5	>0.3	1	Very likely
4	0.03 to 0.3	0.1	Likely
3	0.003 to 0.03	0.01	Occasional
2	0.0003 to 0.003	0.001	Unlikely
1	<0.0003	0.0001	Very unlikely

The central value represents the logarithmic mean value of the given interval.

Table 2
Injury to workers and emergency crew

	Disastrous	Severe	Serious	Considerable	Insignificant
No. of fatalities/injuries	$F > 10$	$1 < F \leqslant 10$, $SI > 10$	1F, $1 < SI \leqslant 10$	1SI, $1 < MI \leqslant 10$	1MI

F, fatality; SI, serious injury and MI, minor injury.

Table 7
Economic loss to owner

	Disastrous	Severe	Serious	Considerable	Insignificant
Loss in Million Euro	>30	3–30	0.3–3	0.03–0.3	<0.03

Table 6
Delay (two alternative examples are shown)

	Disastrous	Severe	Serious	Considerable	Insignificant
Delay (1) (months per hazard)	>10	1–10	0.1–1	0.01–0.1	<0.01
Delay (2) (months per hazard)	>24	6–24	2–6	1/2–2	<1/2

Table 8
Risk matrix (example)

Frequency	Consequence				
	Disastrous	Severe	Serious	Considerable	Insignificant
Very likely	Unacceptable	Unacceptable	Unacceptable	Unwanted	Unwanted
Likely	Unacceptable	Unacceptable	Unwanted	Unwanted	Acceptable
Occasional	Unacceptable	Unwanted	Unwanted	Acceptable	Acceptable
Unlikely	Unwanted	Unwanted	Acceptable	Acceptable	Negligible
Very unlikely	Unwanted	Acceptable[a]	Acceptable	Negligible	Negligible

[a] Depending on the wording of the risk objectives it may be argued that risk reduction shall be considered for all risks with a consequence assessed to be "severe", and thus be classified as "unwanted" risks even for a very low assessed frequency.

- The ITA Guidelines (2004) give detailed instructions on how to perform qualitative risk analysis → important: qualitative descriptions need clear meaning

- Quantitative Analysis (Monte Carlo Simulation) is recommended and will become even more important in the next guideline to represent state of the art.

OGG – Austrian Society for Geomechanics

Guideline for the Cost Determination for Transportation Infrastructure Projects

OGG Guideline - Contents

1. Objectives, Scope and Limits
2. Principles of Cost Determination
3. Cost Components
4. Aggregation of Cost Components
5. Cost Management
6. Tools for practical application

OGG Guideline - Contents

1. **Objectives, Scope and Limits**
2. Principles of Cost Determination
3. Cost Components
4. Aggregation of Cost Components
5. Cost Management
6. Tools for practical application

Objectives

Transportation infrastructure projects are characterised by

- long project duration
- High number of participants and stakeholder
- Factors difficult to predict (Financing, political /legal environment, etc.)
- Uniqueness

Identification of potential risks and consideration of unknown events that we know from experience might occur during planning and execution is essential for succesful infrastructure projects.

The ***Guideline for Cost Determination for Transportation Infrastructure Projects*** provides the basis for an appropriate cost determination, cost stability and achievement of project objectives.

Scopes and Limits

The OGG Guideline can be used for

- Infrastructure projects
- Tunnel construction (cut & cover and mined tunnelling)
- Road construction
- Bridges
- Power Plants
- Airports
- Railway Stations
- Repair and maintenance works, etc.

The guideline governs cost determination in the planning and design phases. Cost monitoring in the construction phase, and actual costs as the project is executed, are not within the scope of this guideline.

→ Owner’s Perspective

Project Phases and Methods of Cost Determination

	Project Initiation Phase	Project Development Phase	Preliminary Project Planning and Design Phase	Project Approval Phase	Tendering / Contracting Phase	Construction / Execution Phase	Final Projec Phase / Contr Closeout
Activity	Conceptual Planning	Basic Planning	Preliminary Design	Project Documents advanced to secure "Approval to Construct"	Contract Documents Published for Bidding / Tender	Project Execution and Construction	Close out Contracts, Fir Payments, Formal Acceptance
Project Milestones	Project objectives, Project start / Project Completion	Product Requirements, Document Purpose and Need	Basic Project Characteristics Defined	Submission to Authorities for Approval to Contract	Transition from Design to Construction	Award / Notice-to-Proceed	Project Completion
Cost Calculation Milestones		Cost Framework Defined, Preliminary Estimate	Update and Advance Cost Estimates	Update, Cost Estimate for Approval	Owner's Tender Cost Estimate	*Not subject of this guideline*	
Costing Methods		Benchmark Method	Benchmark and Element Method	Method according to the planning status: Element Method	Item Method		

Project Phases and Methods of Cost Determination

Project Initiation Phase

Based on the defined purpose and need, project objectives, general characteristics, and an initial cost estimate are defined using conceptual planning.

Project Development Phase:

- Preliminary cost estimate
- Requirements and location analyss, feasibility studies, project conceptualizations.
- Requirement document (incl. Performance, cost and schedule objectives)

Preliminary Project Planning and Design Phase:

- Update and advance cost estimate
- Routes and project alternatives decision
- Costing Method: Benchmark and Element Method

Projektphasen und Methoden der Kostenermittlung

Project Approval Phase:

- Draft and authorization planning documents
- Verification and acceptance by authorities
- Costing Method: Element Method

Tendering/Contracting Phase:

- Prepare and finalize tender documents
- Evaluation of bids
- Can sometimes start during Project Approval Phase
- Costing Method: Item Method

Construction Phase:

- Starts with signing of contract and notice-to-proceed
- Cost monitoring incl. changes

Projektabschlussphase

- Closing-out of contracts, final invoicing, analysis and reconciliation of accounts, benchmarking, and „as built“ documentation

Structing Cost: Work Breakdown structure

The cost structure to be used is based on the project's structure, configuration, and phases. A **Work Breakdown Structure (WBS)** is recommended that separates the project into definable elements and units used for cost estimating and controlling (tasks, partial tasks) (…).

The work breakdown structure can be organized using different approaches:

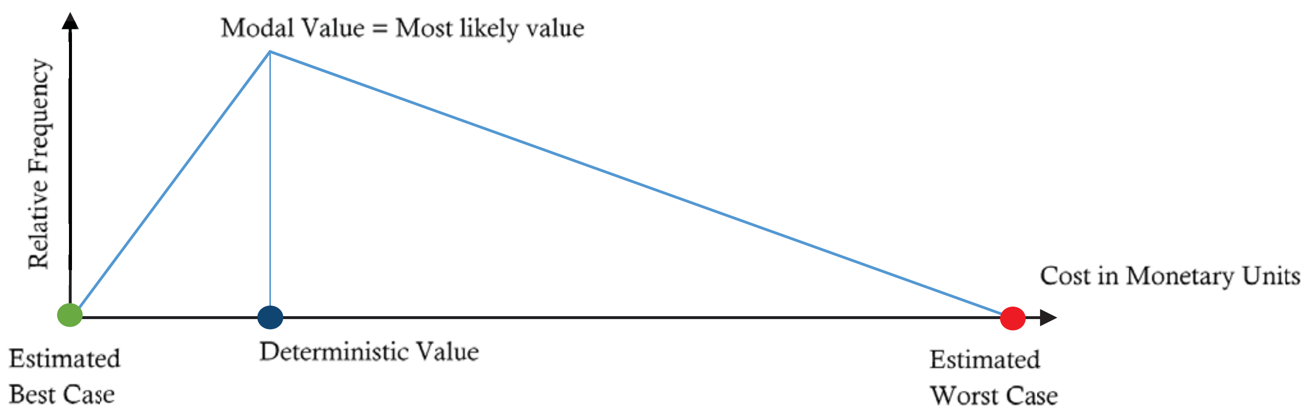
- **Construction Phases**
  Construction phases are finite, time-related or logical segments of a project

- **Objects**
  Individual parts and construction groups based on the similarity of the pertinent objects (bridges, tunnels, …)

- **Organisational function**
  Function-orientated organization of the WBS (contracts, building trades, …)

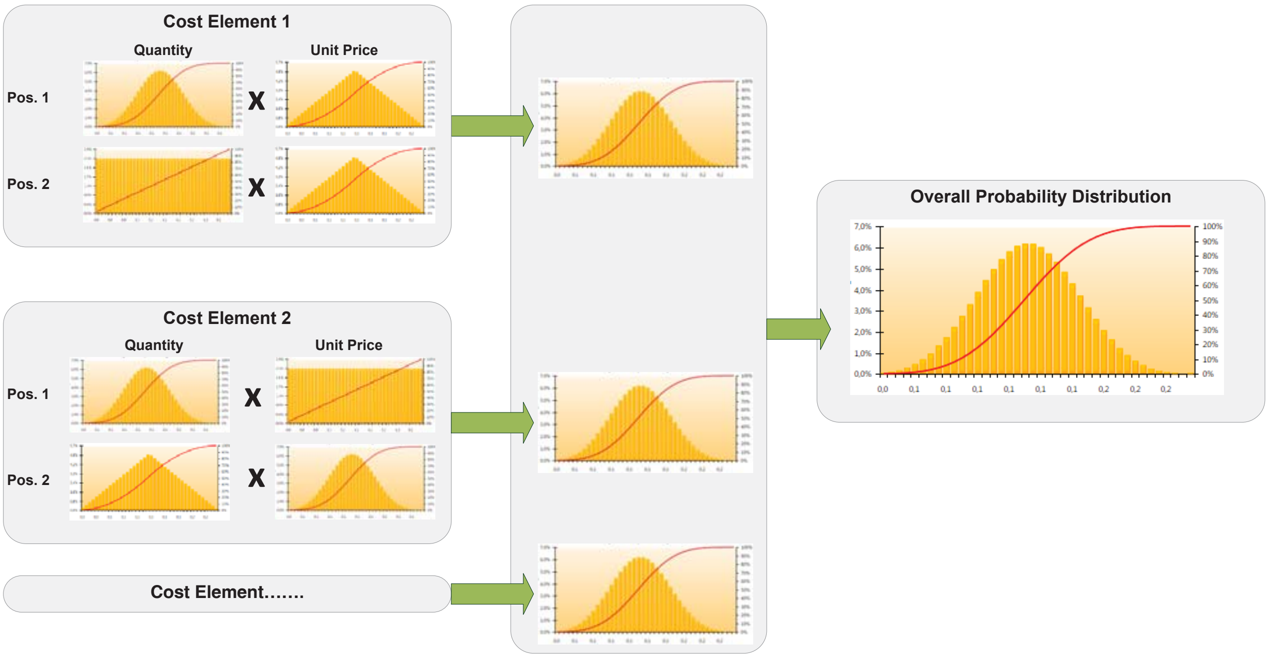
Dealing with Uncertainty

If costs are predicted using a deterministic approach (by single numbers for project elements or in total), there is no allowance for, or quantification of, uncertainty. It is almost certain, how-ever, that so-called "exact values," predicted deterministically, will not materialize exactly during construction.



Dealing with Uncertainty

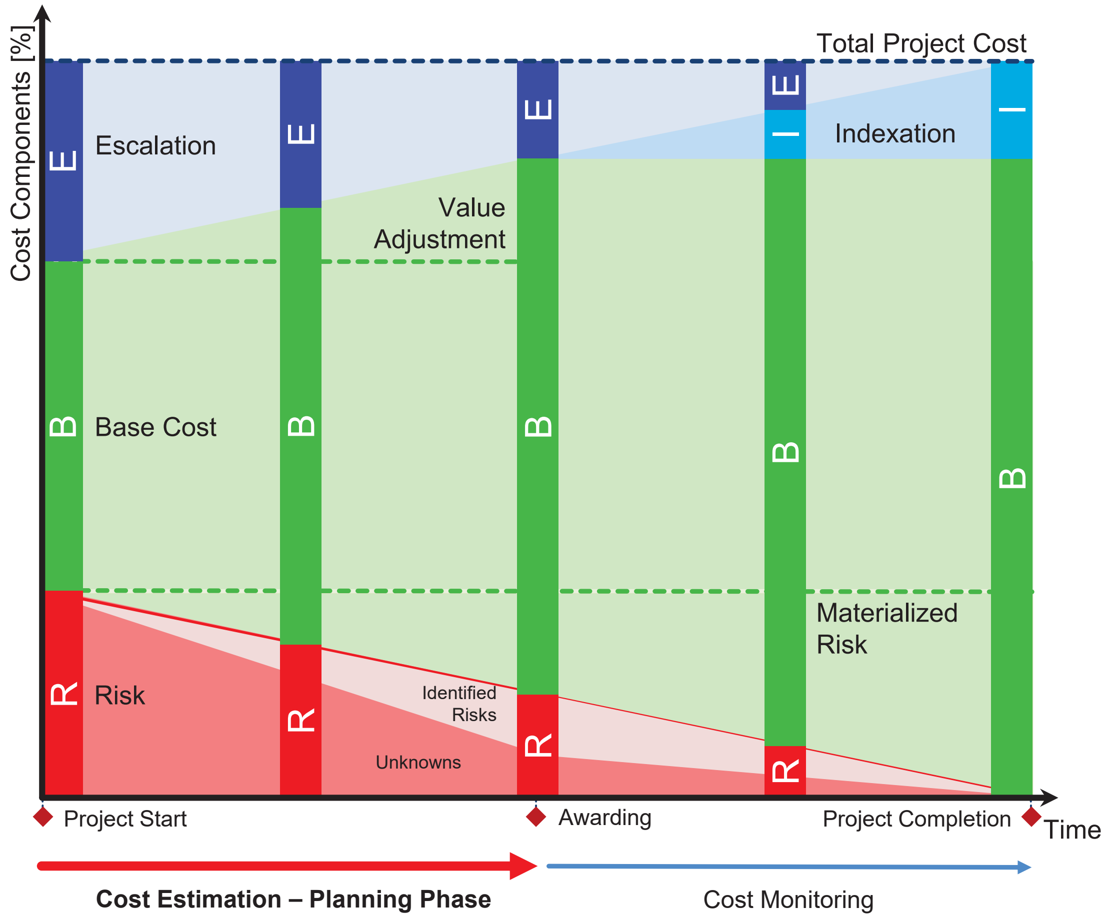
Calculation of overall probability distribution by aggregating cost elements using a probabilistic approach. Individual cost elements are represented by appropriate distributions to account for uncertainty. The result is an aggregated probability distribution of costs that takes prediction-based deviations into account.



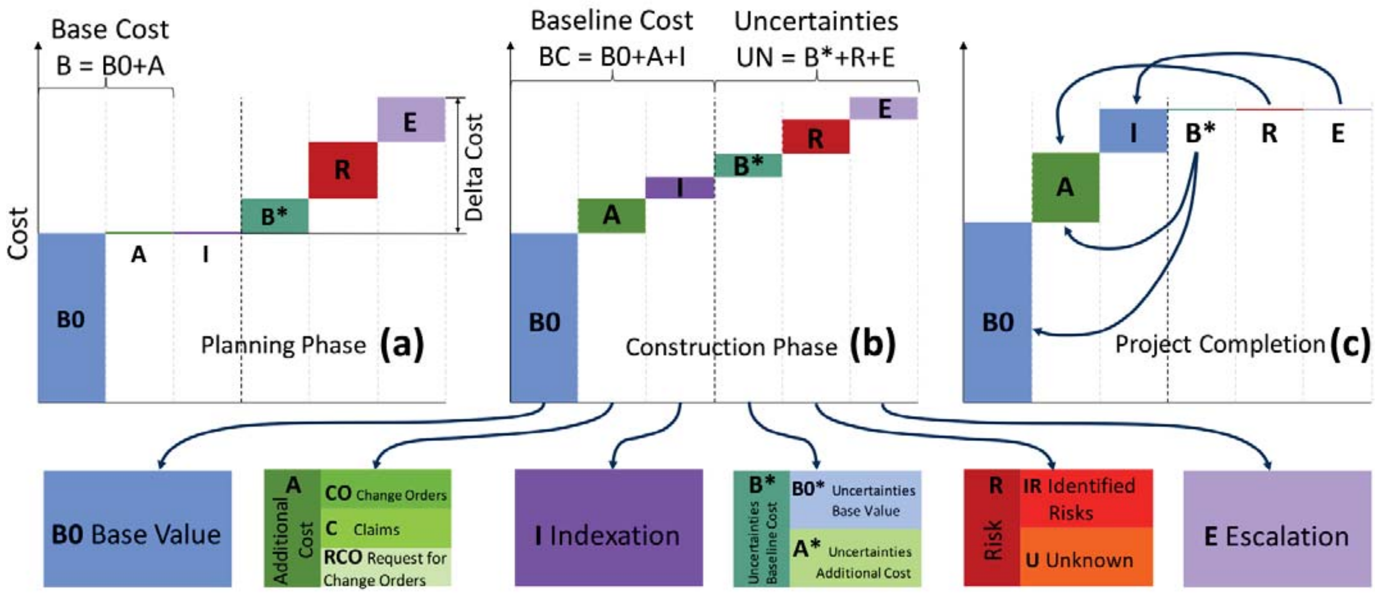
OGG Guideline - Contents

1. Objectives, Scope and Limits
2. Principles of Cost Determination
3. **Cost Components**
4. Aggregation of Cost Components
5. Cost Management
6. Tools for practical application

Cost Components during a project



Cost Components Structure



Base Cost

Base Cost

The base cost is that cost which can reasonably be expected if the project materializes as planned, with a defined content, schedule, and market situation.

The base cost estimate does not include contingency or the cost of potential risk events or escalation. The base cost is determined in accordance with a specific, defined base price and base date.

→ Deterministic Approach or Probabilistic Approach

The choice of method for the determination of base cost depends on the project phase. The following methods can be used, depending on the level of detail required:

- Benchmark method: reference values for high-level components
- Element method: reference values for typical project elements
- Line item method: line items from a bill of quantities

+ Base Cost Allowance (Contingencies for components that are not yet described in detail and are therefore not included in the base cost estimate)

Value Adjustment and Indexation

Value Adjustment

Value Adjustment is used to take into account a real market price development from, or related to, a certain reference date, which was previously included in Escalation.

- Base cost estimation is adjusted to current market prices → result: new price base
- Value Adjustment = Pre-Contract

Indexation

- Contractual clause for price adjustments according to a certain index value
- Indextion = After signing of contracts, relevant for invoicing

With signed (active) contracts, price adjustments are generally planned for and made based on contractually stipulated cost indexes or agreed-upon inflation related to project-specific commodities. In contracts with **fixed pricing**, the cost component for indexation is zero.

Risks

Risks

are Threats or Opportunities. The ability to characterize risk improves with increasing knowledge of the project as well as the experience of the project team.

If risks actually occur during project development and/or construction, in principle the associ-ated cost components can be added to the base cost and removed from the estimated risk cost (since the risk has occurred).

Risk cost is divided as follows:

Identified Risks + Mark-up for Unknowns = Risk Cost (R)

Identified risks include, based on the phase of the project, all characterized individual risks.

Unknowns can be divided into:

Unidentified Risks + Unidentifiable Risks = Unknowns

Approaches to determine Risk Cost

Three methods are used to determine risk costs:

- Benchmark method
- Risk identification and characterization
- A combination of the two

Benchmark method

Risk Cost is determined as a lump sum surcharge on base cost.

The following aspects have to be accounted for:

- Project Phase,
- Project Complexity
- Ground conditions,
- No individual risks are evaluated.

Approaches to determine Risk Cost

Analysis of Individual Risks

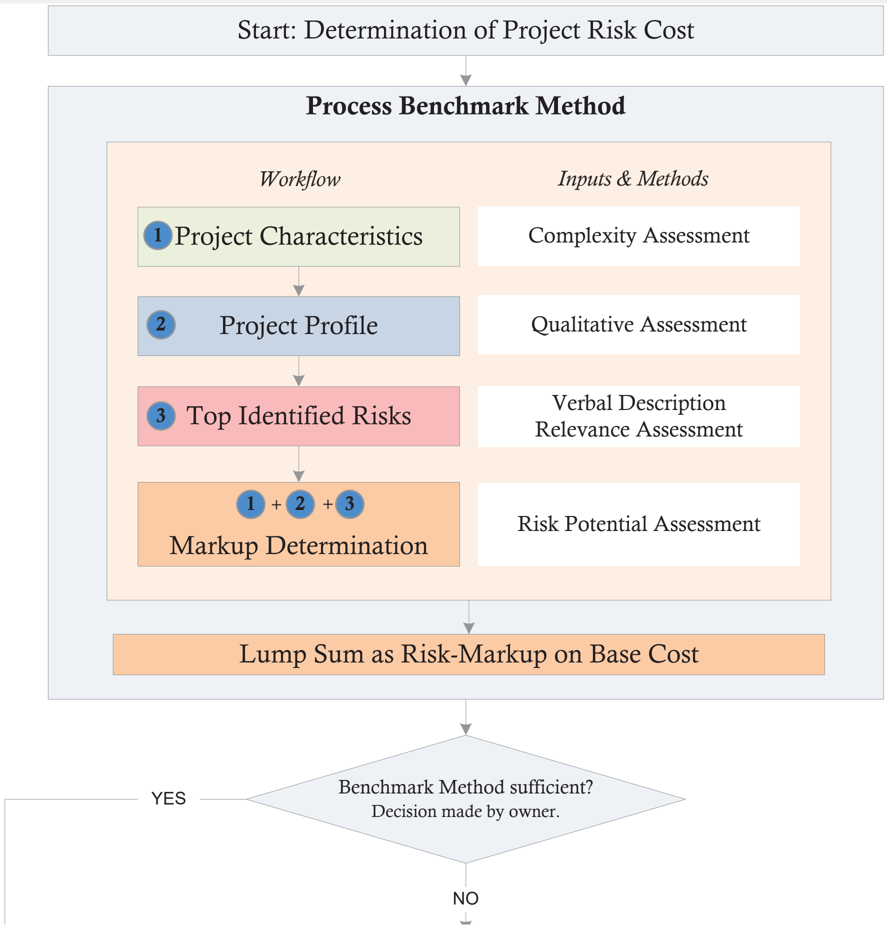
If using an individual risk evaluation, risk costs are determined from the sum of all identified risks plus a certain amount (allowance, contingency) for unknowns that is added to the risk costs. The resulting amount is then added to the base cost to give the total estimated project cost.

This procedure is in accordance with ISO 31000 (→ see previous slides)

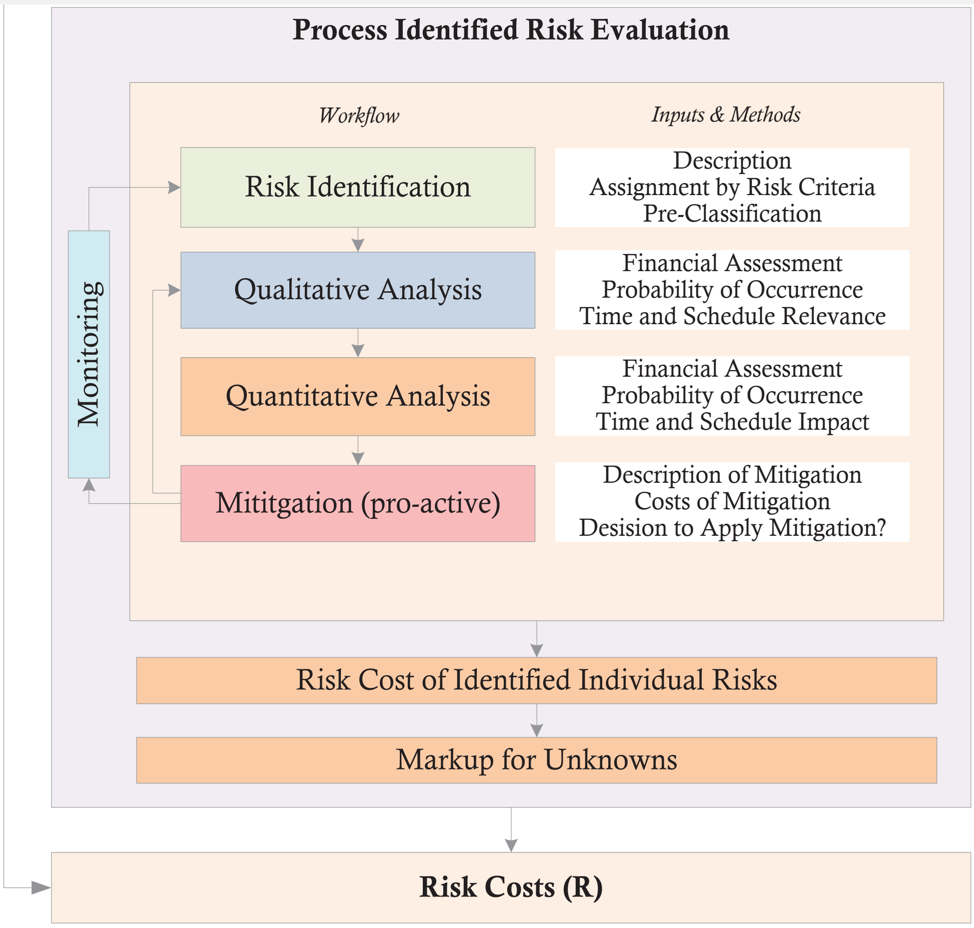
The decision which approach for estimating risk cost is used depends on:

- Project size
- Complexity
- Public perception
- Available resources / data basis

Process Sequence

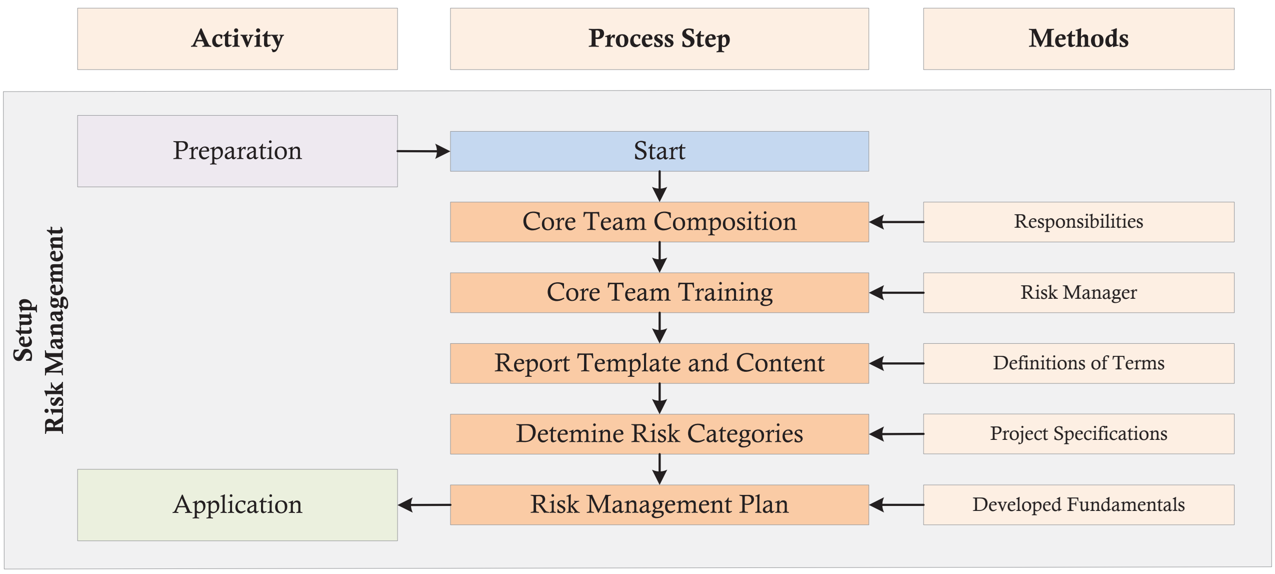


Process Sequence



Vorbereitung Risikoanalyse

It is recommended that this process be organized in a structured manner with an expert cost/risk moderator and that the process be executed as follows:



Risk Breakdown Structure

The following list of risks is divided into categories in order to support administration of the risk identification and characterization process. The following structure follows from an evaluation of risk causes (triggers) to ensure that duplicate risks are not included.

Abbr.	Category	Typical Description	Examples
PD	**Planning Development**	The development of project detail in the planning stage with no change of project scope.	Advancing design of project elements with increased understanding and definition.
CO	**Cost**	Updated estimation of cost with unchanged project scope.	Obtain cost quotes for the E+M cost of a power plant.
RE	**Real Estate**	Cost and/or schedule changes caused by changes or updates in real estate acquisition.	Delays as a result of prolonged processes or required authorizations for real estate acquisition, which is necessary for the project. New considerations of official real estate acquisition requirements.
AU	**Authorizations**	Changes in the requirements for, or processing of, authorization procedures.	Delays in obtaining approvals. Consideration of new official requirements.

Risk Breakdown Structure

CT	**Contract**	Contract modifications	Deviations (changes) in the contract, that are necessary, in order to achieve authorized project
01	*Contract modifications*	Additional specifications or requirements, which do not appear in the contract, but are necessary to complete the project.	Missing work in bill of quantity.
02	*Quantity deviation*	Quantity deviations from the initial contract with no changes to project scope.	Amount of excavation is more than planned
03	*Contract disputes*	Different interpretations of contract by client and contractor.	Type of ground is different that planner by owner and/or anticipated by contractor.
04	*Process optimization*	Changes required for optimization of contracted services with no change of project scope.	Alternative excavation support system, value engineering required changes.
05	*Changes in design*	Changes to design requirements with no change of project scope.	Mistakes or errors in planning or design services.
06	*Compliance with requirements or agreements*	Contract compliance.	Compliance with official requirements and agreements, that were known at the stage of planning/design but were not implemented in the
CH	**Change Order**	New or changed requirements for the project ordered by the client.	Changes in project scope or schedule or conditions, compliance with third-party needs.
GC	**Ground Conditions**	Changed requirements, originating from unknown or insufficiently known underground conditions.	For example: -changes of soil classifications -ingress of water, additional flows -cave-ins
01	*Changed conditions*	Conditions are different than planned or assumed.	Differences between predicted and actual underground conditions, soil types, quantity of water
02	*Design assumptions*	Differences between planned and actually occurring ground or support system behavior.	Changes to shotcrete or reinforcing required in construction under the observational method.
03	*Unforeseen events, circumstances*	Occurrence of unforeseen underground conditions.	Gases, ingress of water, collapse, running sands, high abrasivity.
MF	**Market Forces**	Changes in prices and/or costs, that originate from market forces such as limited availability of labor or materials.	Inflation + escalation, general market conditions, economic conditions, changes in costs or fees, tracking errors, limitations on competition, difficulties in awarding contracts.

FU	**Funding**	Risks due to difficulties in funding or obtaining authorizations, deviations from planned financing models.	Rising interest costs due to short-term financing (supplementary financing) or due to amended foreign currency loans, reduced revenues.
PE	**Project Environment**	Environmental or project context changes, which affect the progress of the project or project costs.	Differences between contractual partners, contractor deficiencies, owner issues, internal/management risks.
01	*Third party costs*	Expenses or requirements relating to local residents or municipalities.	Additional measures (protection against dust, noise, etc. - not required by regulations), public events, citizens' initiatives, demonstrations, educational events, information material.
02	*Basic infrastructure*	Changes in basic infrastructure elements.	Road closures, restrictions of transit at local areas, power and water supply.
03	*External interfaces*	Changes of contract and/or project interfaces, which may not be in the client's sphere of influence.	Changes in authority, responsibilities, deferrals to other projects, changes in laws or regulations, new interpretations of regulations.
04	*Law, regulations, requirements*	Changes in laws, regulations, requirements.	Laws/guidelines/standards/provisions/official requirements.
05	*Adjacent Structures*	Deviations in extent, quantity and/or quality, between assumed and discovered conditions, of buildings or adjacent structures.	Neighboring houses that are in danger of damage or collapse
06	*Safety, Security*	Additional measures required to avoid incidents that endanger the public or construction site safety.	Thievery, vandalism, security services, health and safety requirements on the construction site
IN	**Internal**	Changes as a result of internal changes to project (e.g. management).	
01	*Staff*	Personnel resources and management.	Staff turnover, staff reduction, changes in staff deployment; issues with staff qualifications, staff availability.
02	*Organization*	Organizational management.	Clarity of organization, definition of roles and responsibilities, issues with internal and external communication, management of scope and schedule.
CN	**Contractual**	Contract Changes	Changes in costs or schedule or requirements, associated with project participants and new requirements, not necessarily arising from changes to
01	*Interface*	Interface requirements that are in the client's sphere of influence.	Organizational interfaces with contractor or third parties which impact cost or schedule.
02	*Contractor*	Suitability, capability	Qualifications, quality of execution, potential insolvency, technical, economical and financial performance issues, reliability and authority.
FM	**Higher forces, Force Majure**	Effects of higher level forces or Force Majure to an extent that is more than usually expected in planning or design.	Earthquakes, flood, avalanches, war, extraordinary weather conditions, storms, environmental disasters, strikes, labor disputes.

Escalation

Escalation

Cost indices for escalation are a methodical approach that takes into account assumed future market fluctuations from a specific cut-off date until the end of the project. Unlike value ad-justment (I), these costs consider market price developments as of a certain cut-off date as cost indices for escalation (E).

Estimation of:

- Market price development
- Cash outflow of the project

Value Adjustment & Indexation → Past price increase (adjustment)

Escalation → Future price increase (prediction)

Aggregation of Cost Components

Prognostizierte Projektkosten

The determination of total estimated project costs (BIRE) requires the aggregation of the cost components of Base Cost (B), Escalation (E), Risk (R), and Prospective Value Adjustment (I). The type of aggregation to be used is dependent on the methods used to determine the individ-ual cost components.

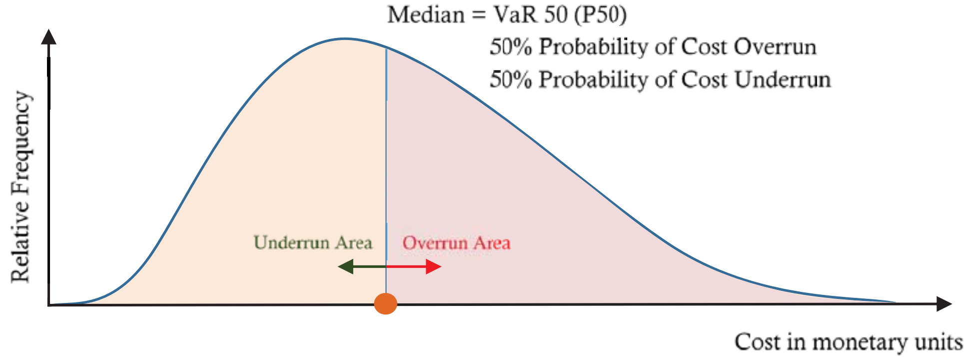
BIRE = B + I + R + E

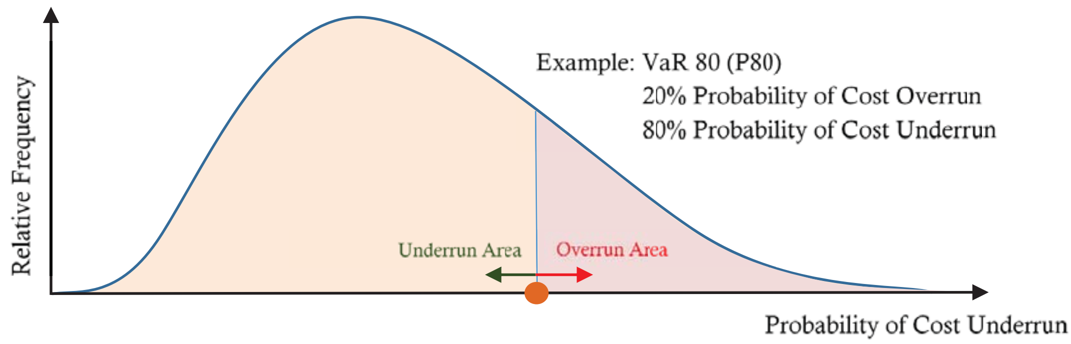
If all cost components have been calculated in a deterministic manner, they are added together arithmetically. The result (BIRE) is then a deterministic value whose probability of occurrence cannot be predicted. Therefore, no quantitative statement can be made as to the degree of cost certainty.

If at least one cost component – for example, risk costs – has been determined using the prob-abilistic method, the aggregation should be carried out according to the rules of the probabilistic method.

Aggregation of Cost Components

For a probabilistic estimation of cost components, the contracting authority can choose a specific probability for budgeting, considering the likelihood of cost over or under runs.



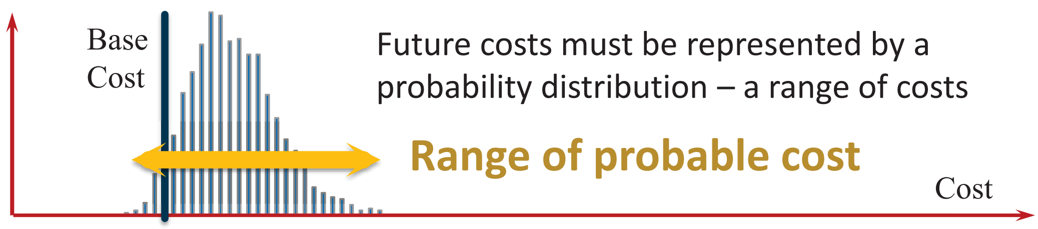


We Must Address Risk and Uncertainty

Components of cost which need to be sufficiently addressed in a cost estimate include:

- Base cost – the cost that will result if “all goes according to plan”
- Variability in base costs
- Risk costs resulting from probable risk events

In the beginning there is a large potential range for a project’s ultimate cost – depending on events that may occur



Cost Management during construction

During the construction phase, cost management requires periodic checks of the estimated project costs. Cost prediction as a whole must be updated taking into consideration the results of the tender procedures and the changes in the services required during execution.Die Kostenverfolgung in der Ausführungsphase wie auch die IST-Kosten als Teil der Projektkosten sind nicht Gegenstand dieser Richtlinie.

Final accounting

Once the project has been completed and after all final invoices have been accepted, the total project costs (actual, out-turn costs) will be determined and defined.

The result is the basis for the subsequent management and amortisation of the infrastructure and is used to assign a value to the infrastructure in order to obtain cost benchmarks.

OGG Guideline - Contents

1. Objectives, Scope and Limits
2. Principles of Cost Determination
3. Cost Components
4. Aggregation of Cost Components
5. Cost Management
6. **Tools for practical application**

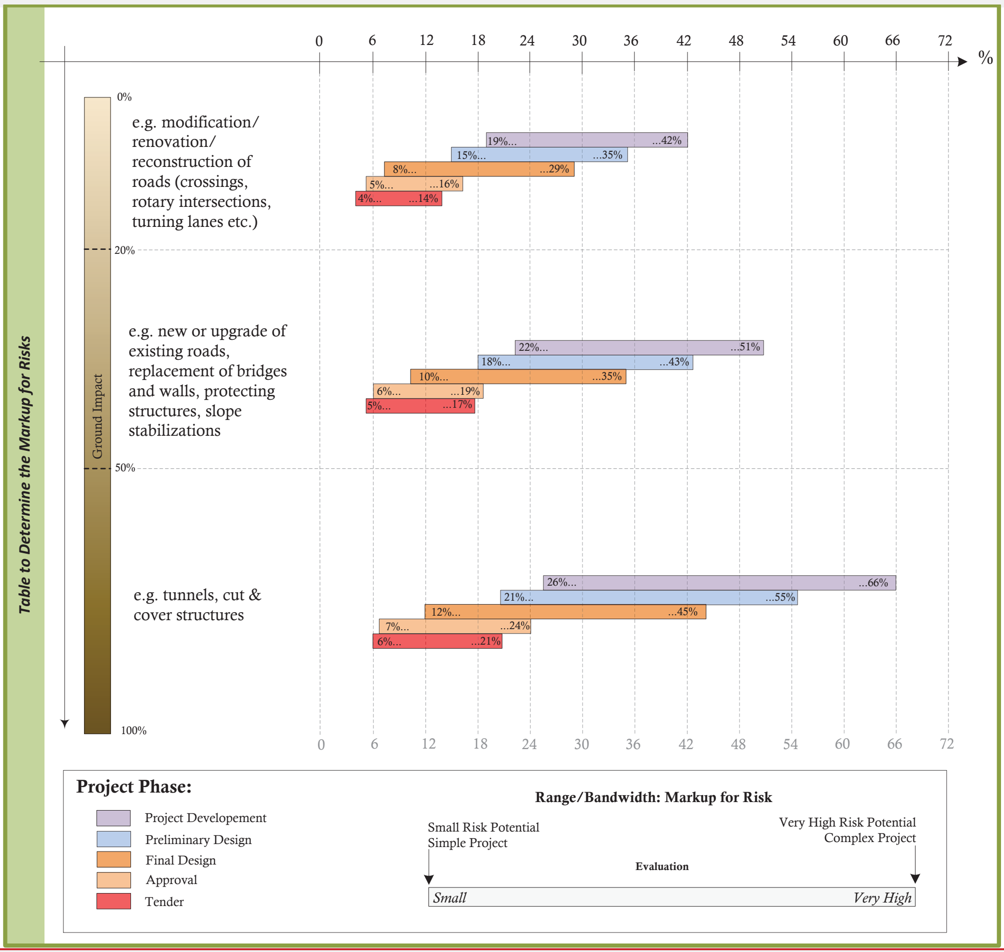
Risk Fact Sheets

The OGG Guideline includes details about Risk Fact Sheets to determine risks using:

- Benchmark method
- Individual Risks

→ See Part 3 of this course

Possible results of the benchmarking method are summarized in this picture:



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Workshop on NATM & TBM Tunnelling incl. Risk Management

2 - Risk Management – Standards and Guidelines

6 – 8th February 2018, New Delhi, India

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3 – Risk Management – Process and Application

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RiskConsult GmbH www.riskcon.at

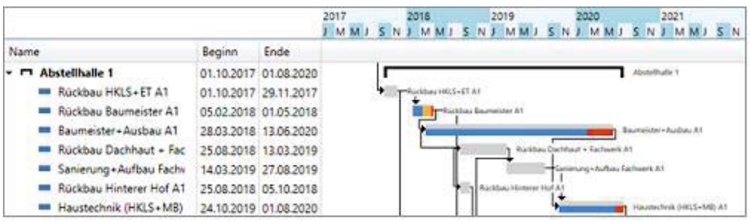
RM-Process

- **Use Cost Component Structure**
  - Base Cost
  - Risk
  - Escalation

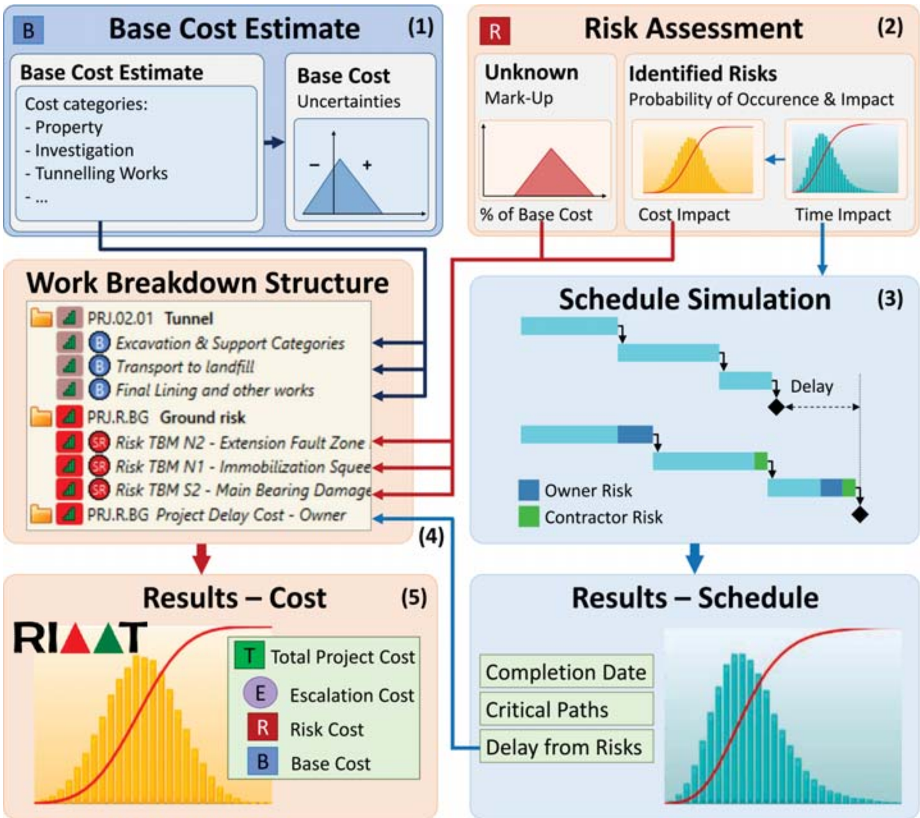
B + R + E = BRE

- **Include uncertainties** (min, most likely, max value)

- **Integrated Cost and Schedule Analysis**
  - Include Cost caused by Delay



RM-Process



Work Flow

(1) Base cost estimate is reviewed, associated with uncertainties and integrated into the WBS.

(2) Risks are assessed (cost & time impact) and integrated into the WBS.

(3) Risks are assigned to tasks in the project's schedule. Subsequently, completion date, critical paths and delays from risks are simulated.

(4) Cost impact from time delay is calculated with time-related cost and integrated into the WBS.

(5) Project Cost including uncertainty is available at all WBS levels and for all cost components.

Live Demonstration – RM-Process

RIAAT
Risk Administration and Analysis Tool

PRAT

B ase Cost

- Cost Estimation
- Ranges (Quantities & Prices)
- Allowance

R isk

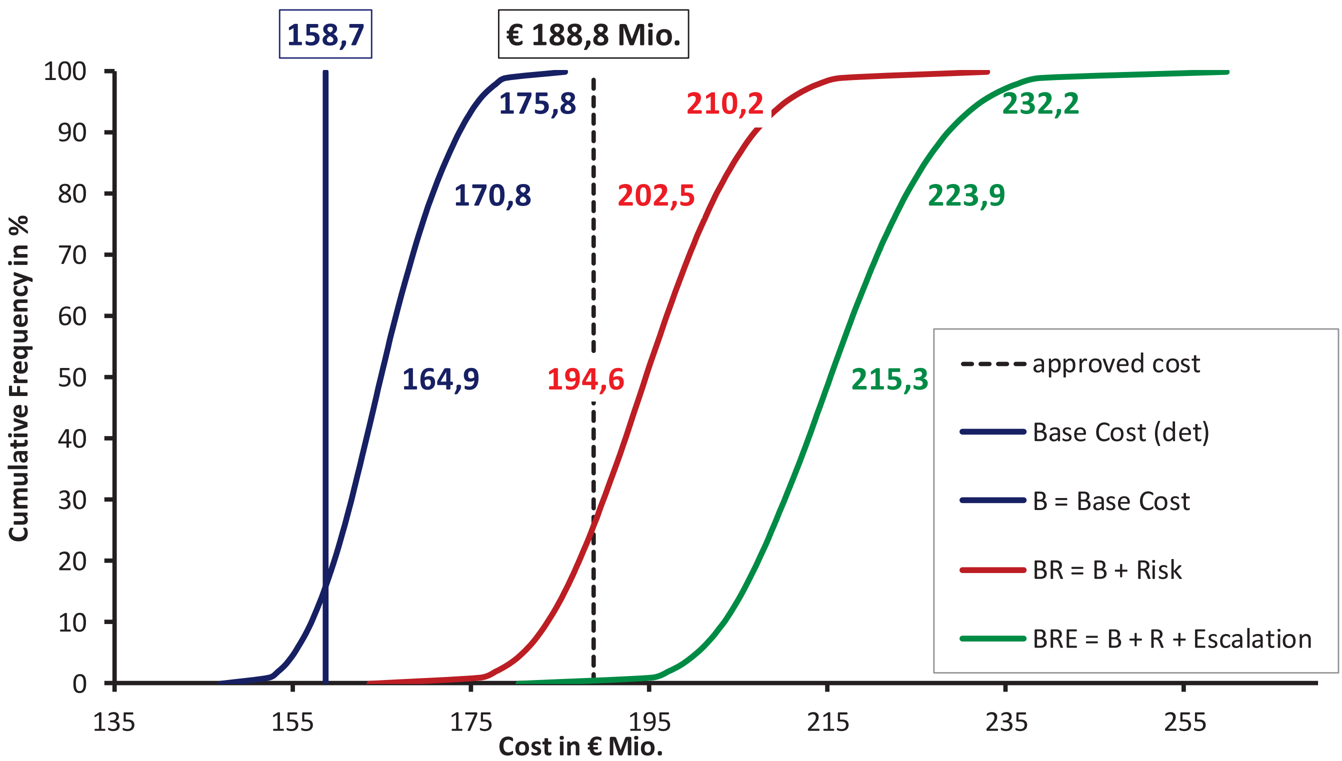
- Benchmark Method
- Identify & analyze Single Risks
- Import into Model

E scalation

- Estimate Price Increase
- Estimate Cash Outflow

BRE

Results



RIAAT – Risk Administation and Analysis Tool

RIAAT

Cost Estimates • Risk Management • Cost Control

Further Information: http://riaat.riskcon.at

- **Cost Estimate**
  Hierarchical project tree, Work Breakdown Structure, central price database
- **Risk Analysis**
  Qualitative and quantitative assessment
- **Probabilistic Methods**
  to increase the value of your forecast
- **Cost control**
  - Managing change orders and procurement
  - Determine cash flow
- **Numerous visualization options**
- **Reports**
  - Custom reports with tables and graphics
  - Various import/export options for MS Excel

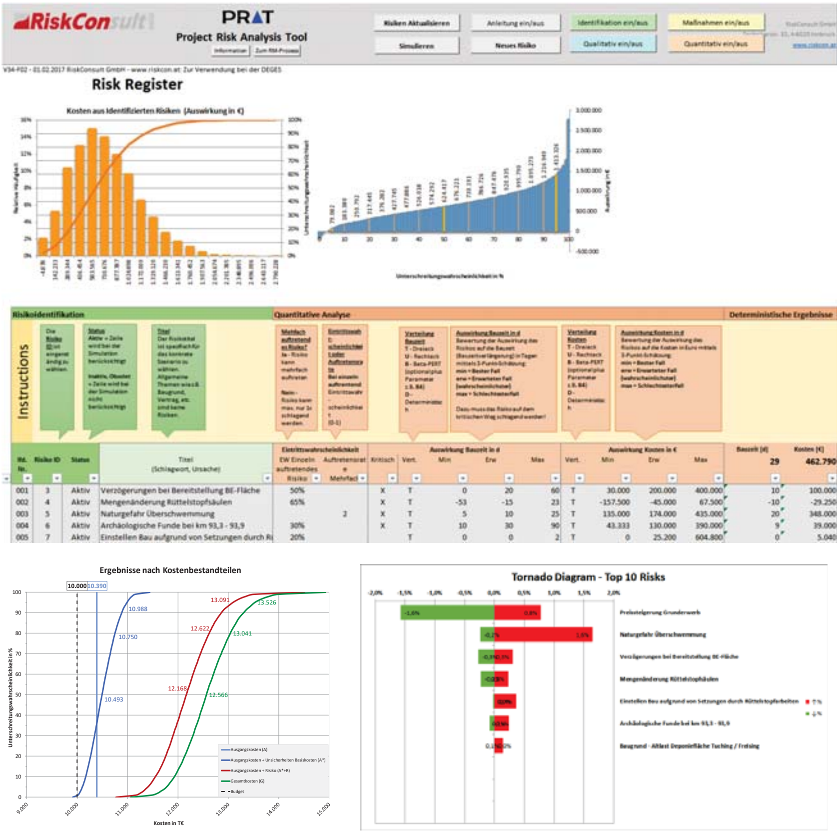
PRAT – Project Risk Analysis Tool

PRAT

Implementation of Risk Management Systems

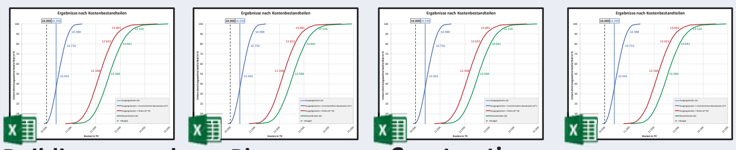
more information on https://riskcon.at → products

- **Excel-VBA Based Tool**
  Allows for a fast and efficient adaptation according to the needs of the organization
- **Risk Management Process**
  implemented RMP according to ISO 31000. For each process step, PRAT offers well-proven tailored methods for construction projects
- **Cost Components**
  factors such as Base Cost, Risk and Escalation help to structure cost according to the needs of an organization.
- **Monte-Carlo-Simulation (MCS)**
  to consider uncertainties, distributions are used to model risks. Results will be depicted using probability distributions.
- **Risk Fact Sheets**
  a guided process for risk identification and analysis providing qualitative and quantitative methods.
- **Risikoregister**
  identified risks will be listed in a comprehensive risk register for further analysis.



PRAT / RIAAT Interface

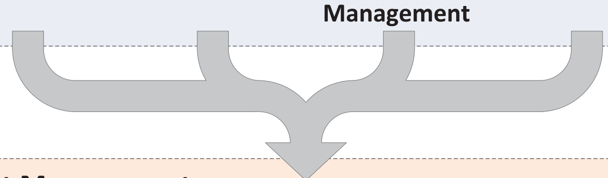
External



Building control | Planner | Construction Management | .....

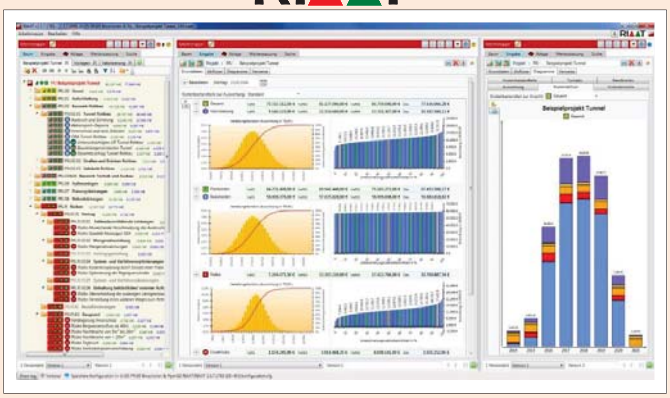
All parties involved can record their costs and risks in their own PRAT-Version.

Via Monte Carlo Simulation the gathered information can be evaluated to draw conclusions about Sensitivity, Bandwidth and Impact of recorded Risks.



Project Management

RIAAT



In collaboratively conducted Workshops the information gathered in the separate PRAT-Files is condensed within one pivotal RIAAT-File.

The data is then aggregated and the results are periodically summarized in management reports.

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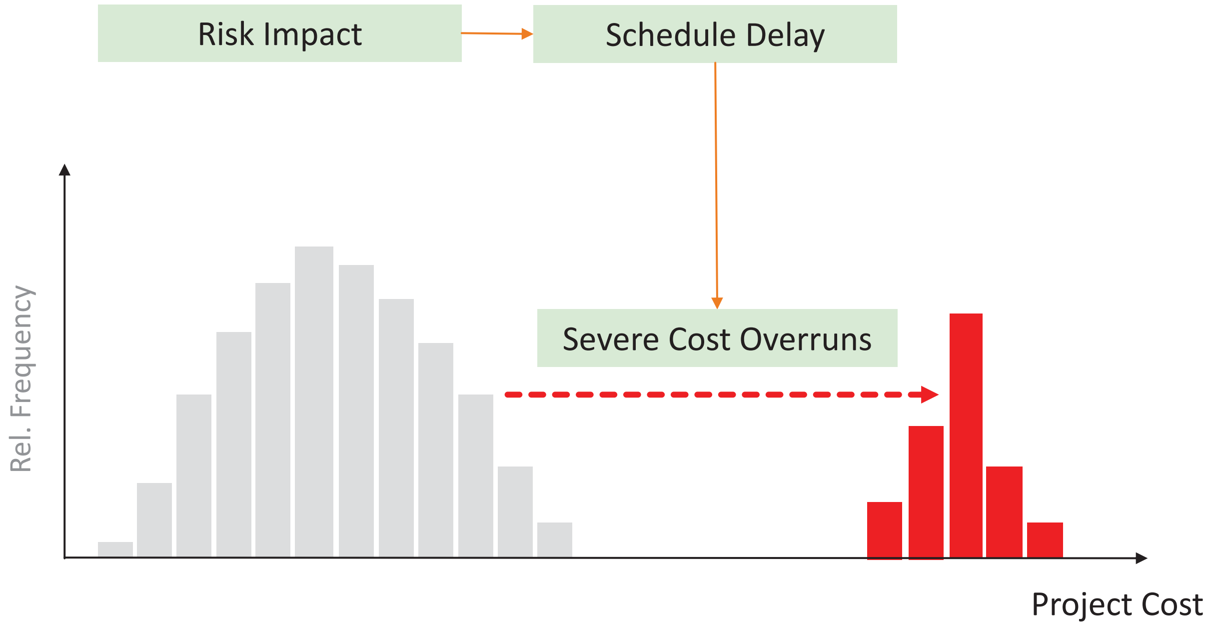
Integrated Cost & Schedule Analysis

Impact of Delays on Project Cost



Cost Prediction for Large-Scale Projects

Standard Approach

→ Cost (Base Cost + Risk + Escalation) and schedule are treated

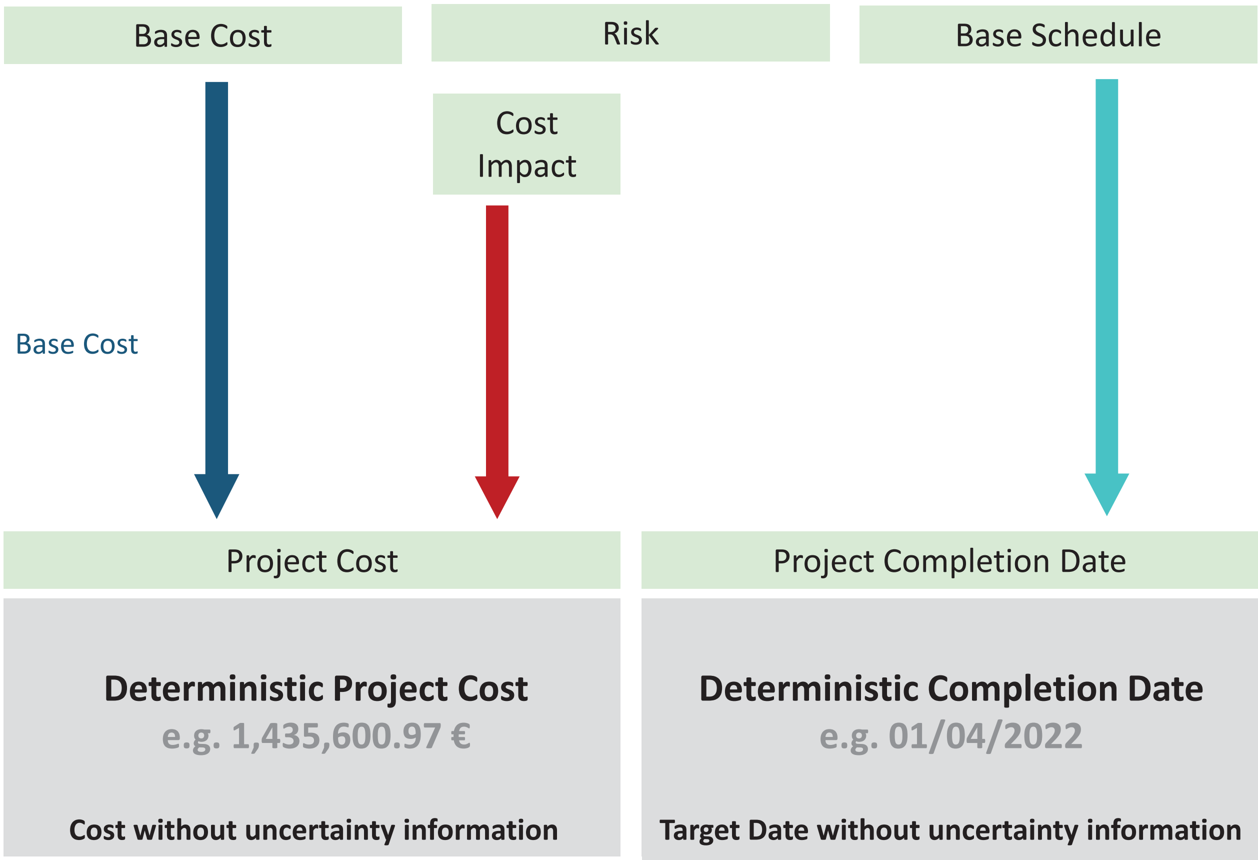
- **separately**
- **deterministically**

Statement

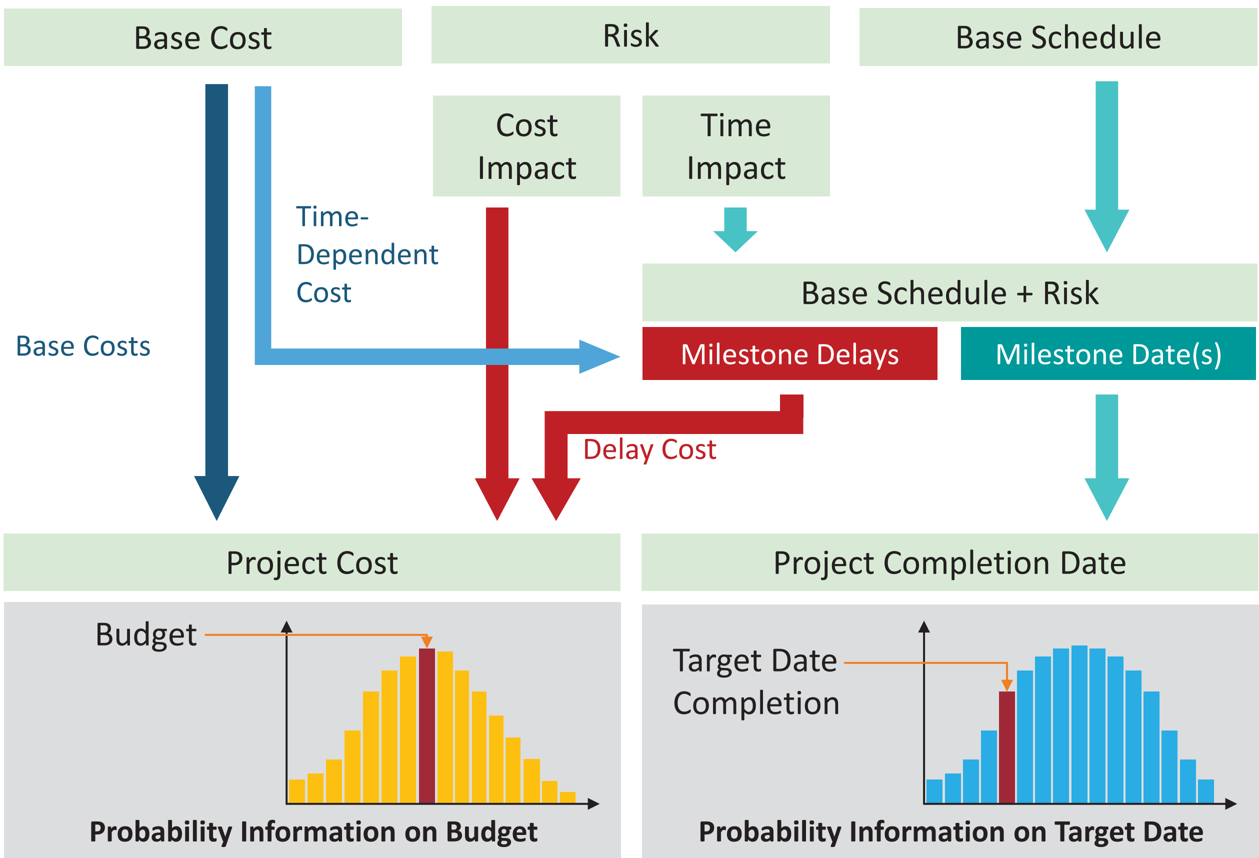
→ **Integrate cost and schedule.**

→ Consider **uncertainties.**

Standard Approach



Integrated Cost & Schedule Analysis



Scheduling – To not see the forest for the trees

1. **Condense Schedule**

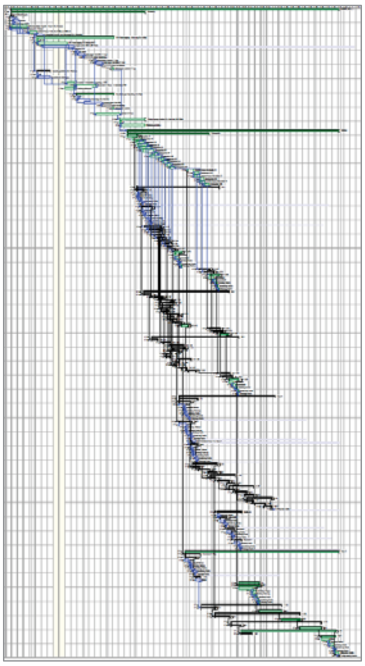
   Convenient level of detail, keep important dependencies, seek for clarity

2. **Ongoing dynamic adaptions**

   Reproduce actual current situation

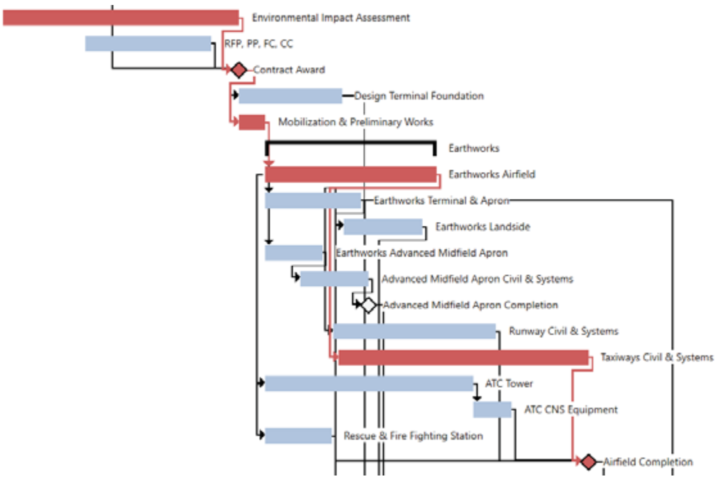
3. **Uncertainty**

   Incorporate uncertainty and risk to understand the impact on your milestones.

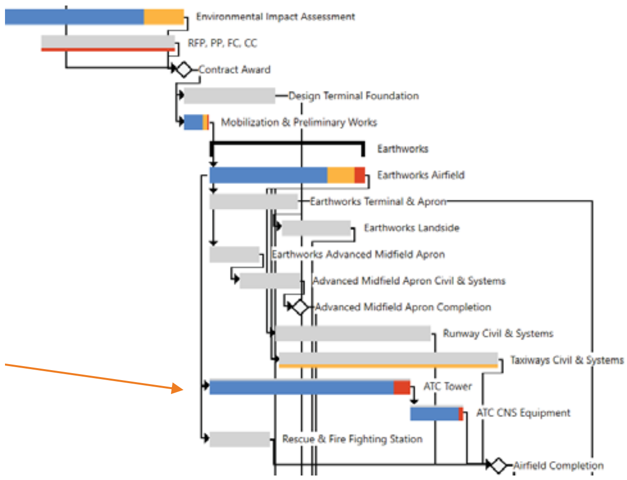


Example – Change of Critical Path

Base Schedule



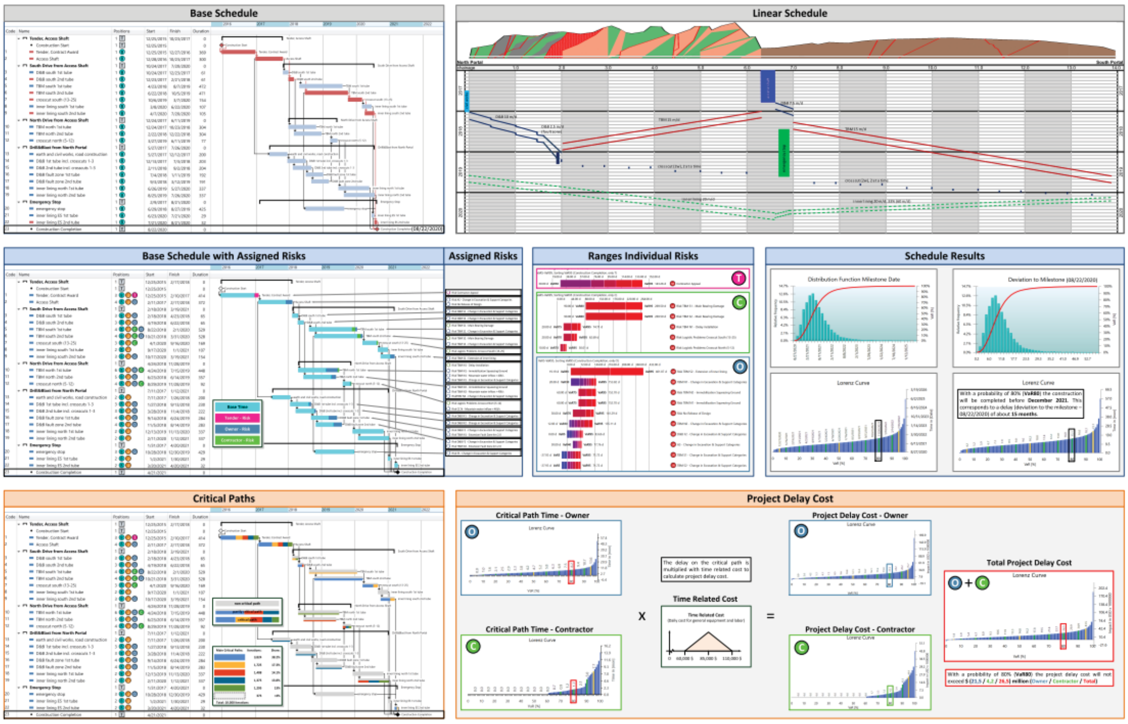
Base Schedule + Risk



Critical path is changing to ATC tower due to risk impact

Live Demonstration – Integrated Cost & Schedule Analysis

RIAAT
Risk Administration and Analysis Tool



Risk Ranking

Risk Mitigation

Ranking / Classification of Risks for Risk Mitigation

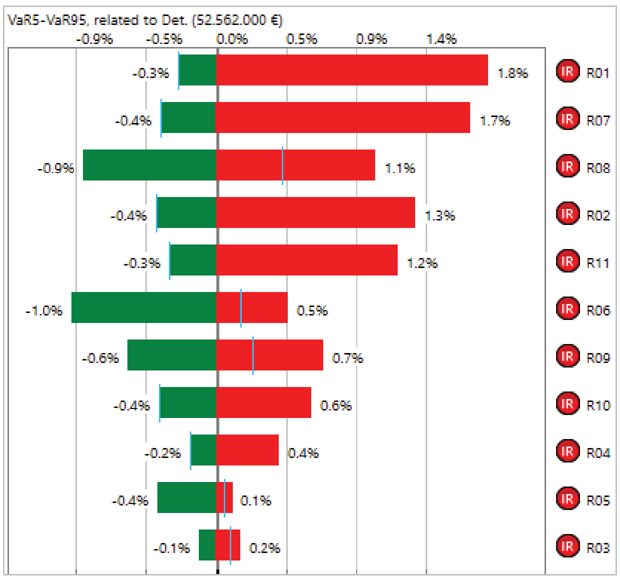
Risk	Pre-Mitigation	
	Probability of Occurence	Impact
R01	15%	900 000
R02	25%	850 000
R03	50%	120 000
R04	40%	230 000
R05	90%	230 000
R06	85%	600 000
R07	30%	650 000
R08	60%	780 000
R09	70%	450 000
R10	45%	450 000
R11	30%	550 000

- Risk Ranking / Risk Classification:
  - Cost
  - Time
  - Milestones
- Selection of Risks:
  - Review Top Risks
  - Select for Action
  - Plan Mitigation Measures
- Decision to activate Mitigation Measures
- Implement Mitigation into Risk Management & Monitoring Plan

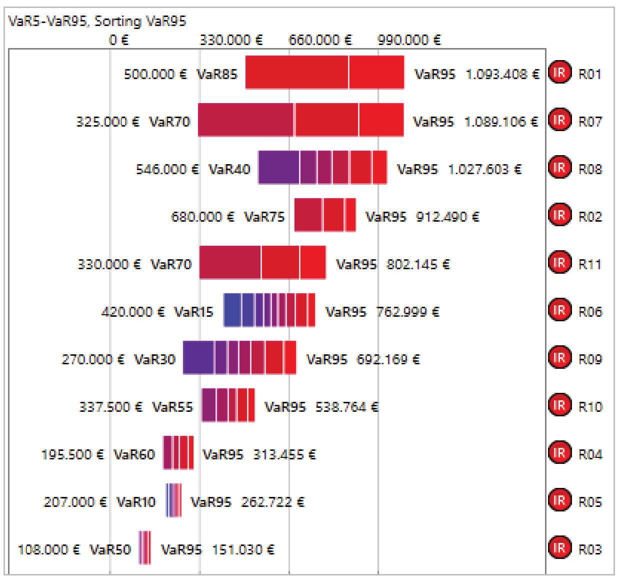
Live Demonstration – Risk Ranking

RIAAT
Risk Administration and Analysis Tool

Tornado Diagram



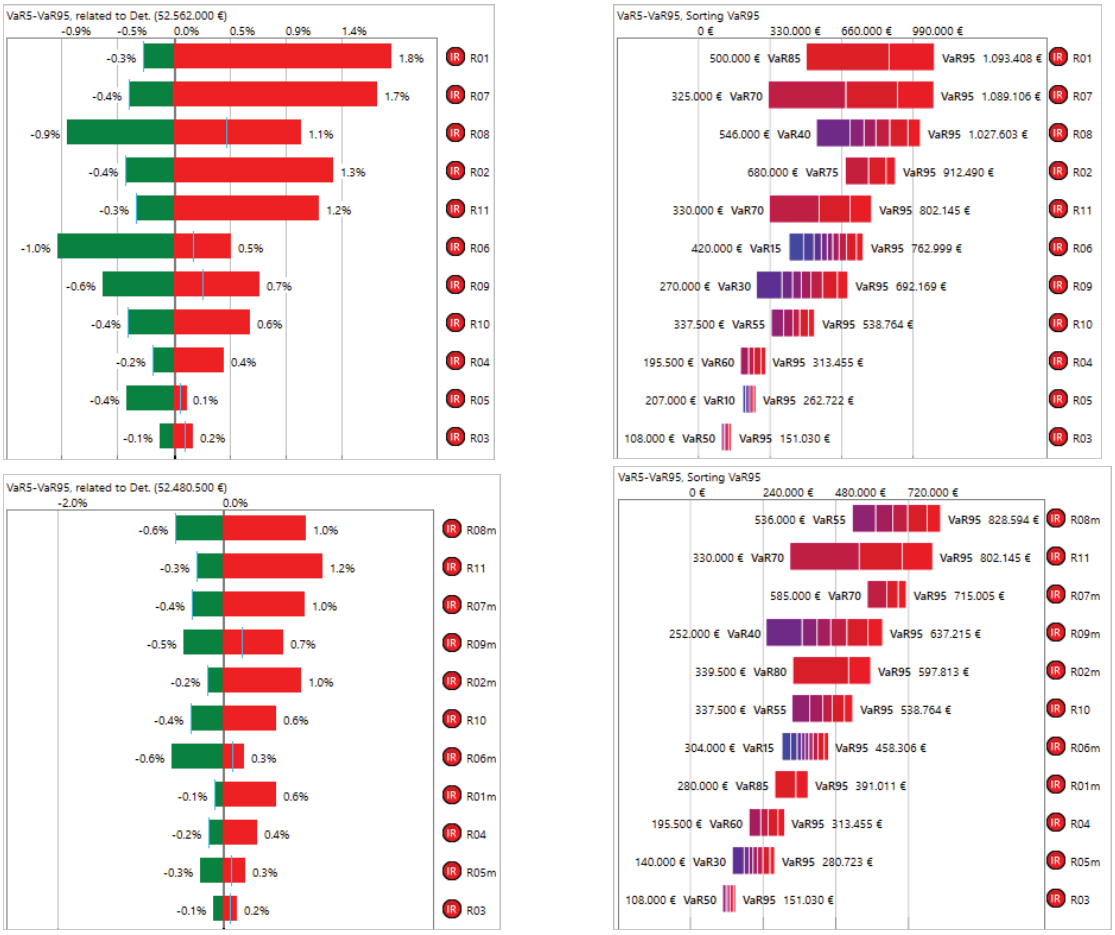
Range Impact Diagram



Risk Mitigation

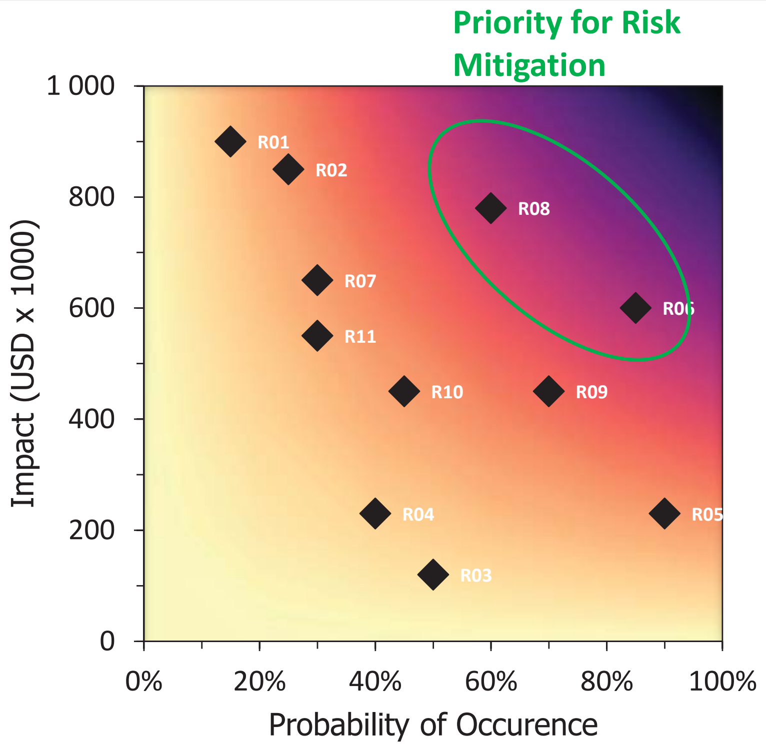
Risk	Pre-Mitigation		Post-Mitigation			
			active		not active	
	Probability of Occurence	Impact	Probability of Occurence	Impact	Probability of Occurence	Impact
R01	15%	900 000	15%	350 000		
R02	25%	850 000	20%	485 000		
R03	50%	120 000			50%	120 000
R04	40%	230 000			40%	230 000
R05	90%	230 000	70%	200 000		
R06	85%	600 000	85%	380 000		
R07	30%	650 000	30%	650 000		
R08	60%	780 000	45%	670 000		
R09	70%	450 000	60%	420 000		
R10	45%	450 000			45%	450 000
R11	30%	550 000			30%	550 000

Comparison Pre-Mitigation / Post-Mitigation

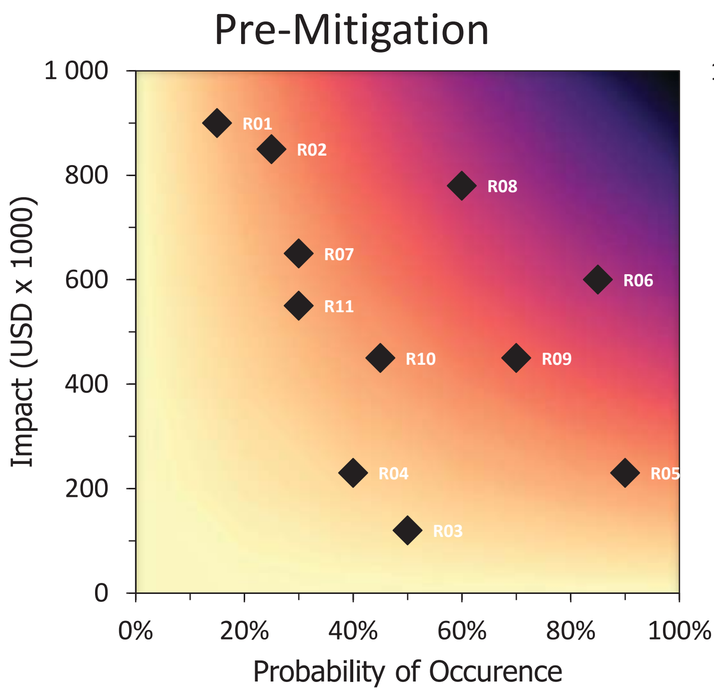


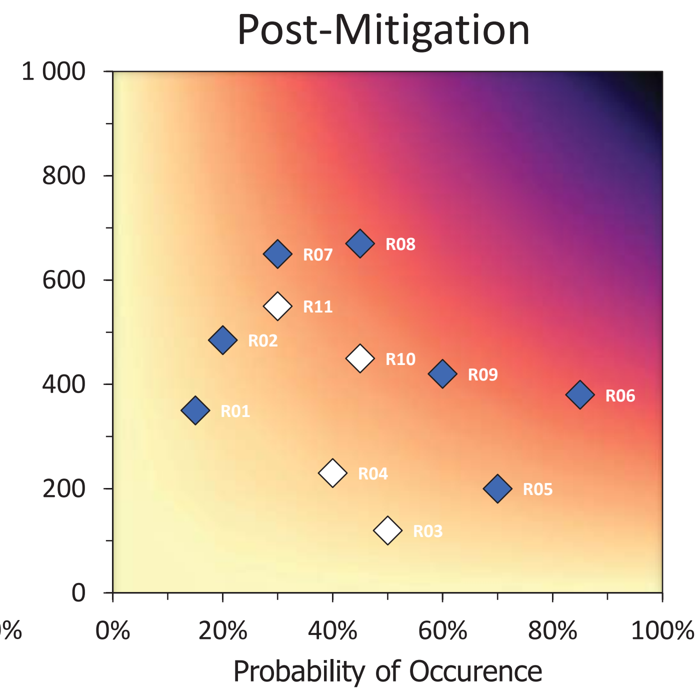
Ranking / Classification of Risks using Heat Maps

Risk	Pre-Mitigation	
	Probability of Occurence	Impact
R01	15%	900 000
R02	25%	850 000
R03	50%	120 000
R04	40%	230 000
R05	90%	230 000
R06	85%	600 000
R07	30%	650 000
R08	60%	780 000
R09	70%	450 000
R10	45%	450 000
R11	30%	550 000



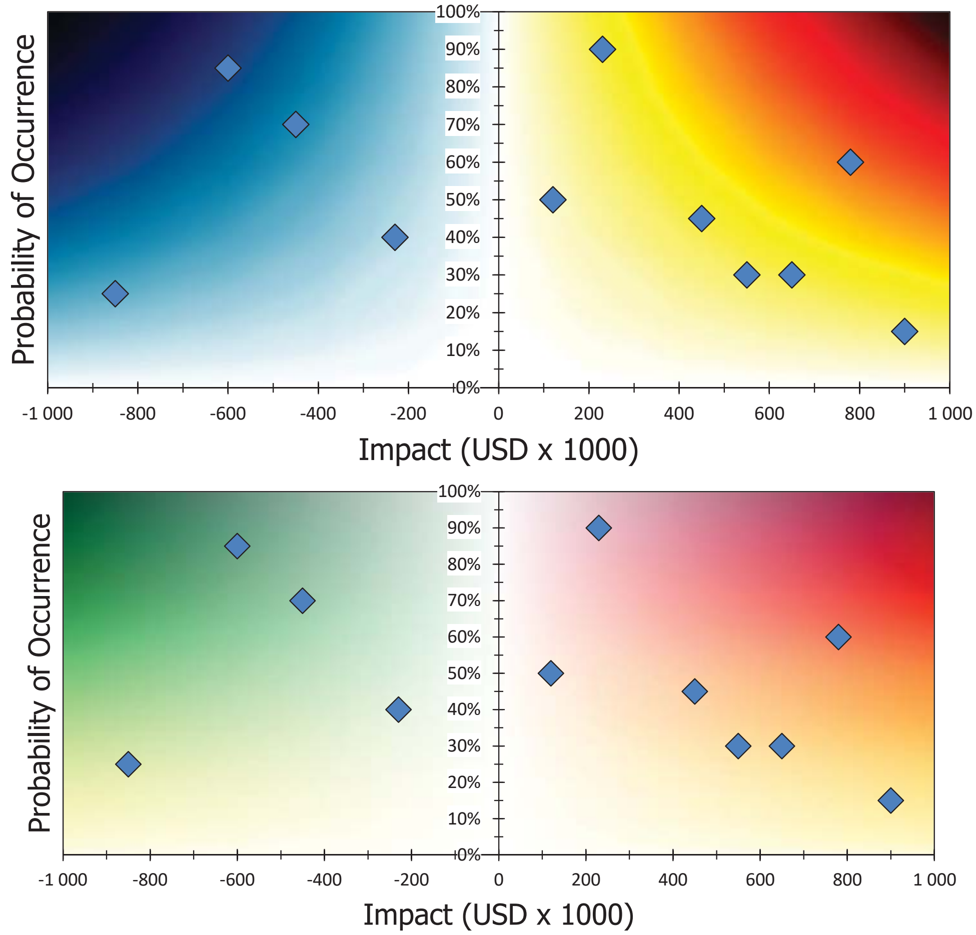
Visualization Pre-Mitigation & Post-Mitigation





Black: Pre-Mitigation
Blue: Mitigation Measures activated
White: Mitigation Measures not activated

Remember: Risk = Threats (negative) & Opportunities (positive)



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International Tunnelling and Underground Space Asssociation

for segme s

6 - 8 February 2018,

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Global Business Developm
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BEKAERT MACCAFERRI

AGENDA

- Why FRC for precast segments?
- Behaviour of FRC ?
- Which standards and specifications ?
- Fire Protection
- Green Solution
- Cost analysis example
- Reference projects
- Conclusion

Why SFRC for precast segments?

Tunnels having different diameter can be excavated with a TBM system (Table 1). Usually the Principal applications and the typical dimensions are:

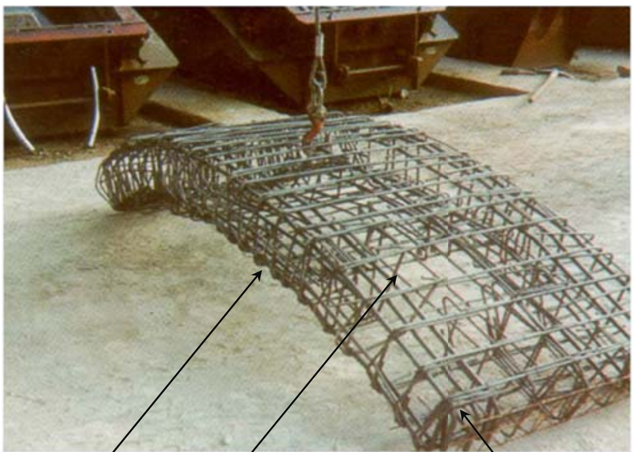
- - hydraulic diameter 3-5 m lining thickness 200-300 mm
- - metro diameter 6-9 m lining thickness 250-350 mm
- - railway diameter 8-12 m lining thickness 300-400 mm
- - road diameter 9 -15 m lining thickness 400-600 mm

Typical cage reinforcement



Conventional reinforcement cage

Heavy reinforcement with rebars: from 60 to 120 kg/m3



Top and bottom mats

Stirrups welded to the mats

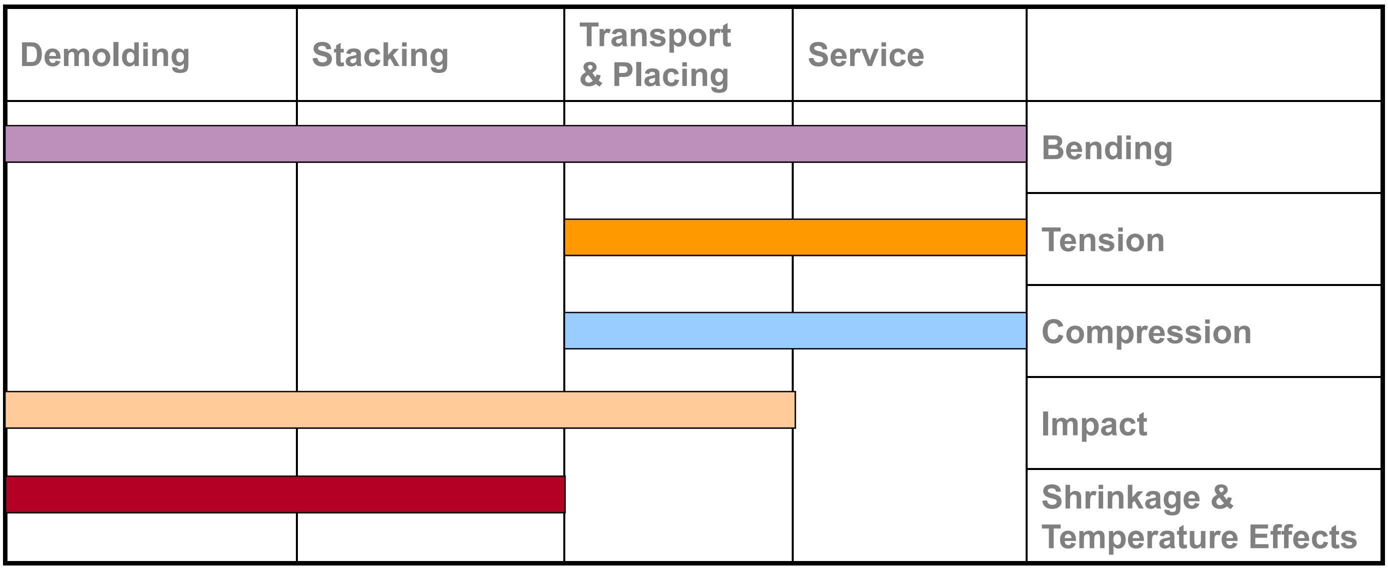
The reinforcement cage has to resist to:

- Demoulding forces
- Stacking forces
- Transportation forces
- Spalling forces
- Jacking forces

Main problems with typical cages reinforcement

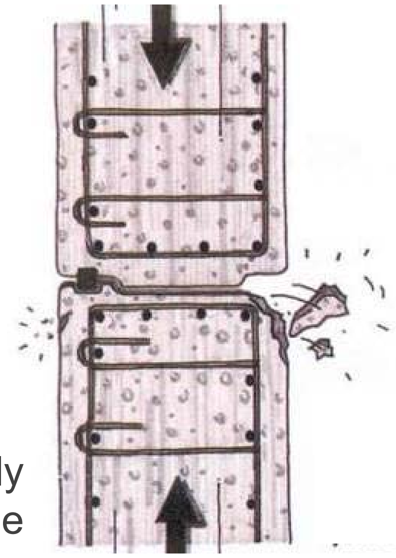
- Construction of cages is time consuming and labour intensive
- Sufficient space and special equipment required for storage
- The positioning of the cages in the moulds is determing for the quality of the segments

Segmental lining design procedure: Acting forces



Precast Segments

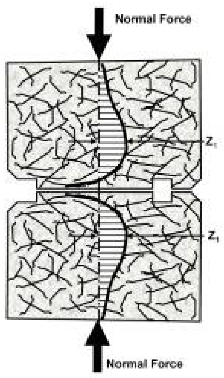
- Minimal concrete cover requirements for corrosion combined with …..
- Particular edge shapes leads to……
- Vulnerable edges



Spalling at a joint with a particularly vulnerable profile

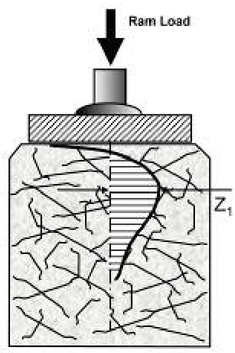
Bursting Forces

Bursting in segments occurs from two different types of loads:



Ring bursting

In-place forces due to compression in the ring



Ram bursting

During installation by the application of ram loads to the edge of the segments

Inadequate reinforcement

Repairs must be made that ensure long term durability

Repairs?

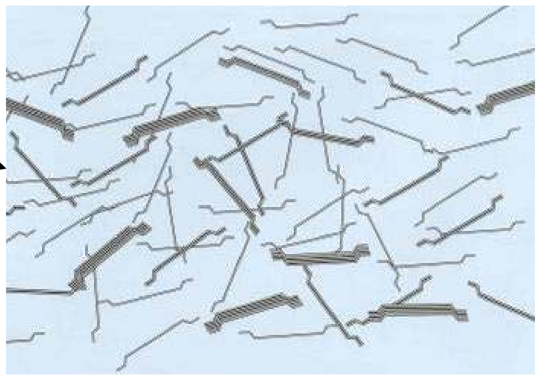
How long will you guarantee this repair?

Voice of the Designer

Load Case	Rebar	Steel fibre
Ground loading	✓	✓
Handling and stacking	✓	✓
Bolting	✓	✓
Erection	✓	✓
Grout Pressure	✓	✓
Ram Loading	?	✓

Application of SFRC is possible by selecting a static system for the tunnel ring in such a way that there is minimal stress from bending moments.

Steel fibre reinforced concrete (SFRC)



Bekaert · Maccaferri Underground Solutions

Advantage of Dramix Steel Fibres in Segmental Lining

Technical Advantages

- High impact resistance
- Multidirectional reinforcement
- No damages at edges and corners due to the spalling forces
- Post fire durability superior to rebar
- Fire protection in combination with micro-polypropilene fibre
- Durability

Economic advantages

- Increase of productivity, time saving
- Reduction of repair cost of damage segments
- Elimination of storage and positioning of reinforcement cages
- Use of automatic dosing and dispensing equipment linked to the control panel of the batching plant

Durability : Best available

Regarding metallic fibres: experience and research conclude:

Steel fibres need only a concrete cover of 1-2 mm compared to 30-40 mm for normal rebar and mesh.

Corrosion of the fibres at the surface may cause discolorations but does **not affect the mechanical properties of the steel fibre concrete reinforced structures.**

Fibres in crack openings smaller than 0,25 mm do not corrode (Brite Euram).

When no stains required, galvanized fibres can be applied.

Galavanized fibre (30gr/m2 mini)

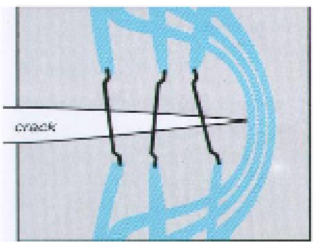
- Linking the aesthetic benefit of a smooth surface with high durability thanks to an environmentally friendly rust inhibitor.

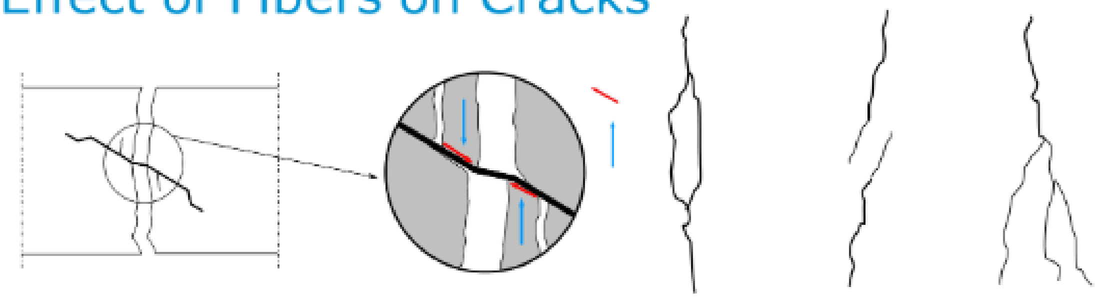
Smooth surface around Dramix Green® fibres with inhibitor

Durability a key issue : 120 years design life

Solution: Segments reinforced with steel fibers, *having a bending hardening behavior*, contain cracks much thinner Effect of Fibers on Cracks segment reinforced with steel rebar.

Effect of Fibers on Cracks





- "Comparing crack width in RC segments with FRC segments indicate a better performance in favor of fibers by as much as an average value of 43%"

FRC BEHAVIOUR

Behaviour of Fibre Reinforced Concrete

The behaviour of fibre reinforced concrete is more than a simple superposition of the characteristics of the concrete matrix and the fibres; to analyse the behaviour of this composite material, also the interaction between both has to be taken into account, i.e. the transfer of loads from the concrete matrix to the fibre system.

Therefore, for efficient load transfer, the following 3 conditions must be satisfied:

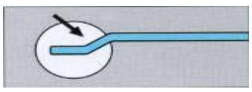
1. Sufficient <u>exchange surface</u> (number, length, diameter of fibres)

2. The <u>nature of the fibre-matrix interface</u> allows for proper load transfer

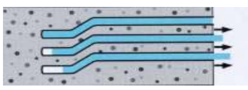
3. The <u>intrinsic mechanical properties</u> (Young's modulus, anchorage and tensile strength) of the fibre allows the forces **to be absorbed without breaking or excessively elongating the fibre.**

The quality of fibre is due to a combination of factors

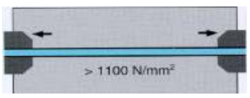
- A **high length-diameter ratio** (L/D ratio)
- **Hooked ends**



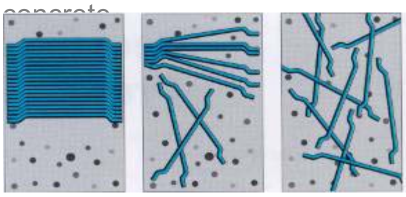
- **Controlled pull-out** (due to deformation of the hook)

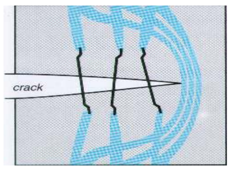


- **High tensile strength steel**

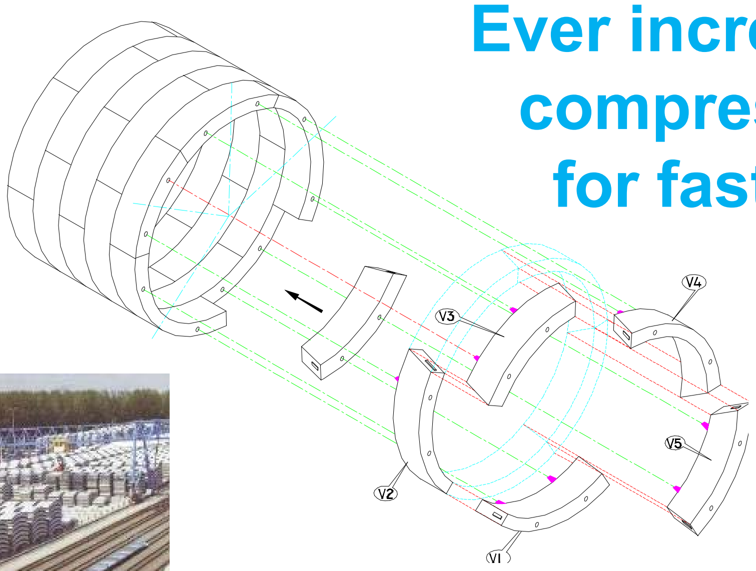


- A system of glued fibre bundles enables fibres with a high L/D ratio to be mixed easily and uniformly throughout the concrete

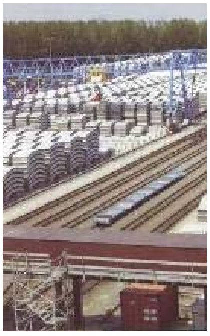




New development in the segmental lining design



Ever increasing concrete compressive strenght for fast demoulding



- Higher concrete compressive strenght

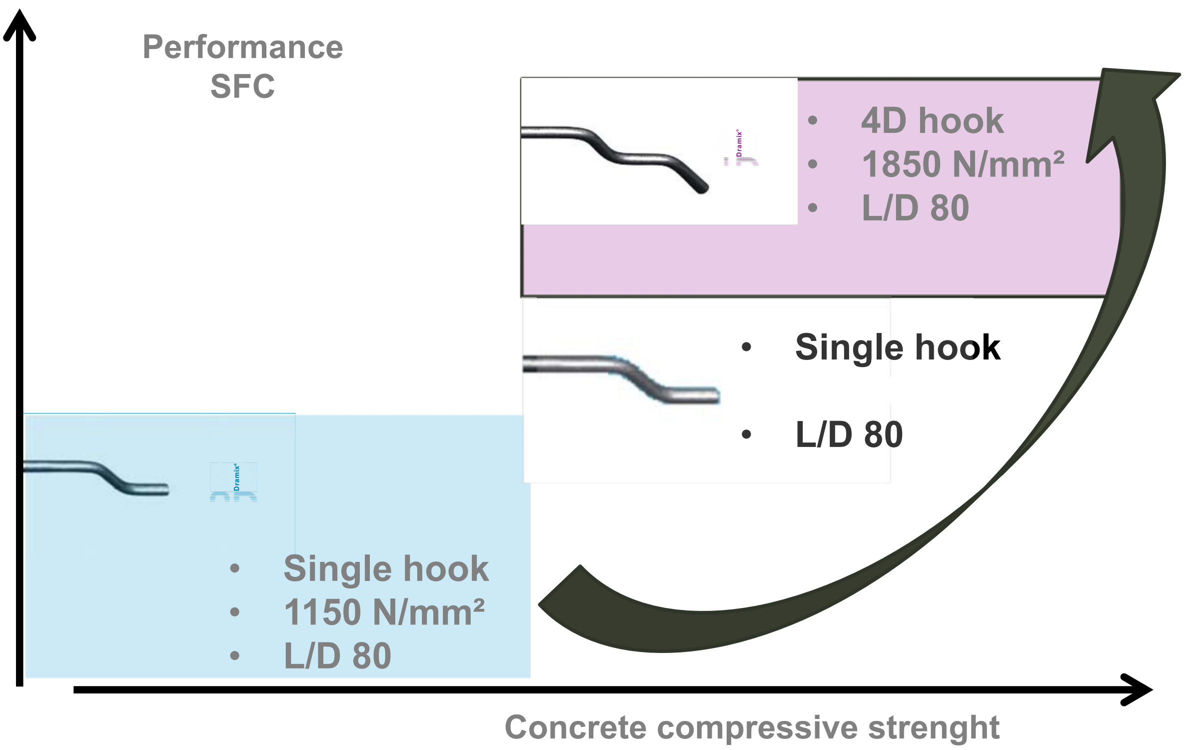
=

- More steel to meet “non brittle failure” requirements

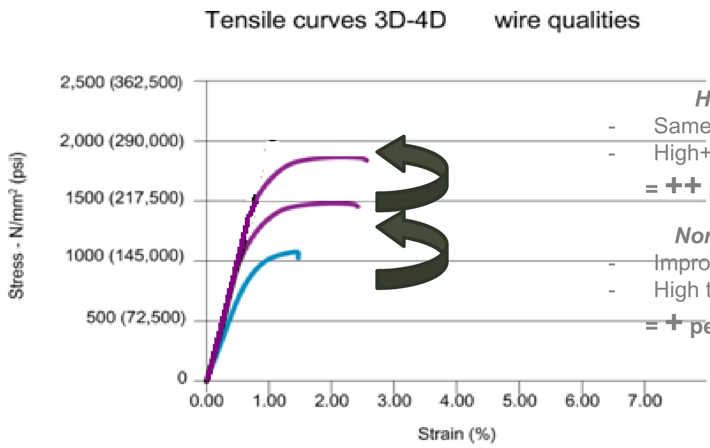
The

Dramix® 4D

for tunnel segments



Tunnel specific fibre



High concrete strenght

- Same 4D hook
- High+ tensile strenght (1850 N/mm²)

= **++ perfomance**

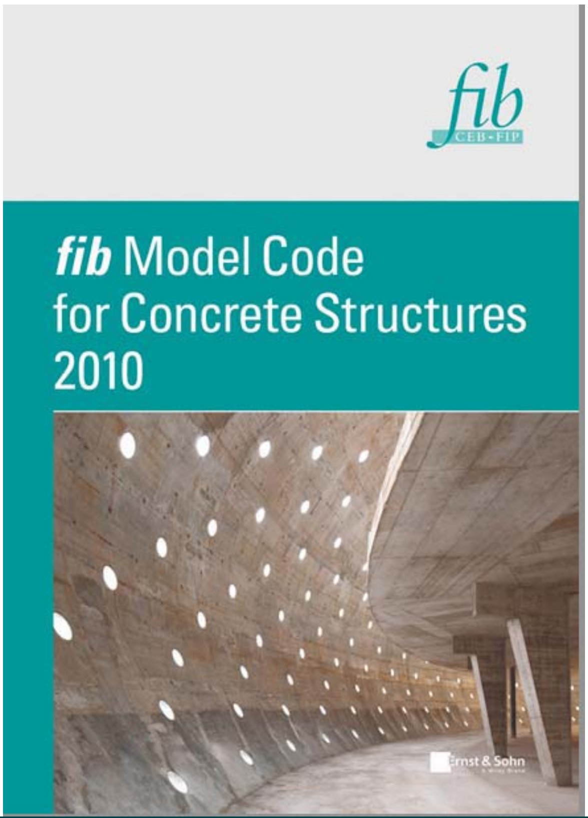
Normal concrete strenght

- Improved hook
- High tensile strenght (1450 N/mm²)

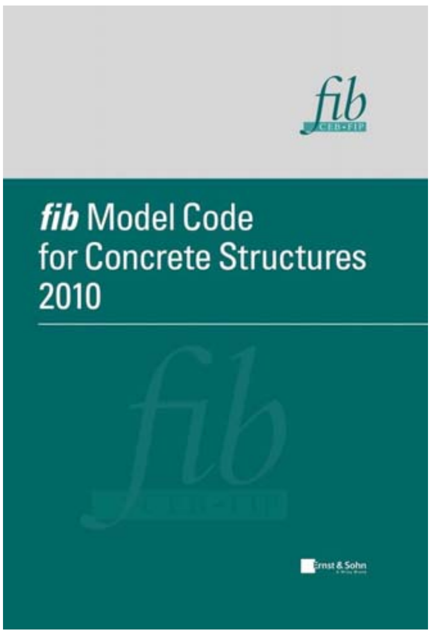
= **+ perfomance**

The standard

Model Code



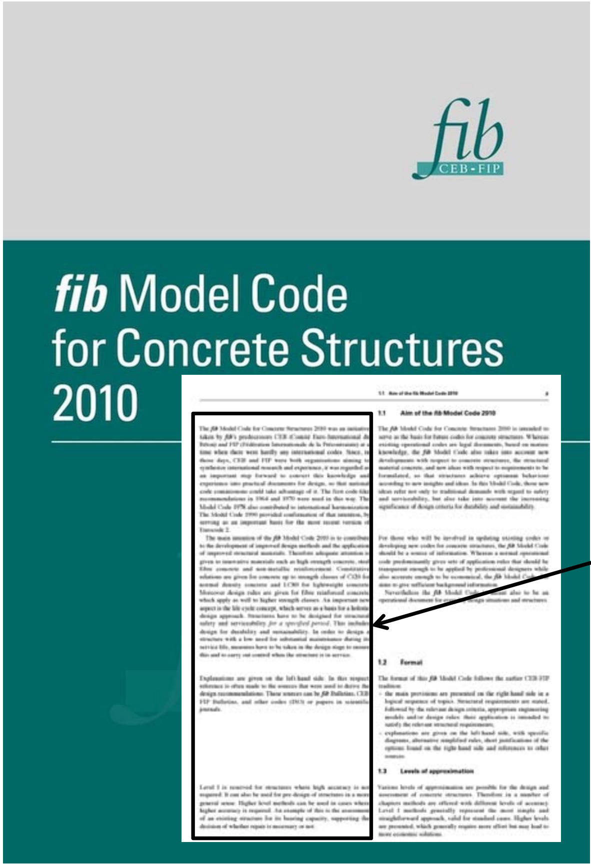
fib Model Code 2010



fib

- stands for
  International Federation for Structural Concrete
- is a pre-normative organisation
- does pioneering work in codification

fib Model Code 2010



- **Model Code 2010**
  - shall serve as the basis for future codes for concrete structures
  - presents new developments
  - gives background information
  - is proposed by *fib* to be used as an operational document

fib Model Code 2010 – Fibre Concrete

- **Fibre Concrete in MC 2010**
  - **5.6**
    Fibres/fibre reinforced concrete
  - **7.7**
    Verification of safety and serviceability of FRC structures
  - references to other chapters

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fib Model Code 2010 – Fibre Concrete

- Chapter 5.6
  - Introduction
  - Material properties
  - Classification
    - Material level
  - Constitutive Laws
  - Stress-strain relationship
  - Partial safety factors
  - Orientation Factor
- Chapter 7.7
  - Classification
    - Structural level
  - Design principles
  - Verification of
    - safety (ULS)
    - serviceability (SLS)

EN 14651

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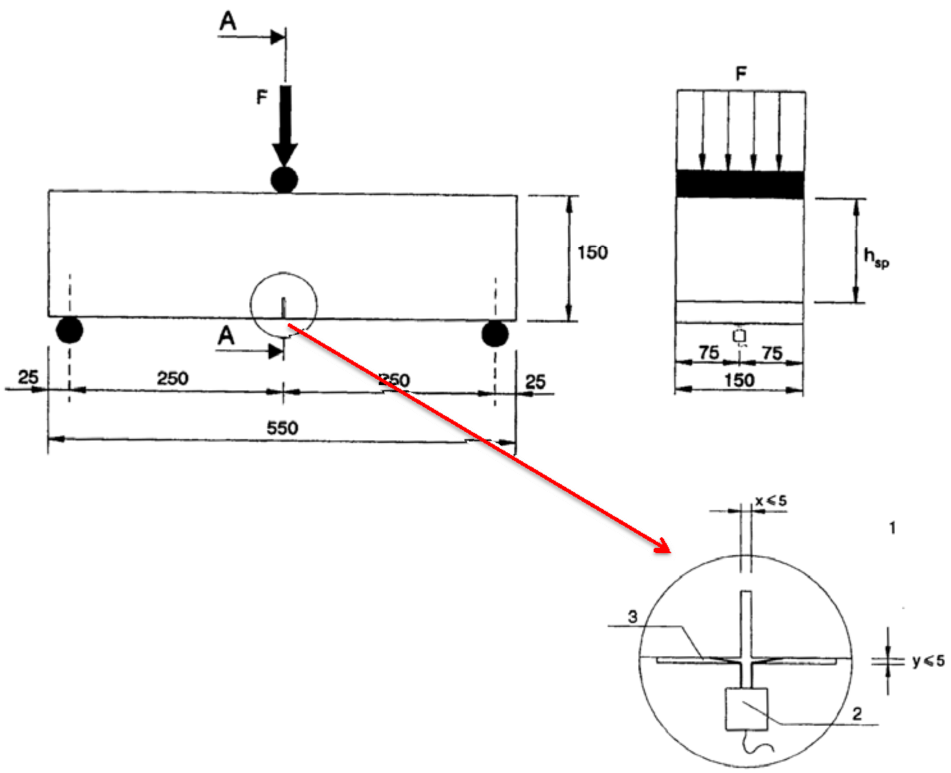
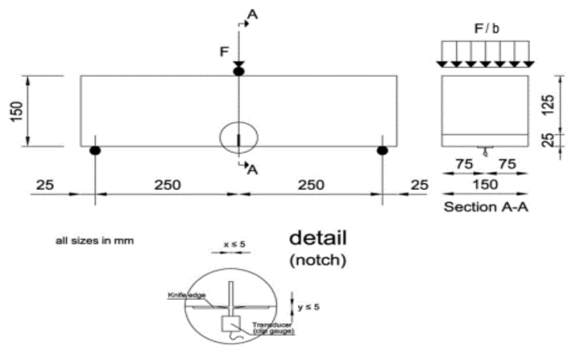
EN 14651



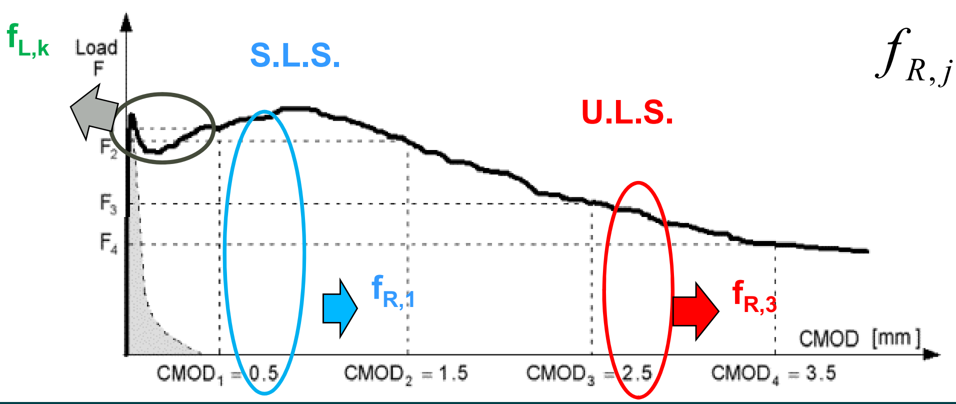
Reference test



EN 14651

h_{sp} = 125 mm

b = 150 mm

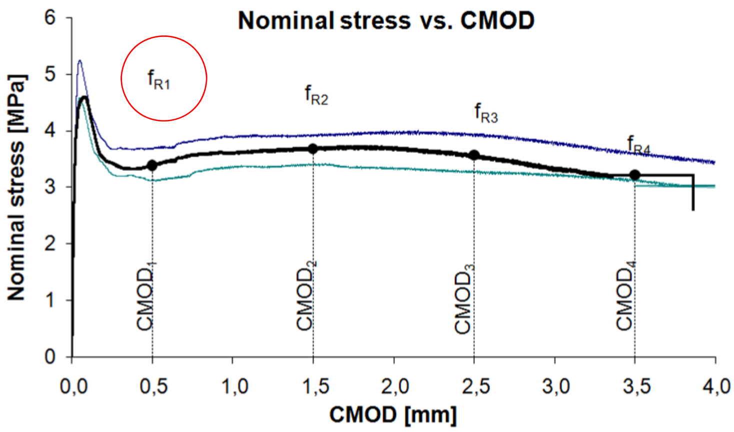


$$f_{R,j} = \frac{3 F_j l}{2 b h_{sp}^2}$$

Model Code

f_{R1k} is the reference value for classification**:**

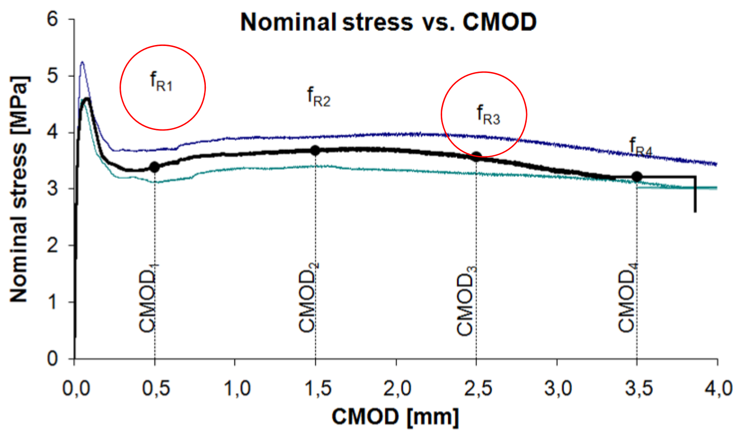
1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0 MPa



Model Code

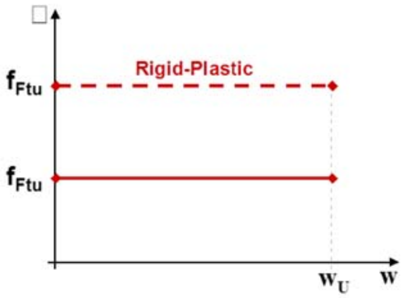
f_{R3k}/f_{R1k}

a. if $0.5 \le f_{R3k}/f_{R1k} \le 0.7$
b. if $0.7 \le f_{R3k}/f_{R1k} \le 0.9$
c. if $0.9 \le f_{R3k}/f_{R1k} \le 1.1$
d. if $1.1 \le f_{R3k}/f_{R1k} \le 1.3$
e. if $f_{R3k}/f_{R1k} \ge 1.3$

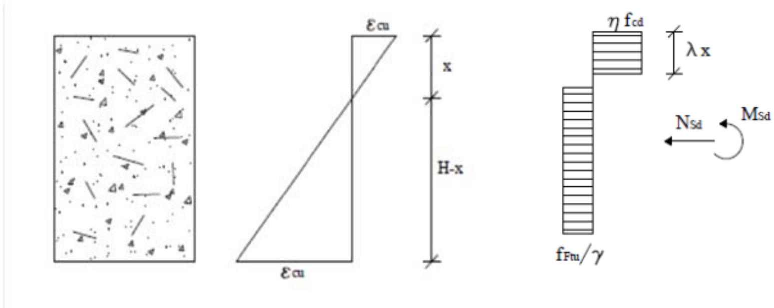


f_{R1k} f_{R3k}

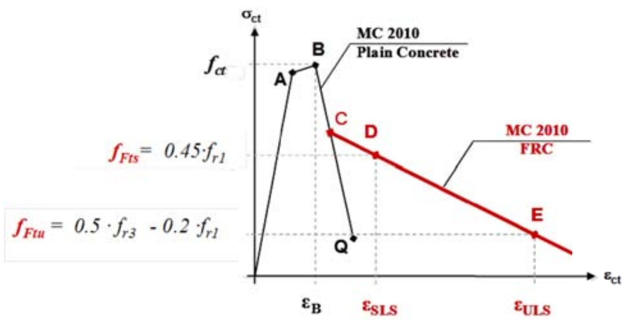
Model Code

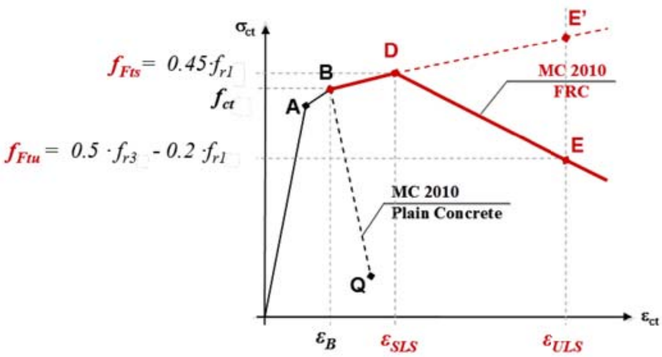


$$f_{Ftu}(t) = \frac{1}{\gamma_F} \cdot \frac{f_{R3k}(t)}{3}$$

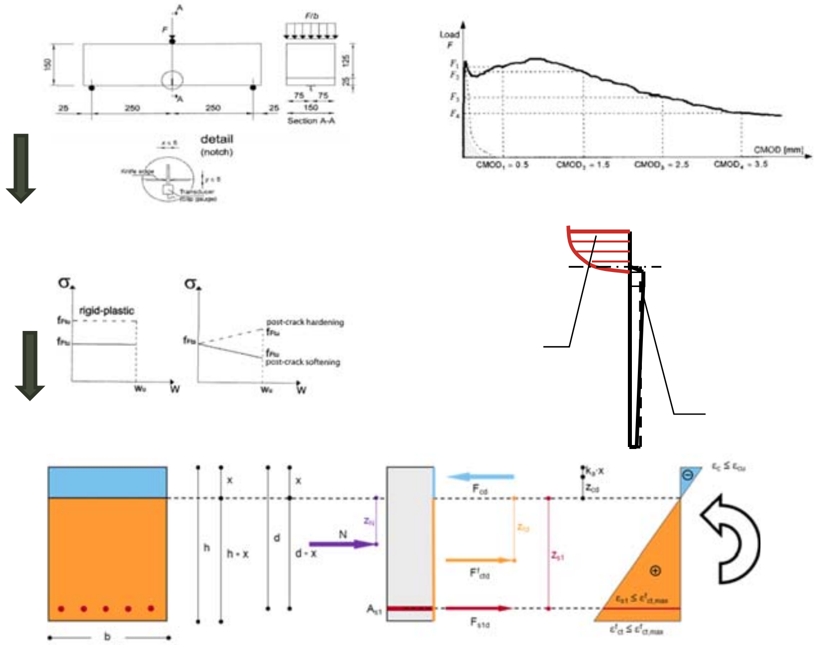


Model Code





Understanding SFRC design – Basic principle



Bending stresses

Tension stresses

capacity

Model Code 2010

MODEL CODE 2010 is considered as reference document in:

ITA tech sub activity group: “fibre reinforced concrete precast segments for tunnel lining application” - GUIDELINE FOR GOOD PRACTICE OF FIBRE REINFORCED CONCRETE PRECAST SEGMENTS – Under preparation

French Tunnelling Association guidelines (AFTES)
DESIGN, DIMENSIONING AND EXECUTION OF PRECAST STEEL FIBRE REINFORCED CONCRETE ARCH SEGMENTS - 2013

MODEL CODE 2010 is already used in several design projects worldwide.

Doha metro

Guideline Focus on precast segment

For the fiber-reinforced concrete segmental lining design, some guidelines have been published in France and Germany and, recently, USA:

- **AFTES Recommendations GT38R1F1** – La conception, le dimensionnement et la realisation de voussoirs préfabriqués en béton de fibres métalliques;
- **DAUB** (German Tunnelling Committee) – Recommendations for the design, production and installation of segmental rings;
- **ACI 544.7R-16 – Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments;**
- **ITA-TECH** (**published in WTC 2016**) – Design Guidance for Precast Fibre Reinforced Concrete Precast Segments – Draft Report;
- **ITA-WG_02** (**published in WTC 2016**) – Twenty years of tunnel segments practice: lessons learnt and proposed design procedure;
- **PAS 8810**, Design of concrete segmental tunnel linings – Code of practice

The upcoming guidelines and codes are:

- **fib TG 1.4.1** – Tunnels in fiber reinforced concrete

AFTES RECOMMENDATION 2013

RECOMMENDATION OF AFTES N°GT38R1A1

Design, dimensioning and execution of precast steel fibre reinforced concrete arch segments

Text presented by **Pascal GUEDON** (Arcadis) Working Group leader

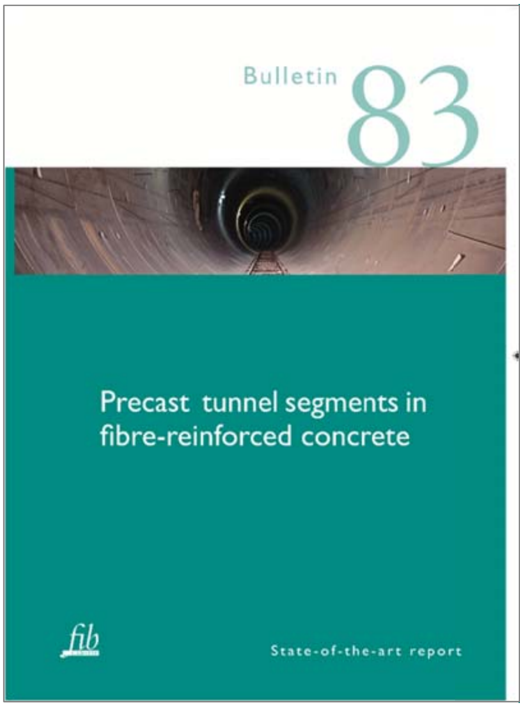
With the collaboration of:
Philippe AUTUORI (Bouygues) - **Rémi BILLANGEON** (Spie Batignolles) - **Bruno DARDARD** (SNCF Ingénierie) - **Benoit de RIVAZ** (Bekaert) **Gabriel DURAND** (Argotech) - **Lionel LINGER** (Vinci) - **Patrick PELTIER** (Stradal) - **François PETIT** (Vinci) - **Pierre ROSSI** (IFSTTAR) - **Bernard RUBY** (RATP) **Jean-François TESSIER** (SIAAP) - **François TOUTLEMONDE** (IFSTTAR) - **Marc VANDEWALLE** (Université Polytechnique de Catalogne)

Thanks for re-reading to:
Daniel BRUNET (Expert) - **Michel DEFFAYET** (CETU) - **Sylvie GIULIANI-LEONARDI** (Vinci) - **Catherine LARIVE** (CETU) - **Jean LAUNAY** (Vinci) **Michel PRÉ** (Setec) - **François RENAULT** (Vinci) - **Loïc THEVENOT** (Eiffage) - **Hubert TOURNERY** (Egis Tunnels) - **Jacques TRICLOT** (Egis Tunnels)

AFTES welcomes all suggestions relating to this text.

NEW GUIDELINE PUBLISHED IN 2016

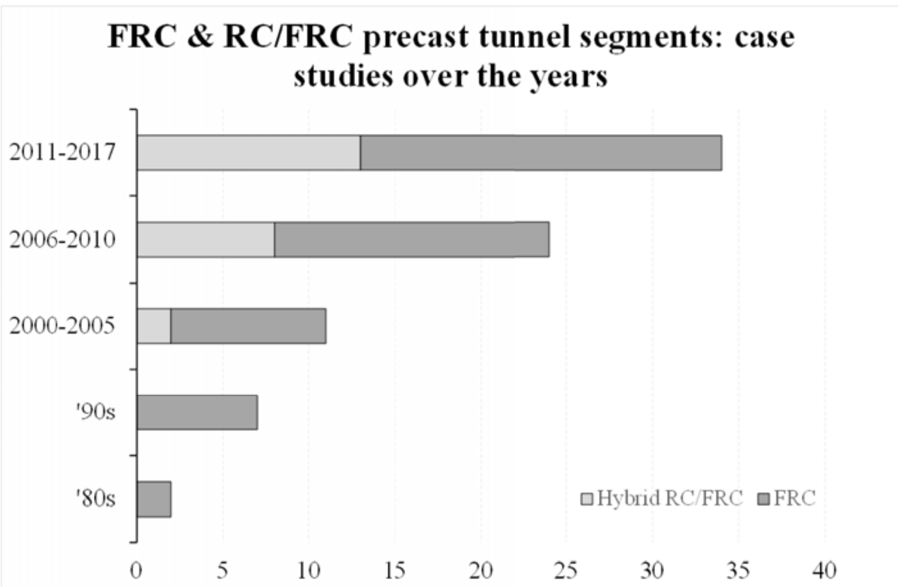
NEW PUBLICATION 2018



Precast tunnel segments in fibre-reinforced concrete

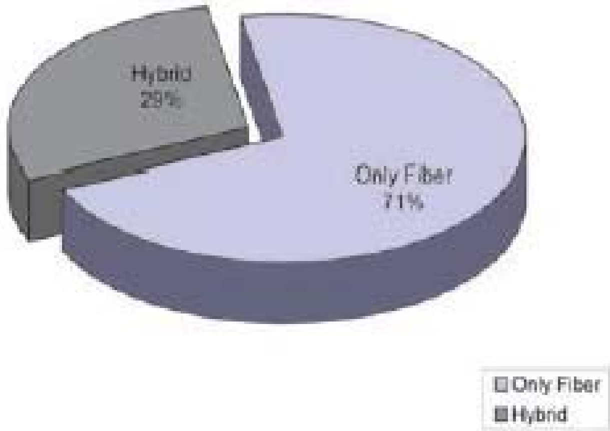
Contents

FRC in TBM tunnels



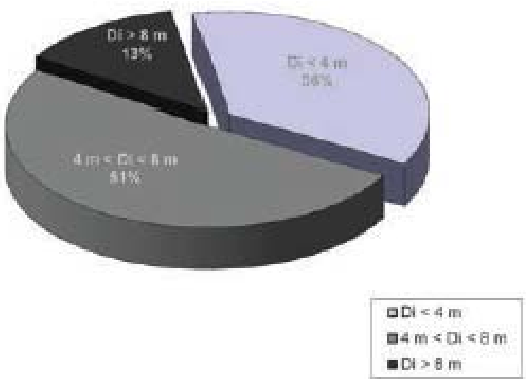
SOME STATISTIC

Tunnel linings

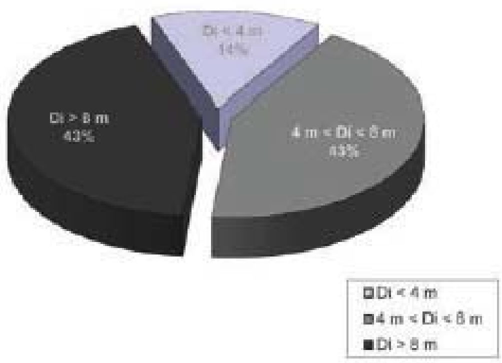


INFLUENCE OF DIAMETER

Tunnel diameter D_i: Only fibers



Tunnel diameter D_i: Fibers + Rebars



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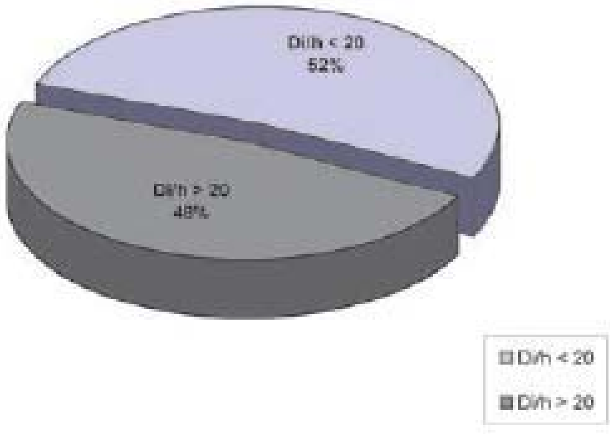
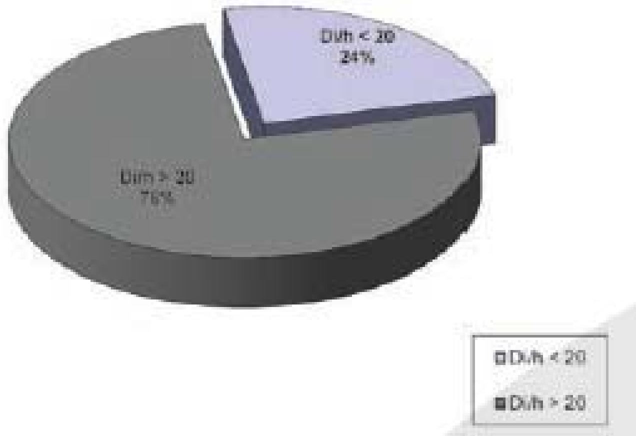
INFLUENCE OF LINING ASPECT RATIO





DEMOULDING

This stage is carried out at concrete age ***t*** provided that a minimum ***fc*** reaches the magnitude specified by the designer; ***t*** usually ranging between 3 and 12 hours after the concrete pouring depending on the concrete
mix as well as on the type of curing process.
This early age magnitude of ***fc*** can be fixed by establishing the minimum ***fct,fl*** required to avoid crackingin this situation.
The relation ***fc***-***fct,fl*** can be obtained performing a material characterization test program before starting the production.
The reinforcement shall be designed considering a partial safety factor for the self-weight (***γG*** = 1.35).

HANDLING

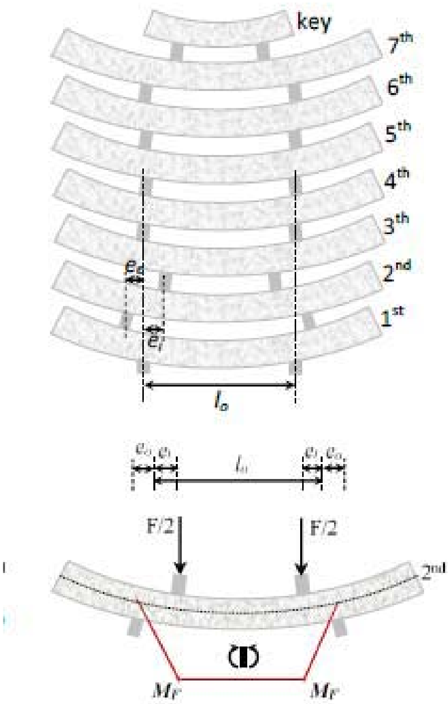
The key design parameter is the required ***fc*** at ***t*** that guarantees that ***fct,fl*** to avoid cracking during each handling phase.

All the loads considered in this situation are associated to the self-weight; therefore, the partial safety factor ***γG*** = 1.35 shall be considered for ULS.

Additionally, a partial safety factor for dynamic loads ***γd*** = 2.0

FIB BULLETIN N° 83

STACKING



FIB BULLETIN N° 83

In some cases, the segments aresubjected to an additional curing process for several days to avoid superficial cracking due to high temperatures or intense drying shrinkage, this can be obtained by storing in humid atmosphere and with the use of curing membranes.

Wooded blocks provide supports for segments placed on the ground as well as segments on top of each other. Designers provide the distance between the stack supports (***lo***), vertically aligned to minimize the bending moment due to self-weight (***p***), ***Mp,pos*** and ***Mp,neg*** at the span centre and at the support, respectively

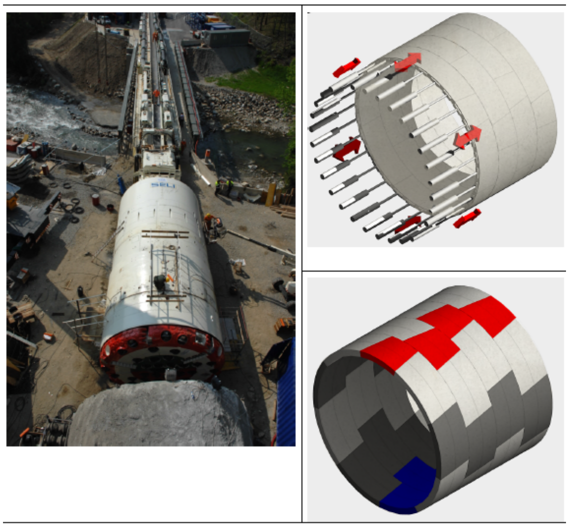
Eccentricities between the ideal locations of the supports should be expected. This eccentricity must be considered for the most unfavourable segment. ***F*** represents the force acting on the segment affected by the eccentricity due to the dead weight of segments positioned above. In this case, in addition to the bending moment caused by ***p***, an extra moment (***MF***) has to be taken into account due to the weight of all above segments and the eccentricity of stack supports.

TRANSPORTATION

FIB BULLETIN N° 83

Similar to the storage phase, wood blocks provide supports for the segments. An accidental magnitude of the eccentricity of 0.10 m is recommended to be considered.
A simply supported beam has demonstrated to be a representative static scheme to simulate this load case.
The design parameter is the required ***fc*** at ***t*** ≥ 28 days that guarantees the minimum value of ***fct,fl*** to avoid
cracking during this phase.
All the load considered in this situation are associated to the self-weight; therefore, the partial safety
factor ***γG*** = 1.35 shall be considered for ULS.
Additionally, a partial safety factor for dynamic loads ***γd*** = **2.0** is recommended to be applied.

TBM trhust



TBM thrust phase is a temporary phase.

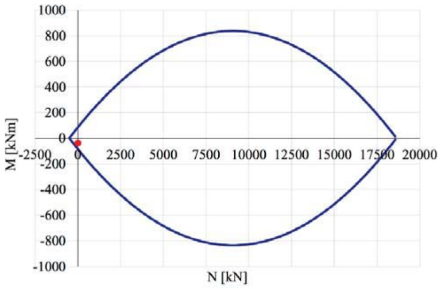
This stage should be principally considered by means o the general design principles, typical of Serviceability Limit State (SLS).

The maximum load achievable by the jacks (according to the maximum pressure of the corresponding hydrauli system) is probably the most conservative condition tha can be assumed in the design process.

By assuming this load level for a given tunnel lining, it is desirable to provide an adequate bearing capacity whicl principally means:
- avoid local crushing in compression of concrete under the plates;
- stable development of cracking phenomena in order tc provide the global increase of the total load.

Evaluate limits for gaps and offsets.

Final state loading condition (Long Term Loading)



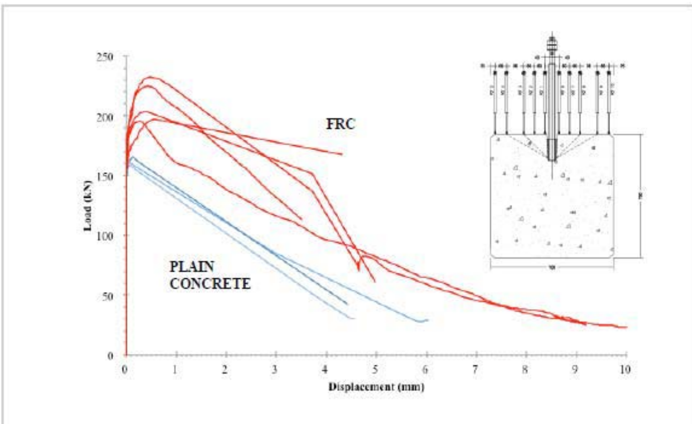
The final stage verification is made on the lining, made of a series of segments.
The actions on the lining are evaluated with a geotechnical analysis and the use of FRC does notchange the global behaviour of the lining.

At geotechnical level there are no difference between ordinary Reinforced Concrete segments and Fibre Reinforce Concrete Segments

The verification at ULS is made by comparing the bending actions and axial forces derived by the geotechnical analysis with M-N envelopes defined at final stage.

FIB BULLETIN N° 83

CONNECTORS



FIB BULLETIN N° 83

Although some research has been performed on fibre reinforced concrete including rebar anchorage anddevelopment lengths in FRC, only a limited amount of studies has been carried out with respect to the influence of fibre reinforcement on fastenings to concretee.

It is considered reasonable to neglect the contribution of fibres, and assume plain concrete for any connector design calculations. The design recommendations below are widely based on the provisions of *fib Bulletin 58 Design ofanchorages in concrete*. (fib, 2011), and the *CEN/TS 1992-4: 2009, Design of fastenings for use in concrete*

Fire design

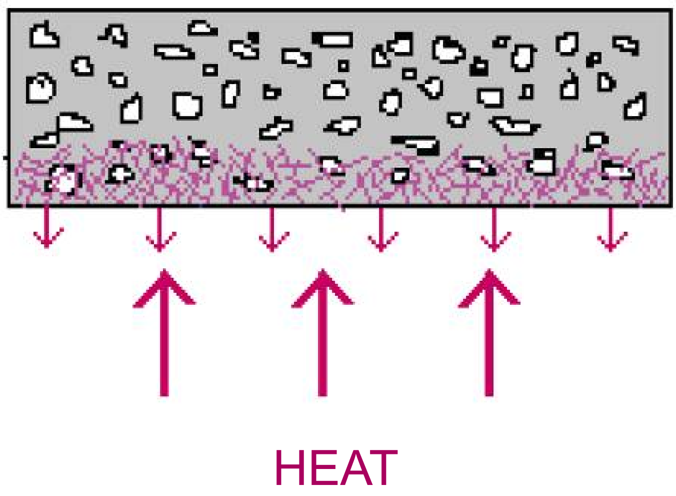
In order to evaluate the fire resistance of a tunnel lining two main aspects have to be take into consideration:

- degradation of the material properties (compressive strength, Young's Modulus, post peak residual tensile strength,..) during an elevated temperature rise;
- occurrence of possible spalling with a reduction of the lining cross-section

FIB BULLETIN N° 83

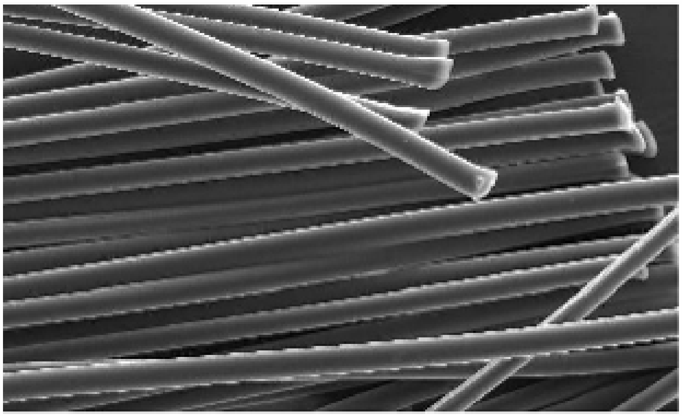
Fire protection performance criteria

Benefits of fiber addition



Fibers melt at 160°C form interconnecting passages for vapour pressure to escape

M6 FIRE dosage 1 to 1,5 kg/m^3



BEKAERT has the finest fibre

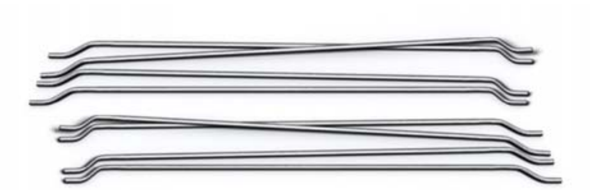
Duomix® Fire

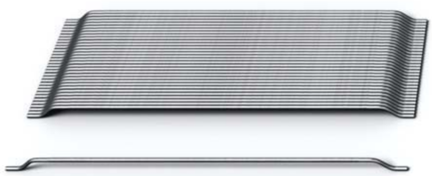
2,3 (2,3 g per 10 km fibre)	
App. 725 mio fibres/kg with an overall surface of 615 m^2	
Length	6 mm
Diameter norminally	18µm
Elongation at rupture	15%
Material	Polypropylen
Density	0.91 kg/dm^3
E-module	3500-3900 N/mm^2
Tensile stength	300 N/mm^2
Melting Point	100- 165°C
Moisture absorption	0%
Colour	transparent white

Duomix® Fire (M6), the monofilament fibre with diameters of less than 20 µm and a length of 6 mm.

Introduction

"The rules in this chapter are based most of all on experience with steel fibre reinforced concrete (SFRC)."





Material Properties

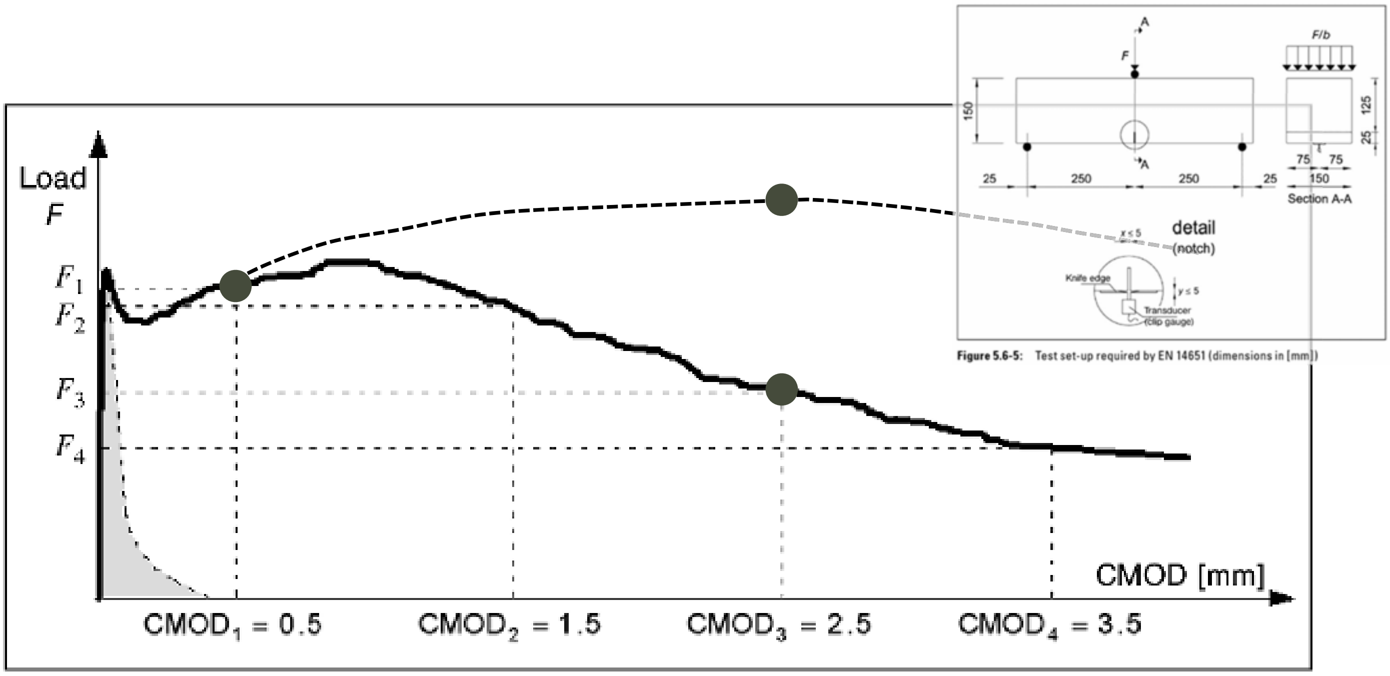
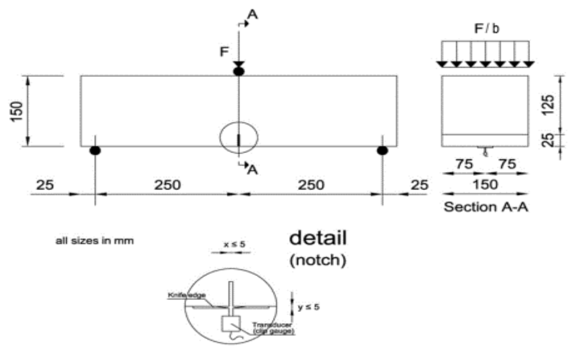


Figure 5.6-5: Test set-up required by EN 14651 (dimensions in [mm])

Figure 5.6-6: Typical load F–CMOD curve for plain concrete and FRC

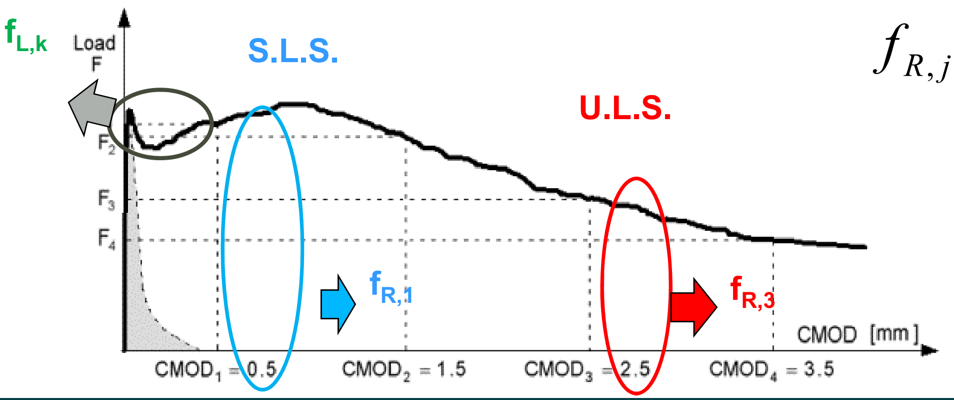
Reference test



EN 14651

h_{sp} = 125 mm

b = 150 mm



$$f_{R,j} = \frac{3\,F_j\,l}{2\,b\,h_{sp}^2}$$

Classification

- SLS, small crack widths: f_{R1k}
  - strength interval for f_{R1k}
  - 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0
- ULS, large crack widths: f_{R3k}
  - ratio f_{R3k}/f_{R1k}
  - a if $0.5 < f_{R3k}/f_{R1k} < 0.7$
  - b if $0.7 < f_{R3k}/f_{R1k} < 0.9$
  - c if $0.9 < f_{R3k}/f_{R1k} < 1.1$
  - d if $1.1 < f_{R3k}/f_{R1k} < 1.3$
  - e if $1.3 < f_{R3k}/f_{R1k}$

minimum requirements

$f_{R1k}/f_{Lk} > 0.4$

$f_{R3k}/f_{R1k} > 0.5$
$f_{R1k}/f_{Lk} > 0.4$
$f_{R3k}/f_{R1k} > 0.5$

MINIMUM PERFORMANCE FOR PRECAST SEGMENT RECOMMANDED

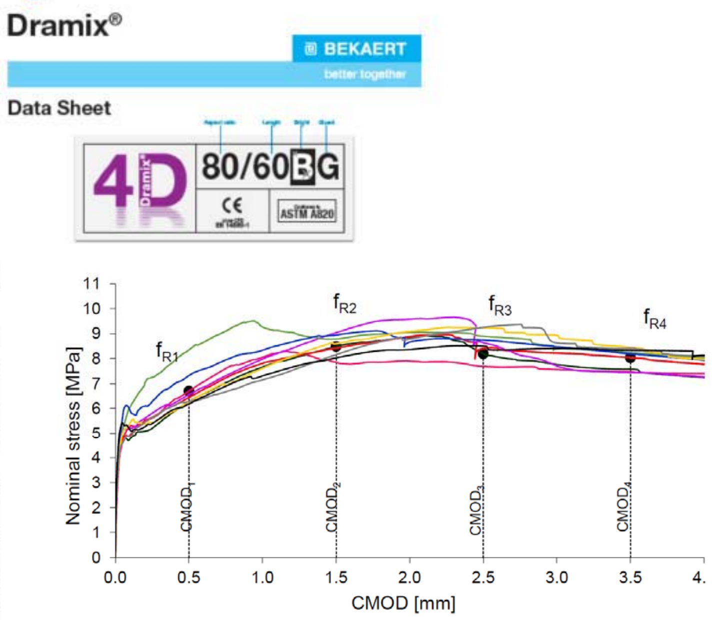
HARDENING POST CRACK BEHAVIOUR FOR CRAKING CONTROL

SFRC Segmental Lining Design

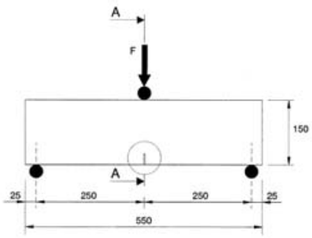
Segmental Lining

Design indications:

Fibre type:	4D 80/60BG
Dosage rate:	40 kg/m³
Concrete class (28 days):	C40/50
MC10 classification:	4c



Type Testing and Product specification



INTERNATIONAL STANDARD

ISO 13270

First edition
2013-01-15

Steel fibres for concrete — Definitions and specifications

Fibres d'acier pour béton — Définitions et spécifications

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 14651

June 2005

ICS 91.100.30

English version

Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

Méthode d'essai du béton de fibres métalliques - Mesurage de la résistance à la traction par flexion (limite de proportionnalité (LOP), résistance résiduelle)

Prüfverfahren für Beton mit metallischen Fasern - Bestimmung der Biegezugfestigkeit (Proportionalitätsgrenze, residuelle Biegezugfestigkeit)

ISO 13270 standard

- Features
- Air content is introduced in the ISO 13270 standard, and should be measured for all fibres (not only glued fibres) in the reference concrete, and should be mentioned on the label. The air content with fibres may not differ more than 2% versus plain concrete -> Point 7.9.
- Fibres with zinc or zinc/aluminium coating: inhibitor is recommended (Like Dramix® Green) -> Point 5 C
- Tolerances on diameter and length: 2 classes are prescribed: more relaxed, the same as EN 14889-1 standard, and more stringent. Please notice that our standard Dramix product quality conforms to the stringent category
- Therefor it is essential to stress the importants in specifying that the tolerances of the fibres must be according class A
- *Point 3.1. -> Note 1 to entry: Steel fibres are suitable reinforcement material for concrete because they possess a thermal expansion coefficient equal to that of concrete, their Young's Modulus is at least 5 times higher than that of concrete and the creep of regular carbon steel fibres can only occur above 370 ° C.*

Materials properties – Wordwide standard and guideline


INTERNATIONAL STANDARD ISO 13270

Steel fibres for concrete — Definitions and specifications

Fiber's geometrical and mechanical characteristics are defined by the following standards:

- **EN 14889-2006:** Fibres for concrete; this standard specifies the requirements of fibres for structural or non-structural use in concrete, mortar and grout;
- **ASTM A820 / A820M-11:** Standard Specification for Steel Fibers for Fiber-Reinforced Concrete;
- **ISO 13270-2013:** Steel fibres for concrete;

The flexural behaviour of Fiber-Reinforced Concrete has been regulated as follows:

Beam Tests:

- **EN 14651-2005:** Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of prop. (LOP), residual);
- **ASTM C1609 / C1609M-2012: Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading);**
- **JSCE-SF4:** Method of tests for flexural strength and flexural toughness of steel fibre reinforced concrete

Minimum Requirements for Precast segments

1. Fibres should comply with the INTERNATIONAL STANDARD ISO 13 270
2. Fibres with CE marking, system 1 (Fibres for structural use) and class A ISO 13 270
3. High l/D ratio > 65 (l/D = 80 is recommended for precast segment)
4. Small tolerance on the product (diameter) to guarantee the performance and a lower scatter. Therefor it is essential to stress the important in specifying that the tolerances of the fibres must be according class A according to ISO 13 270
5. The presence of a mechanical high performance anchorage (Double hook end fibre)
6. Wire tensile strength to be adapted with the concrete class MINI > 1500 Mpa
7. Glued fibres to ensure a good distribution and homogeneity in the concrete. Steel fibres have to be added by automatic dosing system which are perfectly design for glued fibres

Quality control

Quality control

- The procedures for the control of Fibre-Reinforced Concrete performance should be defined in the design process.
- Usually, a quality control procedure considers two steps:
  - initial qualification of the material (trials testing);
  - tests during the segment production (production testing).

Quality control – Initial tests

Before starting the segment production, compressive and bending tests in accordance with EN14651 have to be performed in order to control the fulfilment of the characteristic values defined in the design. In addition, tests should be carried out in order to verify the fibre content or the fibre orientation.

In order to check the compressive properties of the concrete, the same procedure adopted for ordinary concrete should be followed.

For the definition of the tensile properties of the FRC, tests according to EN 14651 should be performed. The material should be classified according to the Model Code 2010: characteristic values of the FRC residual strengths (f_{Lk}, f_{R1k} and f_{R3k}) have to be

In this phase, it is suggested to perform at least 12 beam tests according to EN14651 at 28 days of curing for each fibre dosage/fibre type and concrete mix that is to be considered.

Quality control – Initial tests

The test results can be considered positive if:

⇒ fLk fulfils specific requirement provided by the designer

⇒ the characteristic value of $fR1k$ is higher than the design one

⇒ the ratio between $fR3k$ and $fR1k$ fulfils the design requirement; if a higher strength ratio is obtained, the material can be accepted (if no specific requirements are present in the design)

=> the fulfilment of the Model Code 2010 requirement for substituting the traditional reinforcement with fibre is verified ($fR1k / fLk > 0.4$ and $fR3k / fR1k > 0.5$).

Quality control – Initial tests

$$X_k = m_x \{1 - k_n V_x\}$$

$$V_x = \frac{s_x}{m_x} \qquad s_x = \sqrt{\frac{\sum (x_i - m_x)^2}{(n-1)}}$$

n	k_n
3	3.37
4	2.63
5	2.34
6	2.18
8	2.01
9	1.96
10	1.92
12	1.87
15	1.82

n	k_n
3	1.89
4	1.83
5	1.80
6	1.77
8	1.74
9	1.73
10	1.72
12	1.71
15	1.70

Fire Protection

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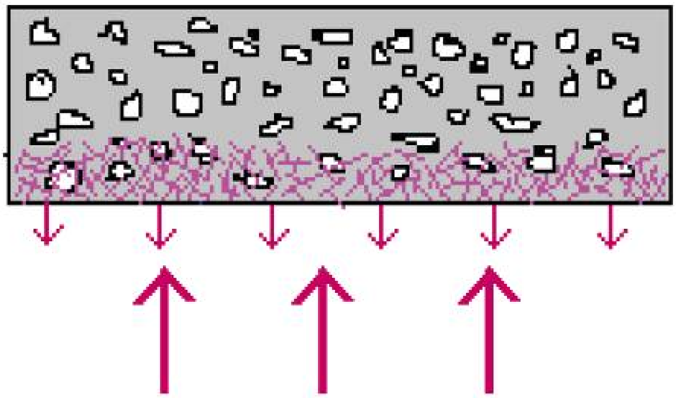
Fire protection performance criteria

Benefits of fiber addition



HEAT

Fibers melt at 160°C form interconnecting passages for vapour pressure to escape

Fire protection performance criteria

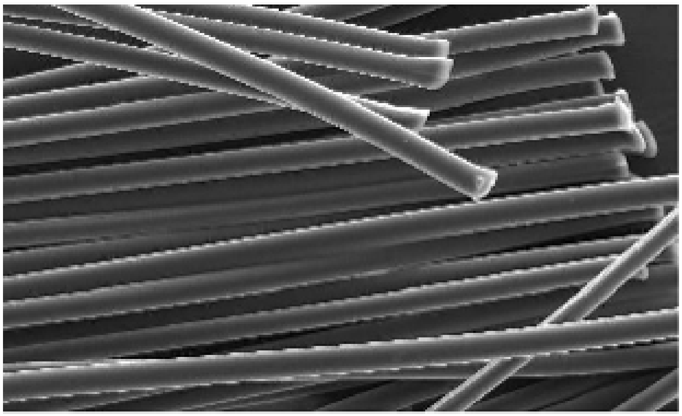
Conclusions from fire tests:

- PP Monofilament fibers at a dosage of 1 kg/m^3 after melting reduce pressure peaks and pressure gradients and have a substantial positive effect on concrete spalling.

- Steel fibers Dramix resist much higher temperatures and keep their reinforcing function during the fire.

Monofilament Fibres

M6 FIRE dosage 1 to 1,5 kg/m^3



BEKAERT has the finest fibre — Duomix® Fire

2,3 (2,3 g per 10 km fibre)	
App. 725 mio fibres/kg with an overall surface of 615 m^2	
Length	6 mm
Diameter norminally	18µm
Elongation at rupture	15%
Material	Polypropylen
Density	0.91 kg/dm^3
E-module	3500-3900 N/mm^2
Tensile stength	300 N/mm^2
Melting Point	100- 165°C
Moisture absorption	0%
Colour	transparent white

Duomix® Fire (M6), the monofilament fibre with diameters of less than 20 µm and a length of 6 mm.

Durability

Durability

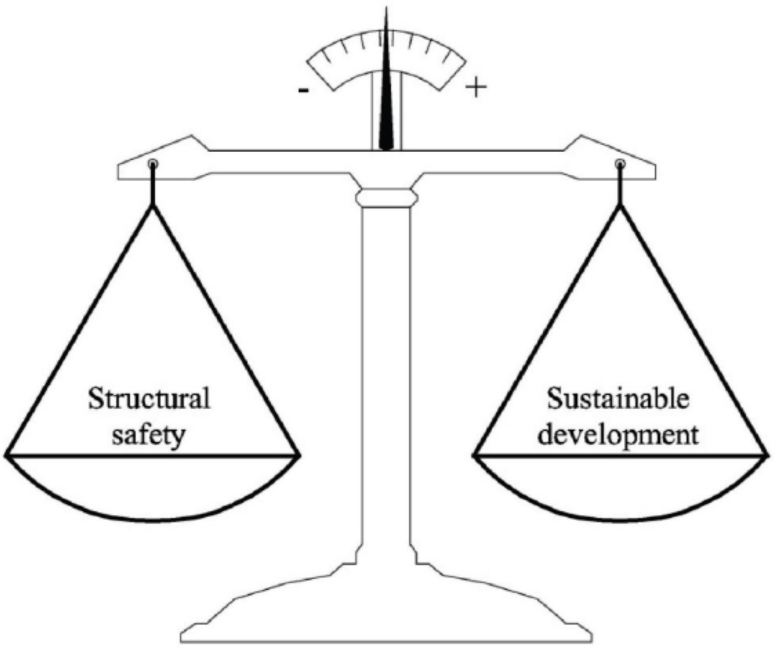
- For uncracked elements, the FRC dutability is higher respect to RC element (the chloride threshold that induce corrosion in FRC is up to 10 time higher respect to black steel);
- For cracked elements, fibers are more sensitive to corrosion and a smaller crack opening should imposed (crack opening are anyway smaller with FRC);
- Risk of having corrosion by stray current in FRC is very low.

Conslusion on DURABILITY

- It can be concluded, that SFRC presents an overall improved durability to corrosion compared to conventional reinforcement
- BEST DURABILITY SOLUTION AVAILABLE

SUSTAINIBILITY

SUSTAINIBILITY



"development that meets the needs of the present without compromising the ability of future generations to meet their own needs

FIB BULLETIN N° 83

Bekaert · Maccaferri Underground Solutions

The sustainability index computed for the three concretes investigated

Materials	CRC	FRC	SC-FRC
CEM I 52.5	315	315	381
Sand 0/5	817	817	1.200
Fine aggregate 5/12	404	404	500
Coarse aggregate 12/20	810	810	200
Water	150	156	165
Superplasticiser	2,80	2.80	4.60
Steel fibres	0	45	50

The sustainability index computed for the three concretes investigated

Indicator	CRC	FRC	SC-FRC
I_1 Direct costs (M€/km)	2.89	2.60	2.61
I_2 Probability of repair	Moderate	Low	Low
I_3 Cement and aggregates (Ton/km)	66,444	66,444	64,603
I_4 Water (Ton/km)	15,590	10,863	11,668
I_5 Reinforcing steel (Ton/km)	1,097	499	449
I_6 CO_2 emissions (TonCO_2-eq/km)	5,305	4,601	5,083
I_7 Embodied energy (MWh/km)	12,411	9,375	9,904
I_8 Noise pollution (Db)	90	90	60
I_9 Risk during handling	Reduced	High	High

	CRC	FRC	SC-FRC
SI	0.578	0.754	0.856

The tests

Dramix :
CTRL(UK) = A very positive return of experience

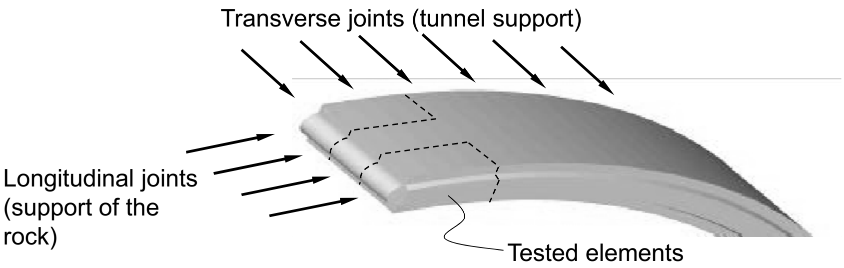
Table 1: Overall damage rate to segments CTRL project published in TT magazine

Manufacturing process			Construction process		
No. of segments made	Rejected	Repaired	Minor damage no repair needed	Minor damage controlled repair	Major repair
(No.)	(%)	(%)	(%)	(%)	(No.)
260,000	0.8	2.8	2.2	0.3	1

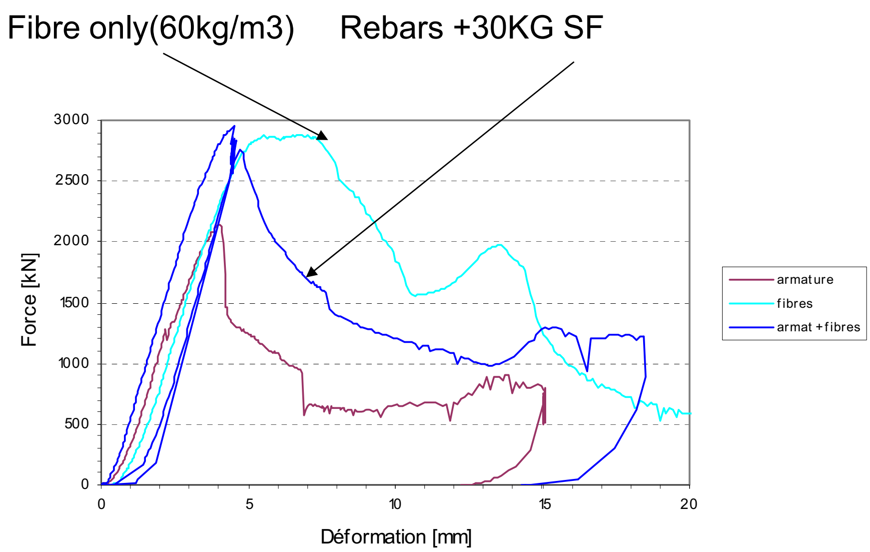
PRECAST SEGMENT Oenzberg Tunnel: A specific test program

The three selected reinforcement solutions were:

- the basic solution, with steel reinforcing bars
- a solution with reinforcement provided by 60 kg/m^3 of Dramix steel fibres
- a mixed solution, with reinforcing bars and 30 kg/m^3 of Dramix steel fibres

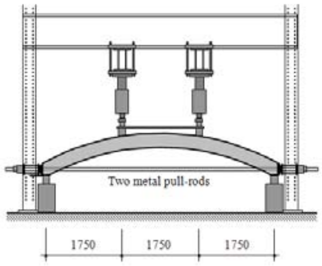


PRECAST SEGMENT Oenzberg Tunnel

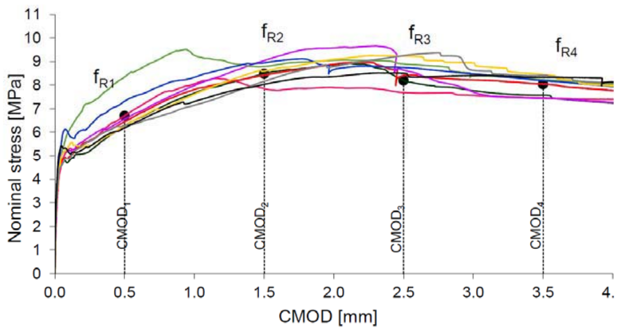


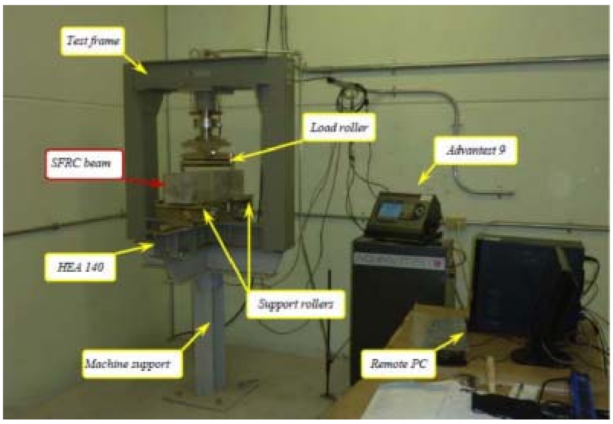
Oenzberg Tunnel : Flexurals tests on tunnel segment

Fibre reinforced concrete
Appears particulary
well-adapted
for precast tunnel
segments subject to high
compression loads



BEAM TEST ACCORDING TO EN 14 651





	f_L [Mpa]	f_{R1} [MPa]	f_{R2} [MPa]	f_{R3} [MPa]	f_{R4} [MPa]
Beam_01	4.68	6.70	7.86	7.69	7.47
Beam_02	4.90	6.28	8.49	8.20	7.58
Beam_03	4.78	6.45	8.41	8.42	8.04
Beam_05	5.15	6.56	9.04	8.64	7.44
Beam_07	5.72	7.33	8.95	8.75	8.19
Beam_10	5.03	6.27	8.60	9.23	8.45
Beam_12	5.63	7.75	10.2	8.99	8.54
Beam_13	4.60	6.28	8.16	9.25	8.40
Beam_14	5.43	6.18	8.03	8.50	8.33

TEST SCALE 1

The segments used in the research are representative of an hydraulic tunnel having an internal diameter equal to 3.2 m. The thickness of the segment is equal to 250 mm.
Figure 1 shows the segment geometry.

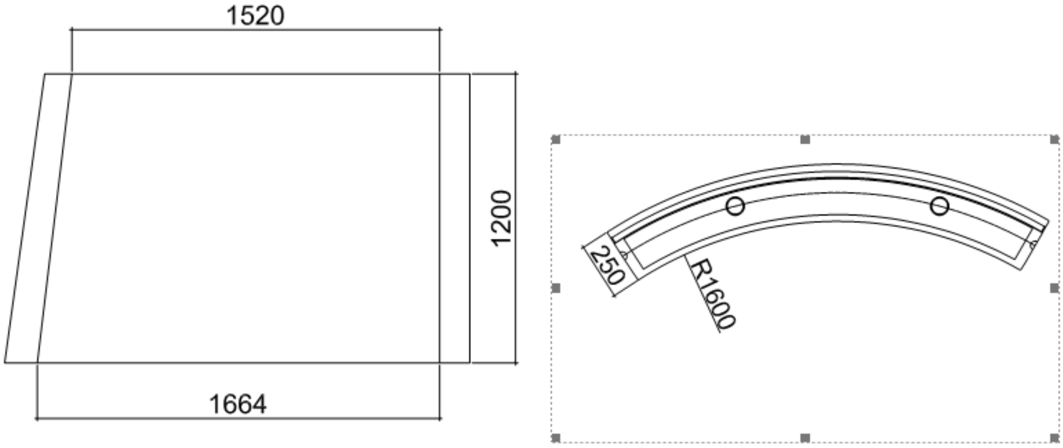


Fig. 1 *Segment geometry.*

TEST SCALE 1 : CASTING SEGMENT

The segments were cast in moulds available at the laboratory of the Rome University "Tor Vergata" (Fig. 2). The concrete was prepared in a track mixer. The adopted moulds have electrical vibrators in order to compact the concrete. Both the segment were made from the same batch, as well as beams and cubes for the material characterization.

Fig. 2 *Segments cast.*

TEST SCALE 1 : BENDING TEST

The test set-up is shown in Figure 5. The tunnel segment was placed on hinge supports with a span of 1200 mm. The load was applied by means of an electromechanical jacket with a PID control and a maximum load of 1000 kN. The tests were conducted up to the failure by using a jacket displacement as control signal. In order to distribute the point load on the segment width, a frame system was used, as shown in Figure 5. The total force was measured with a load cell placed between the jacket and the frame system. The vertical displacements were recorded by three wire transducers, placed at midspan, in the segment intrados (Fig. 6), while the crack openings were measured with two LVDTs placed in the central part of the segment intrados (Fig. 6).

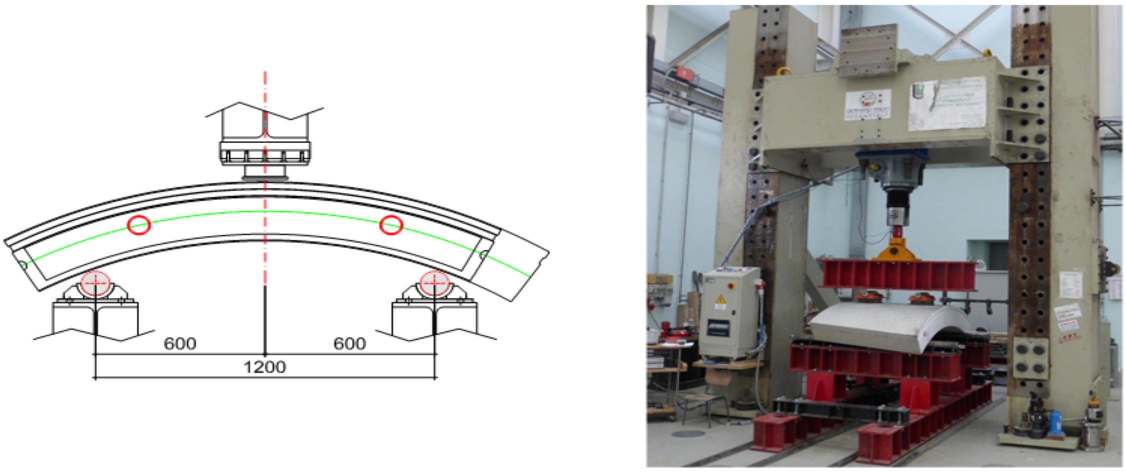
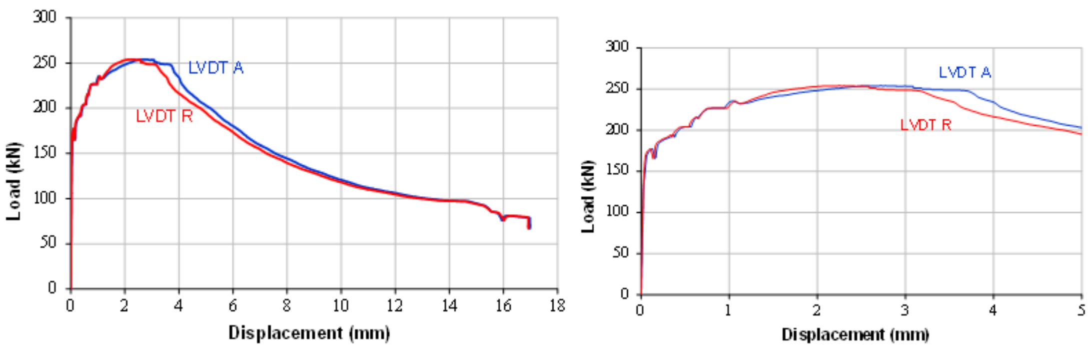


***Fig. 5** Bending test set-up.*

TEST SCALE 1 : BENDING TEST

Finally, in Figure 9 the load is plotted versus the crack opening displacement measured by the two LVDTs (Fig. 4).



a) b)

***Fig. 9** Bending test results: load versus crack opening curve. ; a) full diagram; b)detail up to 14 mm*

The first cracking occurs at a load level of about 177 kN, then the load increases up to a peak load of about 254 kN. Afterwards a softening branch developed, up to maximum displacements of about 45-50 mm.

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TEST SCALE 1 :CONCENTRATED LOAD

The point load test aims to simulate the TBM thrust on the segment. In particular, the behaviour of the segment under this type of action has to be verified, with particular regard to the localisation of spalling and bursting cracks as well as to overall stability.

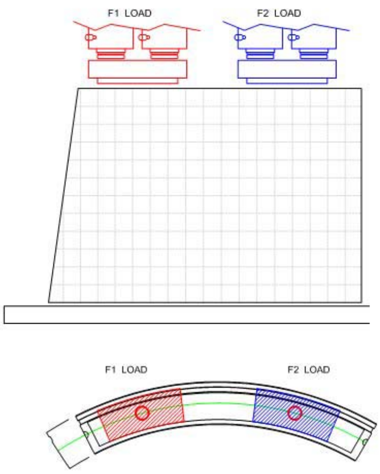


Fig. 10 TBM trusts: test set-up.

TEST SCALE 1 :CONCENTRATED LOAD

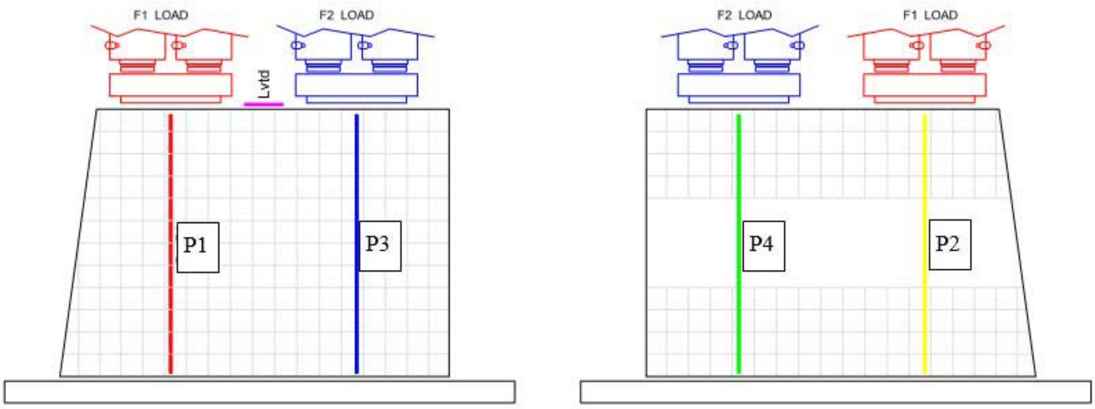
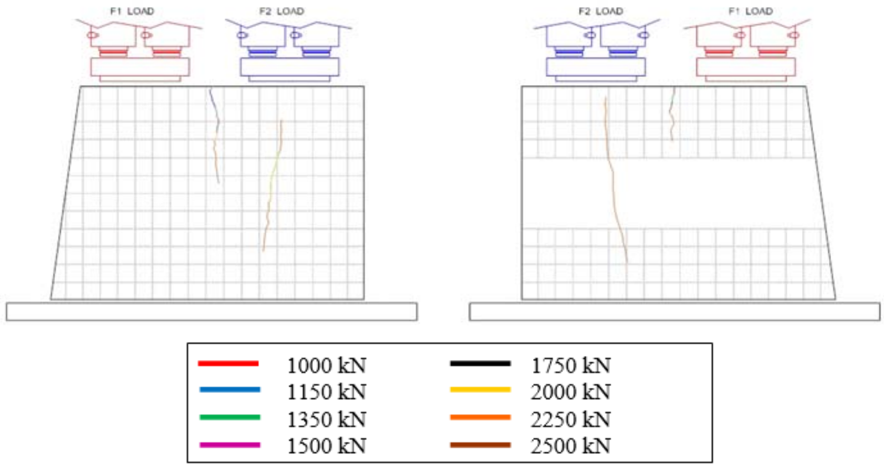


Fig. 11 TBM test: measurement devices.

TEST SCALE 1 :CONCENTRATED LOAD

TBM test: crack pattern



The first crack appeared for a load level of 1000 kN (for each steel pad) between the two shoes at the top and extrados surface. It has to remark that the first crack occurred at a load level higher than the design value (785 kN) and the maximum load of the TBM (1100 kN);

The maximum crack width at the end of the test, after the complete unloading, was about 0.05 mm

The green solution

GREEN PRODUCT

Dramix® minimizes the impact on the environment

1. Using less steel for the same strength compared to rebar
2. Using at least 20% recycled steel in the production process
3. Producing in ISO 14001 certified plants
4. Creating Green products
5. Allowing to build durable structures

Dramix® minimizes the impact on the environment
Using less steel for the same strength

Comparison	Rebar / mesh	Dramix®
Concrete		
Energy consumption (GJ/m³)	2,89	2,89
Reinforcement		
Reinforcement (kg/m³)	100	40
Type	mesh	DRAMIX
Energy consumption (GJ/ton)	22,5	22,5
Energy consumption (GJ/m³)	5,14	3,79
Reduction of energy consumption	**26%**	

Dramix® minimizes the impact on the environment
Using at least 20% recycled steel in the production process

A process using 20% recycled steel

For special projects and on customer request, it is possible to select special wire rod qualities, made with well defined production processes where we can offer a Dramix® product made of minimum 80% recycled steel.

Dramix® minimizes the impact on the environment
Producing in ISO 14001 certified plants

"All Dramix® plants ISO 14001 certified by year end 2011"

ISO 9001/14001
BUREAU VERITAS
Certification

Cost analysis

EXAMPLE OF A COST COMPARISON – FIBRES VS BAR REINFORCEMENT

2) REINFORCEMENT CAGES			
	Unit cost	m3per ring	Cost/Ring
C60 Concrete	84,00	6,48	544,32
	Unit cost / kg	kg/m3	
Reinforcement	0,8	100,00	518,40
Cage Fabrication	Man-Hours/Ring	Cost/Hour	
Labour for fabrication	16	12,00	192,00
Administration/QC costs	1	12,00	12,00
	Total cost		
Jigs	25000		8,33
Rebar fabrication shed area	200000		66,67
Welding/tie wire	3000		1,00
Placing of cages into moulds	Man-Hours/Ring	Cost/Hour	
Labour to place cages	3	10,00	30,00
Cost of cranage	3	25,00	75,00
QC costs (checking cover)	1,5	12,00	18,00
Repair of damaged segments	Percentage	Segments for repair	
% of segments requiring major repairs	10%	300	
	Man-Hours/Segment	Cost/Hour	
Labour for repair	2	14,00	2,80
Cost of craneage in/out repair areas	0,5	25,00	1,25
Administration/QC costs	0,5	14,00	0,70
	Cost/Segment	Total cost	
Cost of repair materials	10,00	3000	1,00
Total Cost/Ring			1471,47

EXAMPLE OF A COST COMPARISON – FIBRES VS BAR REINFORCEMENT

COST SAVING 40 %

No. of rings in project	Segments/Ring	m3 of concrete/ring	
3000	8	6,48	
1) STEEL FIBRE REINFORCED SEGMENTS			
	Unit cost	m3 per ring	Cost/Ring
C60 Concrete	84,00	6,48	544,32
Fibre dispenser	32000		10,67
		kg/m3	
Fibres *	1,4	40	362.88
Repair of damaged segments	Percentage	Segments for repair	
% of segments requiring major repairs	5%	150	
	Man-Hours/Segment	Cost/Hour	
Labour for repair	1	14,00	0,70
Cost of craneage in/out repair areas	0,25	25,00	0,31
Administration/QC costs	0,25	14,00	0,18
	Cost/Segment	Total cost	
Cost of repair materials	10,00	1500	0,50
Total Cost/Ring			919.55

REFERENCE

Precast segmental lining
USA: Big Walnut Sewer Project




Fibre type:
DRAMIX 3D 80/60BG

Reinforcement:
35 kg/m^2

Country:
USA (Ohio)

- High impact resistance
- No damage
- Cost reduction

Diameter: 3,4 m

Precast segmental lining
UK: CTRL (channel tunnel rail link))

Diameter: 7,15 m

Fibre type:
DRAMIX 3D 80/60BG

Thickness:
35 cm

Reinforcement:
SFRC 30 kg/m3
pp fibre 1kg/m3

Year:
2003-2004

Country:
UK

Size:
40 km

A client's perspective: Create a durable solution
- 120 years design life
- Fire resistance with pp fibre
-Quality improvement: no damage during production

Precast segmental lining
Brazil: Metro Sao Paulo

Diameter:
8,43 m

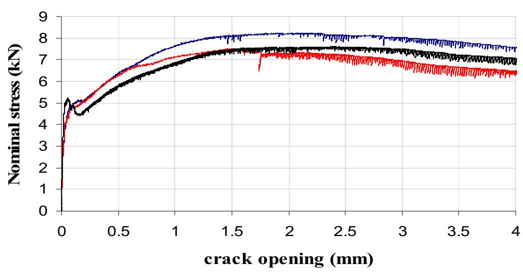
Fibre type:
DRAMIX 80/60

Reinforcement:
35 kg/m³

Country:
Brazil

Concrete Quality:
C40/50

segmental lining MONTE LIRIO/PANDO /EL ALTO



Model Code performance criteria C40/50 5 c

Diameter:
3,7 m

Fibre type:
DRAMIX 4D 80/60BG

Reinforcement:
40 kg/m³

Country:
COSTA RICA

Concrete Quality:
C40/50

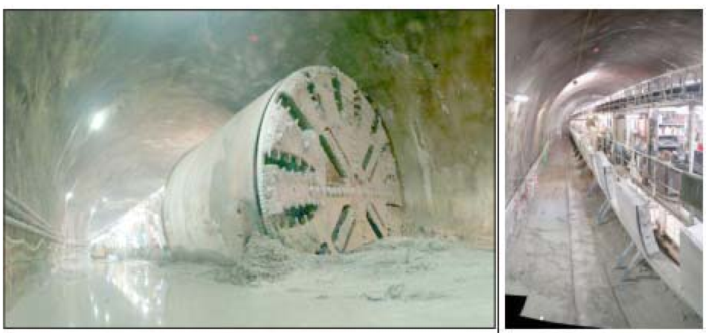
PERFORMANCE CLASS

5c ACCORDING TO MC2010

Precast segmental lining

BRISBANE AIRPORT LINK

At 11.34m internal diameter the mainline TBM tunnels for the Brisbane Airport Link Project are the largest SFRC segmental lining in the



(A) Partial invert excavation

(B) Upstand segment support

Diameter: 11,34 m

Fibre type:
DRAMIX 3D 80/60BG

Reinforcement:
40 kg/m³

Country:
AUSTRALIA

Concrete Quality:
C50/60

Key learning point:
The use of SFRC, rather than conventional bar reinforced concrete, is known to provide significant benefits for long term durability and maintenance of segmental tunnel linings
This has been demonstrated on the TBM tunnels of the recently completed Brisbane Airport Link project, where the majority of the segmental lining was pure steel fiber reinforced concrete (SFRC)—the largest such lining in the world
Program/cost savings from reduction/elimination of conventional re-bar to Steel Fibre Reinforced Concrete (SFRC) segments

Precast segmental lining

LEE TUNNEL

Diameter: 7,2m

Fibre type:
DRAMIX 3D 80/60BG

Reinforcement:
35 kg/m³

Country:
UK

Concrete Quality:
C40/50

Designed by MVB's engineer, Morgan Sindall Underground Professional Services (UnPS), the 1.7m wide, 350mm thick, seven segment + key universal tapered are produce at Morgan Sindall's permanent precast factory, at Ridham Dock, in Kent. A number of emerging technologies have been implemented – such as steel fibre reinforcement, cast-in EPDM gaskets, 3D laser checking of cast segments.

SFRC Segmental Lining Design

Segmental Lining Project References – BKT & OM

- 80 projects worldwide
- 47 only steel fibers reinforced
- 33 combined reinforcement (steel fibers + rebars)
- 24 hydraulic projects, 19 metro lines, 19 utilities, 9 railways, 6 roads, 3 others
- Max Φ_{ext} for only steel fibers solution (Dramix): 12,4 m (North-South Bypass Tunnel (Clem 7), Brisbane & Airport Link / Northern Busway, Brisbane)

conclusion

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Conclusion

- CLEAR MATERIAL PROPERTY TESTING METHOD
- INTERNATIONAL DESIGN GUIDELINE AS MODEL CODE 2010 EDITED BY FIB
- DESIGN BY TEST GUIDANCE PROPOSAL
- THE RIGHT PRODUCT FOR THE RIGHT USED WITH DRAMIX 4D 80/60BG
- WORLWIDE WELL DOCUMENTED RETURN OF EXPERIENCE
  - DURABILITY BEST AVAILBALE
  - Damage due to handling and installation is minimized
  - Performance in the relevant Ultimate and Service Limit States (ULS and SLS) can be reliably demonstrated
  - Reduced waste;
  - Overall manufacturing costs are lower than for conventionally reinforced concrete
  - A lower Carbon foot print

THANK YOU FOR YOUR ATTENTION

Let Dramix® enlighten your underground…

Geo-electrical Real-time Ground Prediction While TBM-Boring

Dr. Sanjay Rana, Director, PARSAN
sanjay@parsan.biz

Abstract

The Bore Tunnelling Electrical Ahead Monitoring (BEAM) system, developed by the GET Company, Germany, is a geophysical ground prediction technique especially designed for TBM operations. BEAM is a non-intrusive focused-electrical induced polarization ground prediction technique, operating simultaneously while TBM advances. The aim is to get a continuous real-time geological forecast ahead of TBMs which is useful to predict the quality of the groundmass and the presence of large quantities of water. The system has proven to be very reliable in providing an accurate forecast of the different hydrogeological parameters of the formations in front of the TBM and of the expected TBM performances and criticalities. The BEAM system's predictions have been reliable in various projects in almost 80-92% of the cases: they allowed the TBM operators to be prepared for the geology ahead of the TBM and enables better planning of TBM operation and maintenance. The system minimizes the geological surprises during tunnelling and gives valuable information to be prepared for geology to be encountered.

Introduction

BEAM is a non-intrusive focused-electrical induced polarisation ground prediction technique, permanently operating during TBM tunnelling. It is a robust and reliable long-term operating geophysical probing technique meeting the practical demands under the rough conditions of tunnelling work in hard rock as well as in soft ground. Main components of the survey system are the measuring instrument placed in the TBM operator cabin and specially adapted excavation tools which are used as electrodes. The unit is connected to the guidance system and receives the boring signals which allows fully automatic data acquisition and visualisation in real-time on an integrated monitor. Communication facilities transfer the forecast results to every authorized computer world wide simultaneously.

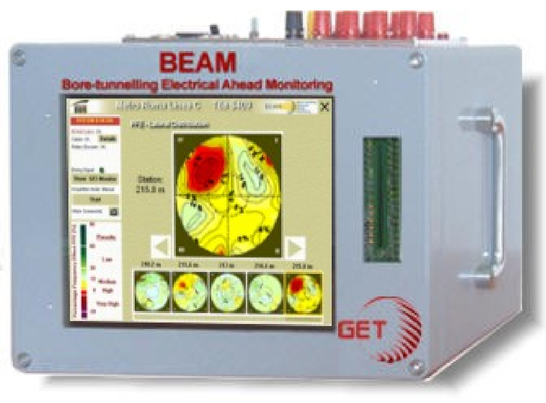


Figure-1: BEAM Multi Channel Unit

Based on the measured data the percentage frequency effect (PFE) and the resistivity R, an advanced evaluation software is established for geoelectrical-geological/ hydrogeological classification and interpretation. Early warning of significant ground changes while tunnelling is advantageous to reduce hazardous risks, in particular during excavation with tunnel boring machines. Accidents or complications and hence expensive standstills can be prevented by planning precautionary and logistical measures. On the condition that TBM operations and lining works should not be obstructed by data acquisition, a probing and documentation without predrillings is one major demand. On the other hand knowledge of non-critical ground conditions ahead of the face allows rapid excavation resulting in high production rates and contributes to safeguard personnel and equipment.

Figure-2: Early warning information for critical ground while TBM boring reduces hazardous geo risks like enhanced water-inflow

Method

BEAM combines well established principles of focusing-electrode logging and frequency-domain induced polarisation (IP) measurements.

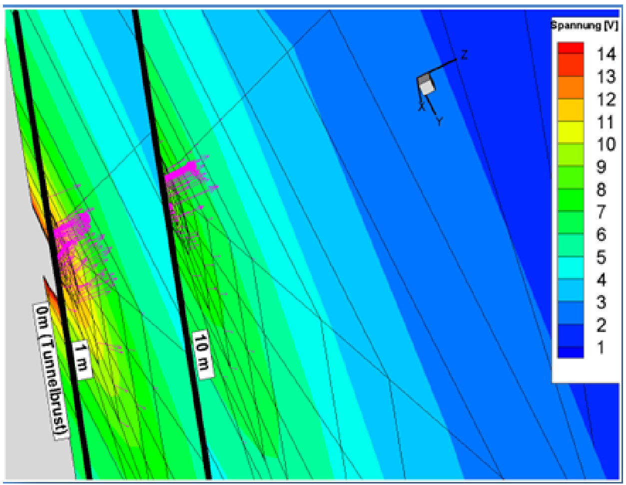


Figure-3: 3D-finite elements calculated model of BEAM-focused current and voltage ahead of the face

Low frequency electrical fields are generated by galvanic injected currents through an excavation specific focusing electrode configuration. By adjusting the same voltage of same polarity simultaneously between the guard electrode A1 (+) and the return electrode B (-) and between the measuring electrode A0 (+) and the return electrode B (-), the measuring current is forced ahead of the face. Thereby, a distinct sensitivity zone for ground changes is established in a forefield distance of about 3 times the guard electrode A1 diameter, which is the tunnel diameter.

The obtained measuring parameters are the frequency-dependent resistivities R (f) and derived IP Percentage Frequency Effect (PFE). Thus, when the tunnel face is advancing towards a ground change, the continuous electrical measurements are directly imaging and providing early warning about the “coming” new geological situation.

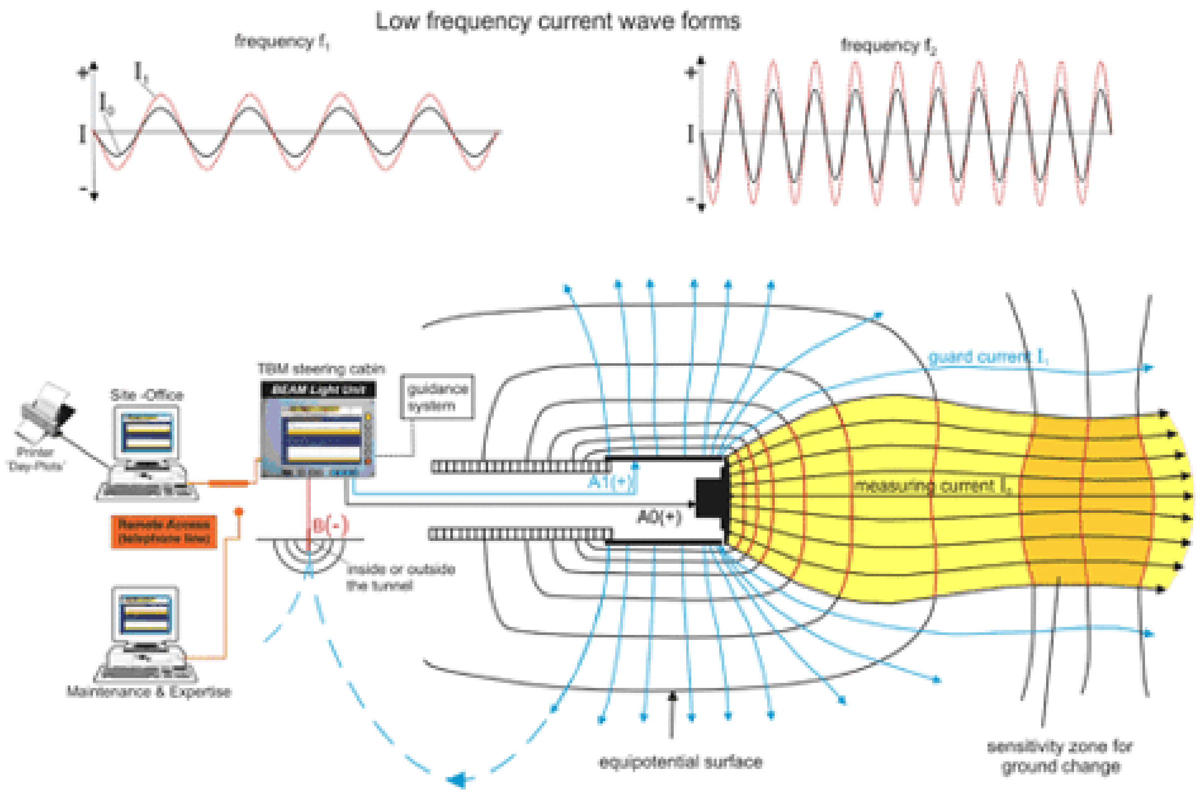


Figure-4: Schematic presentation of focused-electrical field around a TBM heading

BEAM is based on an advanced in-house developed processing, evaluation and visualisation software which shows the measuring data and distribution of percentage frequency effect (PFE) and resistivity (R) for geological classification and hydrogeological characterisation The PFE characterizes the ability of the ground to store electrical energy. Thus, it is reciprocally correlated to the effective porosity (permeability).

The Resistivity provides additional information about the fracture/cavity infillings (e.g. water, gas/air). Ground changes or obstacles are characterized by typical combined PFE/Resistivity-anomalies, which define different geological/hydrogeological ground situations (rock mass types and water-inflow potential). Based on correlation of geoelectrical PFE-data and R-data to documented geological and hydrogeological conditions at different tunnel projects guided by BEAM surveys, a petrophysical classification was developed for hard rock and soft ground, each with 12 types.

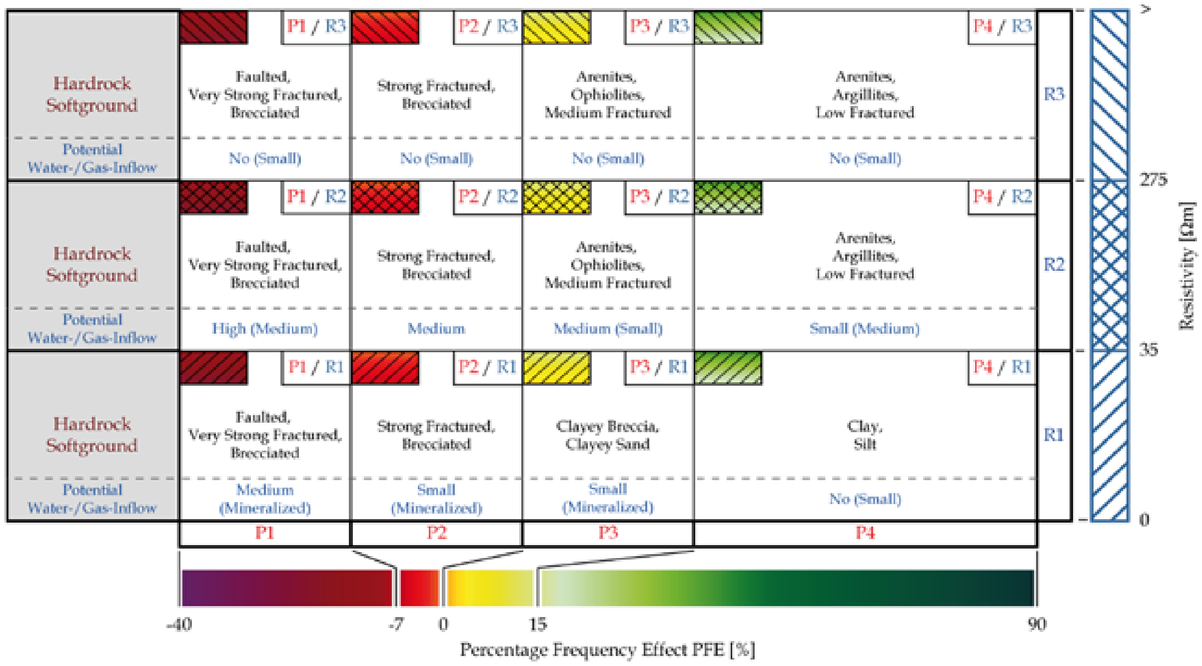


Figure-5: Customized cross correlation and classification matrix: Rock mass types and water-inflow indication according to geophysical parameters Induced Polaization (PFE) and Resistivity (R)

System

The TBM based BEAM system allows a permanent driving accompanying exploration of ground conditions about 3 times the tunnel diameter ahead of the face. Data acquisition and evaluation is performed automatically and prediction results are displayed in real time enabling fast on-site decisions.

An advantageous feature of the system is the utilization of excavation tools and safety constructional components as electrodes, which are automatically electrically coupled to the ground by the TBM itself. Since the used voltages lower than 42V, a continuous operation is possible without any danger for personnel and machine.

General system layout consists of:

- BEAM unit: geoelectrical device placed in the TBM operator cabin as a stand- alone unit with integrated display or mounted in the display panel
- Measuring electrode(s) A0: whole cutterhead with all cutting tools or selected single cutters resp. rippers contacted to the face during boring rotation
- Guard electrode A1: TBM shield or armed lining (including anchors)
- Return electrode B: fixed steel rod or anchor inside or outside tunnel at a large distance to the face
- Automation: connection of the BEAM unit via interface to the TBM guidance system and triggering of measurements by boring signal enables the fully automatic data acquisition with strokewise survey points

- Communication: using internet access or a free telephone line for online maintenance purposes and transferring real-time prediction results from the BEAM unit in the operator cabin to site-office or to any other authorized computer outside tunnel

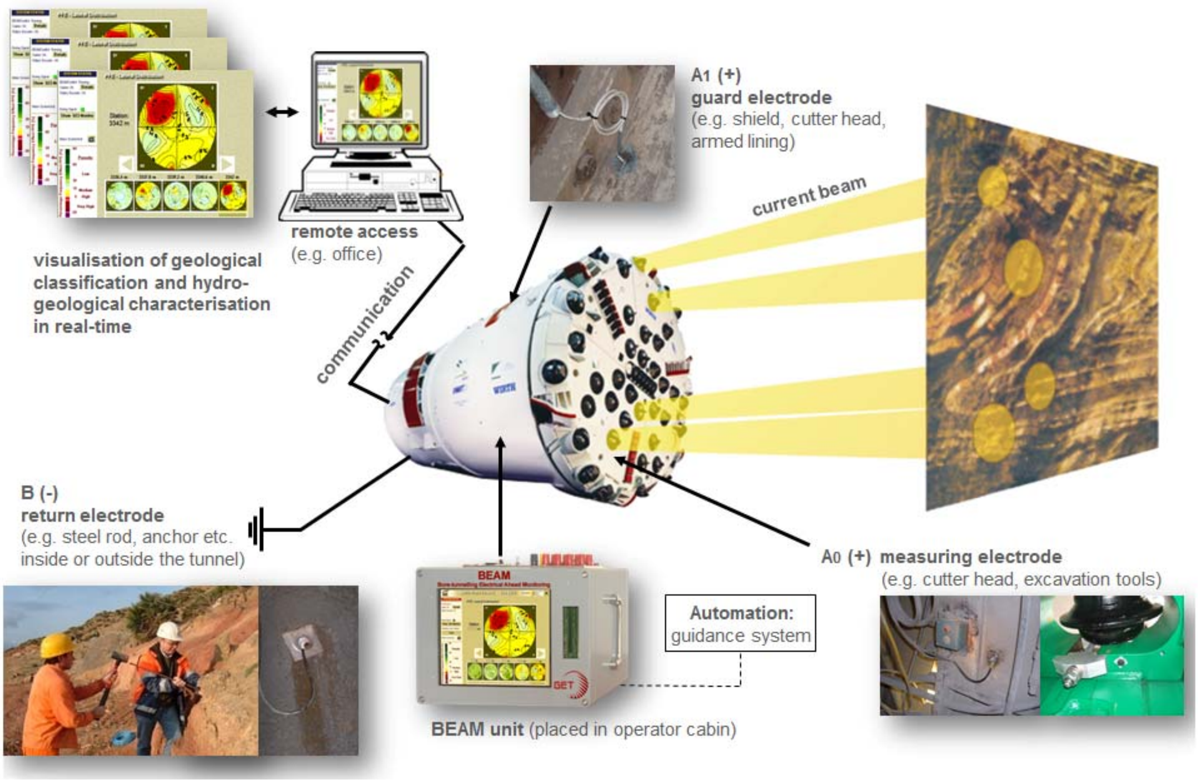


Figure-6: BEAM system layout

BEAM-INTEGRAL is the basic system which uses the whole cutterhead/ cutting wheel as one large measuring electrode A0.

It can be easily and quickly installed in tunnelling projects currently under construction without any disturbance or stoppage of TBM excavation. Forefield prediction results are displayed in one-dimension and indicate investigation targets clear and timely.

The A0-INT measuring electrode is located as close as possible to the centre of the cutterhead, e.g. at or near by the rotary, fixed to the non-rotating parts. Surrounded by the A1 guard electric potential field the current through A0 contact is the measuring current focussed into the forefield.

Figure-7: Connection of the measuring electrode AO (INTEGRAL mode) near cutter head.

BEAM-SCAN system uses additional selected A0 electrodes for an advanced lateral resolution ability, providing more detailed imaging of 2D and 3D targets. Additional installations and requirements like an electrical rotor, information about rotational position of cutterhead via rotary encoder and specially adapted insulated excavation tools (OEM) are necessary or using specific electrode plates along one arm of cutter head. Several prepared excavation tools which must cover the TBM radius work as A0 measuring electrodes for the scan-mode. Installation of the SCAN mode requires some additional preparatory work and should be done before start boring.

In general both systems have the same ability of detection in the forefield range. Significant differences between both systems are the 1D, 3D acquisition and visualisation of ground prediction results.

System / Features	BEAM-SCAN	BEAM-INTEGRAL
Detection sensitivity	✓	✓
Detection distance (3-times TBM diameter)	✓	✓
Resolution/ Visualization	forefield horizontal and lateral (3 dimensional)	forefield horizontal (1 dimensional)
Data transfer quantity	high	low
Installation	support from TBM-supplier	support from an electrician jobsite
Special requirements	electrical rotor, encoder for rotational position, preparation of some cutters	---
Permanent and real-time ground prediction	✓	✓

Figure-8: BEAM Systems in comparison

Visualisation

BEAM is based on an advanced inhouse developed processing, evaluation and visualisation software which shows the measuring data and distribution of percentage frequency effect (PFE) and resistivity R for geological classification and hydrogeological characterization.

Figure-9: BEAM Unit in operator cabin

On the screen, a vertical fixed yellow line indicates the current face indicating position of the cutter head of the TBM. Forecast results in the form of survey points are “moving” strokewise from right to left whereby the red curve represents the PFE [%] which characterizes the rock mass regarding fracture/karst porosity information. The blue curve indicates the resistivity R [Ohm m] which provides information about the fracture/cavity infillings (e.g. water, gas/air, clay). In the middle chart, the combined PFE (colour) and R (hachures) geoelectrical-geological rock mass classification is refreshed after every stroke.

Unique feature of the software program is a dynamic interpretation guide which has integrated a correlation matrix of PFE and resistivity values for indication of geological and hydrogeological results with every stroke. Any significant ground change ahead of the face is shown in a new text box with characterization of rock mass types, signature and tunnel meter as well as an estimation of potential water- and/or gas-inflow into the tunnel.

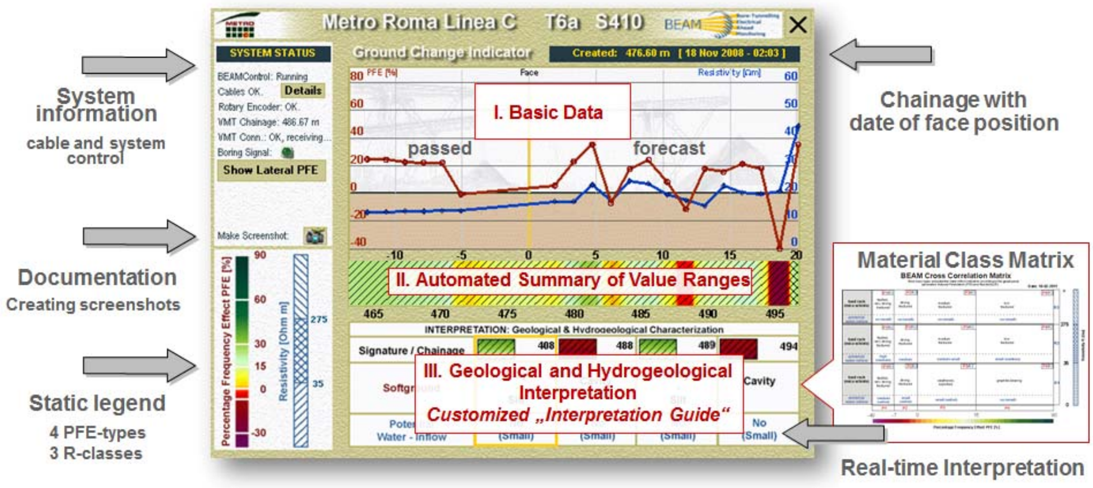


Figure-10: BEAM Integral Visualization

Figure-11: BEAM INTEGRAL user interface 2012; e.g. simultaneously indication of BEAM forecast results on a monitor placed outside the tunnel; BEAM results indicate a cavity zone of about 2m thickness and medium water content in a distance of about 4m ahead of the face yet, whereby the first detection was shown 20 m ahead of the face

The lateral PFE Distribution View is a feature available by BEAM-SCAN system only. Pre-selected excavation tools are prepared to act as measuring electrodes enabling a high resolution scan of the forefield ground during rotation of the cutterhead cutting wheel. The additional PFE lateral distribution can be used for more detailed location and geometry of obstacles, cavities and ground changes. With a button on the left side, one may switch anytime between the Ground Change Indicator View (INTEGRAL-mode) with geological classification as well as hydrogeological characterization and the Lateral PFE Distribution View (SCAN-mode).

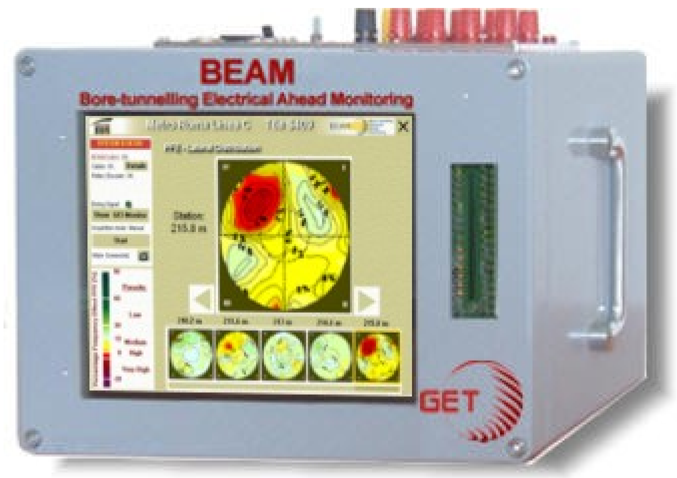


Figure-12: BEAM SCAN view indicates the lateral PFE distribution within a cross-section in a distance of 3-times the tunnel diameter (SCAN-mode); On the screen a red anomaly shows a cavity (high porosity zone) within pyroclastics which will occur on top and left of the TBM.

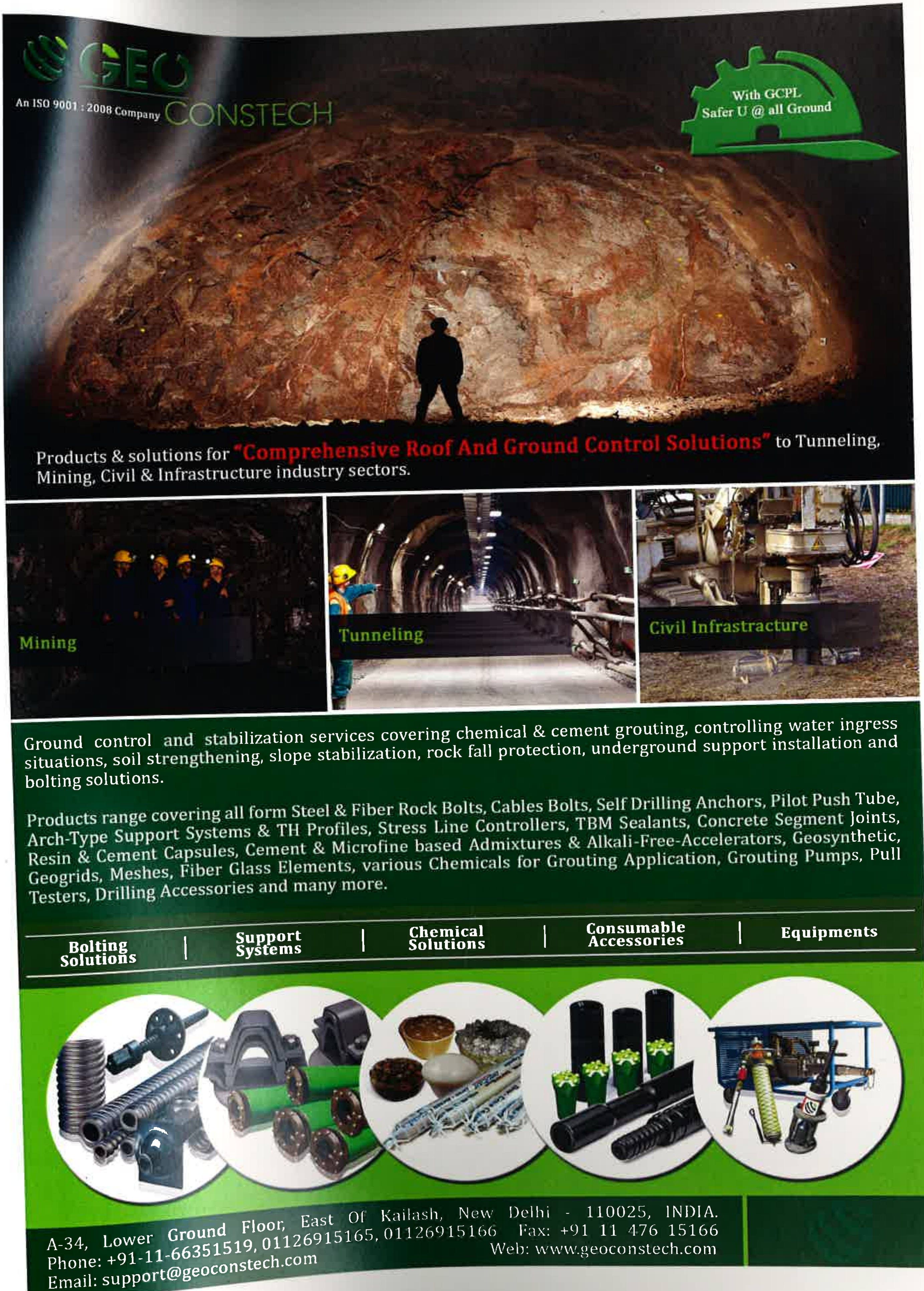
Conclusions

BEAM is a robust and reliable long-term operating geophysical probing technique fulfilling the practical demands under the rough conditions of tunnelling work. BEAM system enables tunnel excavation to achieve significantly high advance rates, due to improved confidence when it shows consistent ground conditions ahead of the face and enable appropriate action to be taken when responses suggest more difficult ground conditions ahead of the face.

The advantages of adopting the system can be summarised as under:

- Permanent automatic high resolution and non-destructive forward prediction while tunnelling;
- Realization of high advancement rates without disturbance and stops of tunnelling work;
- Early detection and warning of changes in geotechnical-geological and hydrogeological ground conditions like fault/karst zones, cavities or permeable water- /gas-bearing zones;
- Geoelectrical-geological/hydrogeological classification of prefield ground changes in real time visualised on the BEAM unit in the operator cabin and also on every other accredited computer in the world;
- Reliable real-time results for geological classification and documentation of fore field ground which are shown on the screen for fast on-site decisions
- Optimum planning of safety and lining measures in advance and with it in- time measures to shelter personnel, tunnel and boring machine;

- No percussion or core drilling is needed to use BEAM;
- Evaluation software comprising geological interpretation is self-instructional for tunnel engineers and miners on jobsite;
- Applicable in any geology as well as above and below the ground water table;
- Implementation in any type of TBM independent of the TBM OEM;
- Effective contribution to lowering geological risks and increasing the safety levels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