International Tunnel Association
Working Group No. 2

Guidelines for Tunnelling Risk Management

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0 Abstract

The paper gives 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 text provides owners and consultants with what is modern-day industry practice for risk assessment, and describes the stages of risk management throughout the entire project from concept to start of operation.

1 Introduction and scope

Tunnelling and underground construction works impose risks on all parties involved as well as on those not directly involved in the project. The very nature of tunnel projects implies that any potential tunnel owner will be facing considerable risks when developing such a project. Due to the inherent uncertainties, including ground and groundwater conditions, there might be significant cost overrun and delay risks as well as environmental risks. Also, as demonstrated by spectacular tunnel collapses and other disasters in the recent past, there is a potential for large scale accidents during tunnelling work. Furthermore, for tunnels in urban areas there is a risk of damage to a range of third party persons and property, which will be of particular concern where heritage designated buildings are involved. Finally there is a risk that the problems which the tunnelling project cause to the public will give rise to public protests affecting the course of the project.

Traditionally, risks have been managed indirectly through the engineering decisions taken during the project development. These guidelines consider that present risk management processes can be significantly improved by using systematic risk management techniques throughout the tunnel project development. By the use of these techniques potential problems can be clearly identified such that appropriate risk mitigation measures can be implemented in a timely manner.

The use of risk management from the early stages of a project, where major decisions such as choice of alignment and selection of construction methods can be influenced, is essential.

The purpose of this document is to

1. indicate to owners what is recommended industry best-practice for risk management; and
2. present guidelines to designers as to the preparation and implementation of a comprehensive tunnel risk management system.

For the purposes of this document "risk management" is the overall term which includes risk identification, risk assessment, risk analysis, risk elimination and risk mitigation and control. See glossary in section 9.

2 Use of risk management

In order to fulfil the scope these guidelines provide a description of risk management activities that may be used for tunnels and underground works. Below is shown how risk management may be used throughout the project from the early planning stage through to start of operation:

- Phase 1: Early Design Stage (Feasibility and Conceptual Design)
  - Establish risk policy (section 4.1)
  - Risk acceptance criteria (section 4.2)
  - Qualitative risk assessment of the project (section 4.3)
  - Detailed analysis of areas of special interest or concern (section 4.4)

- Phase 2: Tendering & Contract Negotiation
  - Requirements in tender documents (section 5.1)
  - Risk assessment in tender evaluation (section 5.2)
  - Risk clauses in contract (section 5.3)

- Phase 3: Construction Phase
  - Contractor's risk management (section 6.1)
  - Owner's risk management (section 6.2)
  - Joint risk management team between the owner and the contractor

In phase 1 the responsibility of establishing a risk policy and carrying out risk assessment is the owner's alone. In phase 2 the potential contractor has certain input to the tender regarding risk management, but the owner is still the primary responsible party. In phase 3 however, the primary responsibility moves on to the contractor to establish a risk management system and to carry out effective risk management. The owner should supervise, inspect and participate in this work. The owner should further continue to assess and mitigate risks not covered by the contractor.

It is important that the risk management is performed in an environment of good cooperation between the parties. To achieve this, partnering may be a valuable tool. The process of partnering may be formulated as an exercise in encouraging good communications between the parties. It may be a formula for minimising cost to the owner while maximising profit for the contractor and encompasses joint planning and problem solving, scheduling, mitigation of delays and value engineering. The process of "partnering" may therefore be seen as a risk mitigation measure for the owner and the contractor.

An overview of the risk management activities as seen from the owner's point of view is presented in figure 1. Risk assessments made by the contractor solely for his own purposes, such as the assessment of the risks he is involved in by submitting the tender, are not included.

	Owner	Contractor
Early Design Stage	***Establish risk policy*** ***Qualitative risk assessment*** ***Specific (quantitative) risk assessment*** ***Project Risk Register***	
Tendering and Contract Negotiation	***Preparation of tender documents, including:*** Description of significant technical risks Technical requirements to mitigate risk Required risk management competence ***Selection of contractor, including evaluation of:*** Contractor's ability to perform risk management Risks involved in contractor's proposed technical solutions ***Prepare contract with risk clauses***	***Preparation of tender, including:*** Proposed risk management system Description of experience and competence in risk management Identification and description of risks associated with the proposed technical solution Identification and description of proposed risk mitigation measures
Award of contract		
Construction Phase	***Joint work in risk management team*** ***Supervision and support of contractor's risk management*** ***Assessment and mitigation of owner's risk*** ***Approve on contractor's risk mitigation***	***Establish risk management system*** ***Detailed risk assessment with participation of owner*** ***Propose risk mitigation*** ***Implement risk mitigation***

Figure 1 - Risk management activity flow for owner and contractor

3 Objectives of risk management

The identification of risks resulting from design and construction is an essential task early in a project. In order to form a common reference for all parties involved (e.g. the owner, designers, insurers and contractors) a construction risk policy should be established by the owner.

A construction risk policy for the project may indicate:

- scope,
- risk objectives, and
- risk management strategy.

3.1 Scope

As an example, the scope may include the following risks or consequences:

1. Risk to the health and safety of workers, including personal injury and, in the extreme, loss of life,
2. Risk to the health and safety of third parties,
3. Risk to third party property, specifically existing buildings and structures, cultural heritage buildings and above and below ground infrastructure,
4. Risks to the environment including possible land, water or air pollution and damage to flora and fauna,
5. Risk to the owner in delay to the completion,
6. Risk to the owner in terms of financial losses and additional unplanned costs.

3.2 Risk objectives

The risk objectives may be given as general objectives supplemented by specific objectives for each type of risk. The general objectives of the construction risk policy could be that proper risk management throughout the project will be ensured at all stages of the project by the:

- Identification of hazards
- Identification of measures to eliminate or mitigate risks

- Implementation of measures to eliminate or mitigate risks where economically feasible or required according to the specific risk objectives or health and safety legislation.

Economically feasible may be defined using the ALARP principle i.e. to reduce all risks covered to a level as low as reasonably practicable.

The construction risk policy may indicate that emphasis should be placed on minimising overall risk by reducing the likelihood of occurrence of events with large consequences, e.g. with several fatalities or of significant political concern. This should be done if the owner considers low probability events with high consequences to be of more concern than high probability events with low consequences; even if the risk, expressed as probability times consequence, is the same.

The construction risk policy may also include some general statements on allocation of risks between parties, e.g. a risk should be allocated to the party who has the best means for controlling the risk.

For each type of risk, specific minimum risk objectives may be defined in addition to the general risk objectives. For example, the general public should be exposed only to a small additional risk from construction of the tunnel or underground works; compared to the risk they are exposed to as users of buildings, cars, bicycles, public transport and when walking in the adjacent streets.

3.3 Risk management strategy

As part of the construction risk policy a risk management strategy should be adopted. A recommended strategy is to carry out construction risk assessments at each stage of design and construction in accordance with the information available and the decisions to be taken or revised at each stage.

Any risk management strategy should include:

- a definition of the risk management responsibilities of the various parties involved (different departments within the owner's organisation, consultants, contractors)

- a short description of the activities to be carried out at different stages of the project in order to achieve the objectives

- a scheme to be used for follow-up on results obtained through the risk management activities by which information about identified hazards (nature and significance) is freely available and in a format that can be communicated to all parties, which may best be accomplished by some form of comprehensive risk register

- follow-up on initial assumptions regarding the operational phase
- monitoring, audit and review procedures

4 Risk management in early design stages

For effective risk management of a tunnelling project (or any other type of construction work) it is vital that risk management is begun as early as possible, preferably during the project feasibility and early planning stages. The owner's risk policy sets the objectives of the exercise and existing members of the project team (and new members when they join the project team) should have the whole risk management process in their minds when carrying out their work.

It is important to note that the success and benefits of implementing effective risk management depends on the quality of the identified risk mitigating actions and on the active involvement, experience and general opinion of the participants (owner, designers and contractors).

Risk management is not achieved by the enforcement of systems and procedures alone, but can be enhanced through seminars and meetings where an understanding and appreciation of the risk management objectives are disseminated throughout the organisations.

4.1 Establish risk policy

The primary step in establishing a risk management system is for the owner to formulate a risk policy as described in section 3.

4.2 Risk acceptance criteria

The risk objectives expressed in general terms in the owners risk policy should be "translated" into risk acceptance criteria suitable for use in the risk assessment activities planned to be carried out. This may include:

- Risk acceptance criteria to be used in qualitative risk assessment. The risk classification shown in section 7.3.3 is an example of such criteria.

- Risk acceptance criteria to be used in quantitative risk assessments. For each type of risk to be covered by a quantitative risk assessment they would usually be expressed as:

- A limit above which the risk is considered unacceptable and thus must be reduced regardless of the costs.
- A limit below which it is not required to consider further risk reduction.
- An area between the two limits where risk mitigation shall be considered and mitigation measures implemented according to the circumstances, e.g. using the ALARP principle mentioned in section 3.

A document should be provided that explains how the risk acceptance criteria were established in relation to the statements on risk objectives in the owner's risk policy.

4.3 Qualitative risk assessment

During the early design stage, a qualitative risk assessment should be carried out focussed on the identification of potential hazards to the construction activities expected to be included in the project, and covering all types of risk noted in the construction risk policy.

The main purposes of this work is to raise the awareness of all concerned to the major risks involved in the construction and to provide a structured basis for the design decisions to be taken in the early design stage. The results can also be used for selection of specific topics for more detailed analyses as described in section 4.4. Finally the work can be used as starting point for the risk management during tendering.

The timing of the qualitative risk assessment should be such that major design changes are still possible. Depending on the time schedule of the early design it may be feasible to update the first qualitative risk assessment later in this design phase.

The qualitative risk assessment should include:

- Hazard identification. See section 7.2.
- Classification of the identified hazards. See section 7.3.
- Identification of risk mitigation measures.
- Details of the risks in the project risk register indicating risk class and risk mitigation measures for each hazard.

The identification and classification is best carried out through brainstorming sessions with risk screening teams consisting of multi-disciplinary, technically and practically experienced experts guided by experienced risk analysts. The aim should be to identify all conceivable hazardous events threatening the project including those risks of low frequency but high possible consequence.

In the identification and classification process due regard should be taken of common causes for hazardous events such as:

- Complexity and maturity of the applied technology
- Adverse unexpected ground and groundwater conditions
- Technical and/or managerial incompetence
- Human factors and/or human errors.
- Lack of sufficient communication and co-ordination between internal and external interfaces
- Combinations of several unwanted events that individually are not necessarily critical

The identified hazards are classified according to the magnitude of the risk they represent. The purpose of this classification is to provide a framework for the decisions to be made on implementation of risk mitigation measures. Classification systems should be established covering frequencies and consequences as well as classification of risks on the basis of the frequency and consequence classes. The classification system may be included in the risk acceptance criteria, see section 4.2.

The identification of risk mitigation measures may be carried out by the same or a different team and this team should preferably have a representative of all the major parties to the project.

Where risk levels conflict with the project's risk acceptance criteria, it is mandatory to identify risk-reducing actions and provide documentation for the management decision on which actions are to be implemented. The results should be registered in the project risk register.

Risk mitigation in this phase of the project will primarily result in changes in technical solutions and possibly in alternative working procedures. Further, many risk-reducing actions can be decisions or statements to be written into the tender documents.

At this point it should be possible to establish whether implementation of a set of risk-mitigating actions will in fact reduce the risk to an acceptable level. If this does not appear to be the case, other approaches must be explored.

4.4 Specific risk assessment

For hazards of specific interest, e.g. due to the severity of the risk involved or the significance of the design decision to be taken, a more detailed risk analysis than the general qualitative analysis described in section 4.3 may be carried out. The outcome of this analysis should also be documented in the project risk register.

The work may comprise one or more of the following:

- A fault tree analysis of the causes of the hazards, see section 8
- An event tree analysis of the consequences, see section 8
- A full quantification of the risk, see section 7.4, e.g. with the purpose of evaluating the cost-benefit ratio of implementation of mitigating measures or providing a quantitative basis for a decision between alternative courses of action.

5 Risk management during tendering and contract negotiation

5.1 Risk management during preparation of tender documents

5.1.1 Main risk management activities

The following risk management activities should be carried out during preparation of the tender documents:

- Specification of technical and other requirements in the tender documents such that the risks are managed in accordance with the risk policy. The results of the qualitative risk assessment carried out during the early design stage should be used as part of the basis.

  The specification of technical and other requirements should detail responsibilities for risks in accordance with any general principles adopted for the project covering allocation of risks. E.g. risks should be allocated to the party who has the best means for controlling them, as mentioned in section 3.2.

- The qualitative risk assessment carried out in the early design stages should be repeated when the tender documents are near completion as the basis for final modifications of the tender documents and to document that risk has been managed in accordance with the risk policy.

- Definition of the information requested from the tenderers in order to allow an evaluation of the tenderers' ability to manage risk and of the differences in risk between the proposals made by the different tenderers. See section 5.1.2.

- Specification of requirements in the tender document concerning the contractor's risk management activities during execution of the contract, see section 5.1.3.

5.1.2 Information to be provided with the tender

In order to ensure a basis for comparing and evaluating the tenderers, the tender documents should state the information that each tenderer must present in this respect. This information should include:

- Information on structured risk management in similar projects and their outcomes
- CV for persons to be responsible for the risk management and details of any specialist organisation that has been involved
- General description of the tenderer's intentions regarding his project-specific organisation and his risk management objectives
- Overview and description of the major risks perceived by the tenderer in the project
- The tenderer's proposed strategy for the management of major risks to the project and how success will be defined and measured.

It should be stated that some or all of the above information provided by the tenderers will be used as a basis for the owner's tender evaluation. The information will help to illustrate whether the contractor is capable of carrying out the necessary systematic risk analysis, and the expected risk management performance.

5.1.3 Requirements to be specified in the tender documents

The tender documents should specify that the contractor must perform risk management in accordance with the owner's risk policy. The contractor's risk management system and approaches must be compatible with the owner's, thereby reducing and controlling risks both to himself, to the owner and the public.

Requirements concerning the contractor's risk management system should be described. This could include such matters as:

- Organisation and qualifications of risk management staff
- Types of risks to be considered and evaluated. These will be concerned with construction issues and any related design activities under the contractor's control.
- Activities, i.e. description of a minimum requirement of activities to be included in the contractor's risk management, including systematic risk identification, classification of risks by frequency and consequence, and identification of risk elimination and risk mitigating measures

- Time schedule for risk management activities (including requirements to carry out risk assessment in time to allow implementation of identified risk mitigating measures)

- Co-ordination with the owner's risk management and risk management team

- Co-ordination with the other contractors' risk management

- Co-ordination between risk management and the contractor's other systems, such as quality management and environmental management.

- Control of risks from sub-contractors' activities

- Specific requirements concerning risk management in explicit fields should be stated (examples could be modification to the construction methods for areas identified as of particular concern, i.e. construction methods related to risk to third party buildings or requirements concerning securing against unintentional ground water lowering)

The owner's risk policy, risk acceptance criteria and risk classification system should be stated in the tender documents. The owner's risk management activities should be briefly mentioned. It should be carefully considered and pointed out to what extent the contractor will have insight into the owner's risk analysis results. Further, it should be stated in the tender documents that the contractor is responsible for effective risk management regardless of the extent and detail of the risk information deriving from the owner.

It is recommended that the tender documents require that the owner be involved in the risk management during construction and that a risk management team is established with participants from the contractor and from the owner (see figure 1).

5.2 Risk management during selection of contractor

Providing tenderers are clearly informed in tender documents, the application of risk management techniques by the owner can be valuable in the selection of the successful tenderer. Identifying risk issues in the tenders can be used as a basis for tender negotiations. The evaluation of tenders in respect of risk may be qualitative (based on a points system) or on a quantitative basis to the extent that the tender price might be adjusted accordingly.

The evaluation of the risk issues in the tenders should include:

- An evaluation of the contractor's ability to identify and control risks by the choice and implementation of technical solutions. An evaluation is also needed of his ability to apply systematic risk management in the work that he will undertake;

- Systematic assessment of the differences in risk between the project proposals by different tenderers;
- Evaluation of the risk management expertise at the contractor's disposal

Where a qualitative risk assessment is envisaged, the means of achieving this need to be considered during the preparation of the tender documentation. For each identified risk, the tenders need to be compared and areas where there are differences should be highlighted.

Where a quantitative risk assessment is envisaged, the recommended approach is first to carry out a quantitative risk assessment on the owner's project as described in Section 7.4. This could be carried out in the time period between the issue and the receipt of tenders. The risk in each tender is quantified by taking the owner's quantitative risk assessment and for each risk considering the differences in frequency and consequence. The input to the quantification could be obtained from reliable information obtained from external sources and/or through brainstorming sessions. The experience and competence of those on the brainstorming team is vital. The final outcome will be the quantification of the risks involved in each tender. This has the benefit of a level comparison even if the absolute value of the risk is uncertain.

This quantification is particularly useful for the risk of economic loss to the owner, and the risk of delay to the completion of the project. These evaluations could be directly compared with the contract price in the tenders and the assignment of a certain monetary value might be made per month's estimated or potential delay of project completion.

For other risks it may be more difficult to obtain reliable results from a full quantification analysis, and a qualitative comparison may be all that is practicable.

5.3 Risk clauses in contract

When a contractor has been chosen, negotiations between the owner and the contractor may lead to a detailed contractual description of the risk management system to be implemented on the project. This may be based on a combination of the intentions of the owner and the suggested procedures of the contractor with the purpose of improving the co-operation between the parties.

Alternative technical solutions will also be negotiated on the basis of risk assessments carried out and stated in the contract.

The risk assessment of the successful tender may have identified some previously undetected areas of risk or special concern. In order to reduce these risks to an acceptable level, additional risk mitigation clauses may be introduced in the contract. An example could be that the contractor has proposed a modification to the construction methods envisaged by the owner, which is advantageous except for a secondary risk of impact to the environment. This risk to the environment is then mitigated by additional requirements.

6 Risk management during construction

In the early design and tender and contract negotiation phases certain risks may be transferred, either contractually or through insurance, others may be retained and some risks can be eliminated and/or mitigated. In the construction phase, possibilities of risk transfer are minimal and the most advantageous strategy for both owner and contractor is to reduce the severity of as many risks as possible through the planning and implementation of risk eliminating and/or risk mitigating initiatives.

6.1 Contractor's risk management

Based on what has been agreed in the contract, the contractor's responsibility could be as proposed in figure 1. The contractor is responsible for the fulfilment of the owner's risk policy and should start by establishing a carefully planned, well-structured and easy-to-use risk management system.

The structure of the risk management system is of great importance for the straightforwardness of the further work with detailed identification of hazards and assessment of risks. See section 7.

The contractor must identify hazards and classify risks using systems which are compatible with the systems used by the owner (see section 7.2 and 7.3) and should propose mitigation measures to reduce the identified risks. In cases where the implementation of the mitigation measures could lead to major delay or could in any other way cause a loss to the owner, the owner should approve the intended mitigation prior to its implementation.

The contractor's risk management strategy should be implemented by all members of his staff whatever their job functions. The identification of hazards and control of risk, and the techniques involved, should be seen as an essential part of all the design and construction activities of the project. Information and training should be given, as necessary, to all personnel throughout the project. The owner should be invited to be present and to participate in the contractor's risk management meetings, presentations and training sessions.

Timely consideration and actions are of the essence in risk mitigation measures. The aim is to anticipate, and put in place effective proactive preventative measures. The processes of identification of hazards, classification of risks, decision-making and risk mitigation actions should be well understood and the contractor should be capable of rapidly implementing the results.

It is recommended that the contractor keeps and maintains a project risk register containing details of identified hazards and risks with their assessed risk levels. All accidents, incidents, near misses and other experienced events should be both listed and investigated. The results of investigations shall be made known throughout the project in a timely manner with a view to both the prevention of a similar occurrence and in the objective of continuous improvement of the risk management system.

Contingency and emergency plans must be devised, implemented and maintained throughout the entire project period to address foreseeable accidents and emergencies. This will involve cooperation, communication with all parties to the project and the public emergency services.

Throughout the construction phase the contractor is also responsible for the implementation of the initiatives provided by the owner to mitigate risks.

6.2 Owner's risk management

It is recommended that the owner continues to perform risk assessment for risks that are the owner's responsibility and are not covered by the contractor. This could be contractual risks, including contractual aspects of technical risks identified by the contractor. Of primary concern are risks related to economic loss to the owner, or delay. Mitigation actions should be identified and implemented by the owner, but some mitigation measures may be handed over to the contractor for implementation.

In addition to this, the owner should encourage and monitor the contractor's risk management. Quality control audits instituted by the owner are one way of doing this.

These activities will allow the owner to be informed of risks identified by the contractor, and enable the owner to ensure that the contractor's risk management system is properly implemented and functioning effectively.

The owner, or the joint risk management team, is advised to look out for practices on site that are at variance with the risk mitigation measures that have been agreed upon. Such findings may point to failures in the contractor's systems to implement the risk mitigation measures devised and agreed at an earlier stage.

7 Typical components of risk management

7.1 Introduction

The descriptions provided in this section on typical components of risk management should be considered as examples and guidance on how these activities could be carried out and not as detailed recommendations.

7.2 Hazard identification

The process of identification may rely upon; i) a review of world-wide operational experience of similar projects drawn from the literature with written submissions from partner companies, ii) the study of generic guidance on hazards associated with the type of work being undertaken, and iii) discussions with qualified and experienced staff from the project team and other organisations around the world. It is important to identify the potential hazards in a structured process. A suggestion for grouping is proposed below.

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.

The hazards above have been grouped into general hazards and specific hazards. The specific hazards should be considered for each part of the project, whereas the general hazards may be considered generally for each contract. It may be argued that the 10 hazards are at different levels, but experience has shown that they result in a reasonable coverage of all issues of concern.

7.3 Classification

Frequency of occurrence and extent of consequences for each hazard should be assessed according to a classification system established specifically to suit the requirements and scale of the project. Also a risk classification system should be established, which based on the frequency and consequence classification for a given hazard provides a classification of the risk, thereby indicating the action to be taken according to the level of risk.

The classification of frequency, consequence and risk should be established in accordance with the risk objectives and risk acceptance criteria defined for the project, as described in section 3 and section 4.2.

The frequency classification system should be common for all types of risk covered, whereas a consequence classification system must be established separately for each type of risk to be covered, see the types of risks listed in section 3. Preferably the different consequence classification systems should be co-ordinated in such a way that a common risk classification system can be used for all types of risk covered.

An example of classification of frequency, consequence and risk level is outlined in the following, using 5-fold classification systems. The proposed classification takes its offset in previous risk assessments carried out for similar projects and recommendations provided in the general literature on the subject.

7.3.1 Frequency classification

In addition to published statistics (in the few instances where these are available) expert judgement drawn from a number of sources within the project team, and staff of collaborating organisations, may be used to arrive at the classification.

In order to facilitate the task of the members of the team, guidelines for frequency assessment should be set as explicitly and comprehensively as possible.

A proposed way of assessing frequency is to have a risk assessment team, consisting of experienced tunnel engineers to formulate their own guidelines for frequency classes. These could be related to the number of events experienced by the participants, the number of events they have heard of, the number of experienced near-misses and the number of near-misses they have heard of; all in relation to the number of projects they have been involved in or are aware of. It would be of great benefit for a risk analyst to guide such a risk assessment team through the identification and assessment of hazards.

A separation into 5 classes or intervals is generally recommended as a practical way of classifying frequency. Frequency classification can be set up relating the number of events (hazards occurring) to a "per year" or "per km of tunnel" unit. However, it is proposed as the most suitable to use a classification that relates to the potential number of events during the whole construction period. An example of such classification is shown in table 1.

Frequency of occurrence			
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

Table-1 Frequency of occurrence (in the construction period). The central value represents the logarithmic mean value of the given interval.

7.3.2 Consequence classification

It is recommended that consequences be classified into five classes or intervals. The selection of consequence types and potential severity will vary according to the scope and nature of the project. The examples below are in line with general practice, but it is important to note that guidelines and classification classes must be defined for each particular project in consideration of the specific risk policy. In the example used, the basis has been underground construction projects with a project value of approximately 1 billion Euro and duration of approximately 5-7 years.

Injury to workers or emergency crew
The consequence classification and thus the acceptance criteria for harm to workers and emergency must be calibrated against the risk policy for the project to form a realistic basis for the risk assessment.

An example of consequence classification with guideline description of injuries is shown in table 2.

Consequence class (Injury to workers and emergency crew)					
	Disastrous	Severe	Serious	Considerable	Insignificant
No. of fatalities/Injuries	F > 10	1< F ≤ 10 SI > 10	1 F 1 < SI ≤ 10	1 SI 1< MI ≤ 10	1 MI

Table 2 Injury to workers and emergency crew.
F = fatality, SI = serious injury, MI = minor injury.

Injury to third parties
When considering injury to third parties, as compared with injury to workers and emergency crews, the risk tolerance is normally decreased. The argument being that the third party has no benefit from the construction work and should not be subjected to a higher risk than if the construction work was not being carried out. An example of a consequence classification is proposed in table 3, where the consequence scale is stricter for injury to third parties compared to injury to workers and emergency crew in table 2.

Consequence class (Injury to third parties)					
	Disastrous	Severe	Serious	Considerable	Insignificant
No. of fatalities/Injuries	F > 1 SI > 10	1 F 1 < SI≤ 10	1 SI 1 < MI ≤ 10	1 MI	-

Table 3 Injury to third parties.
F = fatality, SI = serious injury, MI = minor injury.

Damage to third party property
Damage or economic loss to third party property should be covered by a separate consequence class with a less tolerant classification compared to Economic loss suffered by the owner (table 7). Practice shows that Clients of large civil engineering contracts are usually exposed to economic risks in excess of what is considered reasonable to third parties who, in many cases, are not the direct beneficiaries of the project. An example of a consequence classification is proposed (loss per hazard) in table 4.

Consequence class (Damage or economic loss to third party)					
	Disastrous	Severe	Serious	Consider-able	Insignificant
Loss in Mio. Euro	> 3	0.3 to 3	0.03 to 0.3	0.003 to 0.03	< 0.003

Table 4 Damage or economic loss to third party.

Harm to the environment
Environmental issues are generally handled in other terms within the environmental management system of a project. It is rather complex to classify environmental damage in a risk context. It is proposed to assess the likely harm to the environment in relation to the potential permanency and severity of the potential damage. Table 5 below outlines a preliminary example of such a consequence classification which needs further development. As for the other consequences, the descriptive consequence classes should be defined specifically for the project being considered.

Consequence class (Harm to the environment)					
	Disastrous	Severe	Serious	Consider-able	Insignificant
Guideline for propor-tions of damage	Permanent severe damage	Permanent minor damage	Long-term effects	Temporary severe damage	Temporary minor damage

Table 5 Harm to the environment. A definition of "long-term" and "temporary" should be provided in relation to the project duration.

Delay
The potential consequence of delay can initially be assessed as the delay of the specific activity regardless of whether the activity is on the critical path. A separate evaluation of the delay should then be made to assess the estimated delay to the critical path.

In order to achieve only one risk matrix to cover all consequences, intervals of a factor of ten could be maintained for delay (Delay 1 in table 6), but the less meaningful descriptors - "insignificant" and "considerable" - are unavoidable. Alternatively, a more realistic classification can be defined (Delay 2 in table 6) but this system may require an exclusive risk matrix for delay because the classification differs from that of the other consequences.

However, this classification is recommended because it is more easily understood.

Consequence class (Delay)					
	Disastrous	Severe	Serious	Considerable	Insignificant
Delay (1) (months per hazard)	> 10	1 to 10	0.1to 1	0.01 to 0.1	<0.01
Delay (2) (months per hazard)	> 24	6-24	2-6	½-2	< ½

Table 6 Delay (two alternative examples are shown)

Economic loss to owner
This consequence type relates to the additional costs to the owner as a consequence of a hazards occurring, and covers additional costs during the construction phase expected to be defrayed by the owner. Losses to the Contractor (or Insurer) are not included. However, if it cannot readily be established whether additional costs are to be covered by the owner or by other parties, it should be assumed that the loss is defrayed by the owner.

Direct additional costs as a consequence of delays are included in this example whereas any other consequential costs - mainly financial costs - from any delay are not included.

It should be decided early on whether capitalised costs of inconveniences during operation (e.g. increased maintenance and operation costs due to substandard works) should be covered under the relevant hazards during the construction phase.

A proposed example of consequence classification of economic loss to owner (per hazard) is shown in table 7.

Consequence class (Economic loss to owner)					
	Disastrous	Severe	Serious	Consider-able	Insignificant
Loss in Mio. Euro	> 30	3 to 30	0.3 to 3	0.03 to 0.3	< 0.03

Table 7 Economic loss to owner

Loss of goodwill
For projects that are politically, economically or environmentally sensitive and where public opinion can be expected to have a severe impact on the project development, loss of goodwill could be a relevant consequence category to assess. However, it is proposed to consider loss of goodwill as a part of loss to owner.

Loss of goodwill is highly correlated with events causing the consequences in the classes described above. Loss of goodwill will occur especially in the event of consequences to third parties and the environment, which are normally assessed to rank high on the political agenda. All realisations of hazards, which lead to bad press, may have a significant impact on the public and political goodwill to the project.

7.3.3 Risk classification and risk acceptance

An example of a risk matrix for the determination of risk level is shown in table 8. The example is in line with general practice, but it is important to note, that the risk classification system must be defined for each particular project in consideration of the specific risk policy.

	Consequence				
Frequency	**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*	Acceptable	Negligible	Negligible

Table 8 Risk matrix (Example).

*: 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 "serious", and thus be classified as "unwanted" risks even for a very low assessed frequency.

By using a step of 10 between the different frequency and consequence classes the usual logarithmic interpretation of risk distributions can be maintained.

The actions to be carried out for each hazard depend on whether the related risk is classified as Unacceptable, Unwanted, Acceptable or Negligible. Examples of such actions are:

Unacceptable The risk shall be reduced at least to Unwanted regardless of the costs of risk mitigation

Unwanted Risk mitigation measures shall be identified. The measures shall be implemented as long as the costs of the measures are not disproportionate with the risk reduction obtained. (ALARP principle, see section 3).

Acceptable The hazard shall be managed throughout the project. Consideration of risk mitigation is not required.

Negligible No further consideration of the hazard is needed.

The descriptions of actions to be carried out may include the definition of the level in the project organisation at which decisions on risk mitigation measures should be taken.

The risk matrix presented in table 8 is intended as basis for decision on acceptability for each hazard considered. By controlling the magnitude of the risks from the individual hazards, the total risk involved in the project is controlled without considering a total risk estimate. It is a precondition for this approach that no undue subdivision of a hazard is carried out in order to reduce the frequency of occurrence, e.g. by considering each 100m of the tunnel separately. When establishing the risk matrix on the basis of the risk objectives the expected number of hazards in the various classes should be taken into account.

Since this is a simple classification, these guidelines do not present a suggested weighting or combination of the different consequence groups.

7.4 Quantitative risk assessment

The risk matrix method is considered too coarse to provide reliable quantitative risk estimates. However, it is a feasible task to quantify the identified risks.

The risk may simply be quantified for each hazard by assigning a number, F, for the frequency and a number, C, for the consequence. The risk for this hazard is then estimated as F times C and the total risk for the project by a summation over all hazards.

This simple approach provides a single risk figure for each type of risk, indicating a best estimate for the risk.

The disadvantage of this simple approach is that it does not describe the uncertainties of the risk estimates.

A description of the uncertainties can be obtained by considering each consequence as a stochastic variable and assigning a distribution for each variable instead of a single figure. The distribution can be obtained by assigning a most likely, a minimum and a maximum figure. The same approach may be used for the frequency estimate, but the adequacy of this approach is debated, such that a sensitivity check of the result of changes in frequencies may be more appropriate. From the most likely, minimum and maximum figures a triangular or other distributions can be assumed. The total risk can then for instance be obtained by a Monte Carlo simulation, see section 8.5, taking into account the correlation between the variables.

The advantages of this more complex approach are:

- Rather than by a single figure, the risk is better described by assigning a most likely, minimum and maximum figure for each consequence (and possibly also frequency).

- In view of the considerable uncertainties in the frequencies and consequences, which normally will have to be assigned based on engineering judgement rather than on statistical analysis of records of experience, the use of the estimated ranges instead of a single figure will make it easier for the persons doing the risk assessment to decide on the figures to be used.

- The resulting risk estimate is a probability distribution instead of a single figure. This allows presentation of e.g. 50%, 75% and 95% fractiles for the risk.

The quantification methods described above are most suitable for estimation of the risk of economic loss and delay but, in principle, can be used for all types of risk and consequence.

Multirisk, see section 8.4, is a method for establishing cost estimates and time schedules including uncertainties. The method may be used to cover contribution to costs and time from hazards with a rather high frequency of occurrence by including the consequences of such hazards in the maximum estimates. The method cannot be used to cover contributions from hazards with a low frequency of occurrence which may be significant within underground construction, as they have very high consequences.

8 Risk management tools

Judgement of risk during planning and through the different phases of a tunnelling project requires appropriate tools. The types of problems to be solved using risk analysis tools are to identify risk, quantify risk, visualise causes and effects, and the course (chain) of events. Most tools are developed for applications outside the underground industry. However, most tools can be used for problems encountered in underground construction without any major adjustments.

The intention of this chapter is to provide a brief introduction to a number of techniques with references for further reading.

8.1 Fault tree analysis

Fault tree analysis can be used to analyse a single or combined causal connection (relation) that precedes a negative event. Fault tree analysis is utilised either with or without quantifying probabilities for events. By using this tool, complex problems with many interacting events can be structured.

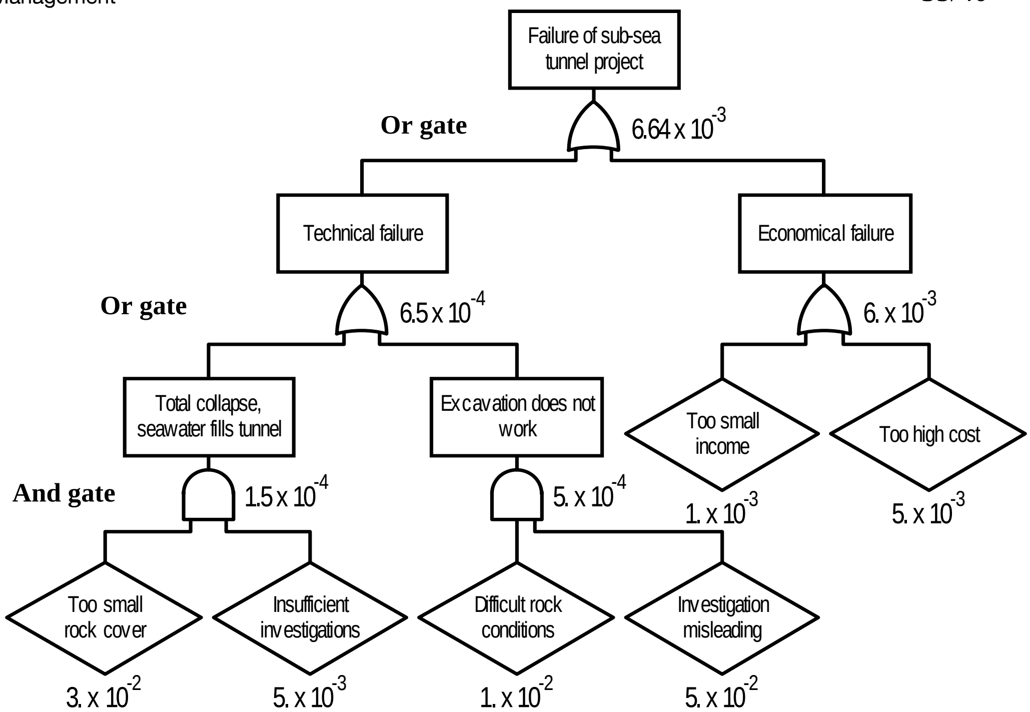

Figure 2. Example of a fault tree with “and gates” and “or gates” and evaluated probabilities.

For further reading, see [Sturk 1998] and [Ang & Tang 1984].

8.2 Event tree analysis

The description of the development from an initial event, through possible sequences to a defined final state can be carried out by event tree analysis. Assessing probabilities for different outcomes give a quantitative analysis.

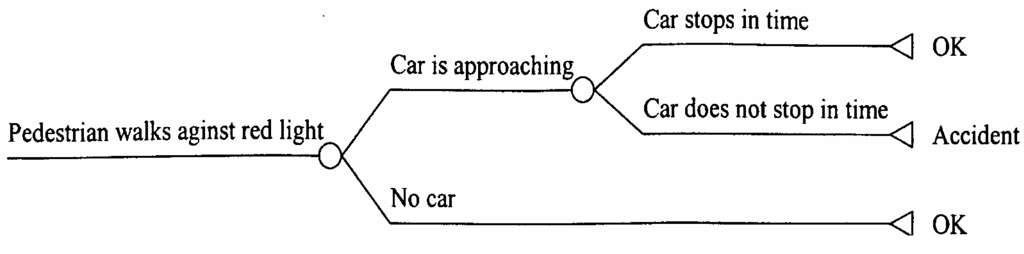

Figure 3. Principle event tree for the event: pedestrian walks against a red light without watching. Rings = chance nodes, triangles = terminal nodes.

For further reading see [Benjamin & Cornell 1970].

8.3 Decision tree analysis

Decision tree analysis is utilised to analyse the best decision based on the available information. Many of the decisions in underground construction contain a large uncertainty, and by using decision tree analysis these are presented in a structured format. This might then form a better base for decision than would otherwise be the case.

The tree structure is build up from left to right as for event tree analyses, see above. A decision tree can be described as several event trees, see Figure 4 below.

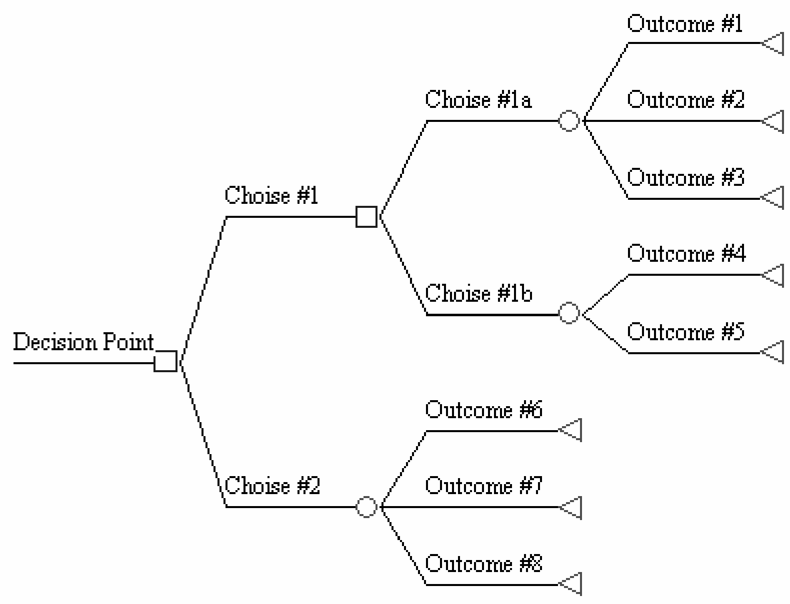

Figure 4. Example of a decision tree. Triangles = terminal nodes, circles = chance nodes, squares = decision nodes where the decision-maker makes an active choice.

For further reading see [Ang & Tang 1984], [Benjamin & Cornell 1970] and [Jaselskis & Russel 1992].

8.4 Multirisk

This method, for cost and time calculation, is an approximate method to calculate functions with stochastic variables. Multirisk is most useful when a high degree of uncertainty exists. The method is computer based and for cost calculation it is structured in 7 consecutive steps:

1. Identify a number (few) of independent main cost items

2. Estimate the cost of each item by three values: minimum, most likely, and maximum.

3. The expected value and uncertainty range is calculated for each cost item.

4. The total sum and variance for the cost is calculated.

5. If the total variance is too large, the item which has the largest influence on the uncertainty is divided into independent sub-items.

6. Steps 2-5 are repeated until an acceptable total variance is reached.

7. The result is presented as an average cost and standard deviation.

The time planning follows the same principles.

The method is based on statistically independent items. If this is not the case, then time and cost items are identified as “general items” for the whole project. Examples of general cost items are wages, authority problems, weather and level of quality, and these are then treated as separate items.

For further reading see [Lichtenberg 1974] and [Lichtenberg 1989].

8.5 Monte Carlo simulation

The type of estimation we encounter in underground projects often includes equations with several stochastic variables. Analytical solutions to this type of problems can be very complicated, even if an analytical expression can be established. By using simulation, an approximate solution can be computed for example, by Monte Carlo simulation which is used widely within different engineering branches.

The equation is established using stochastic variables and constants. The distribution for respective stochastic variable and the correlations between the variables are specified. An approximate result for the equation can then be simulated. In each simulation step the equation is calculated by randomly selecting a sample from each stochastic variable according to the distribution of the variable and the correlations. The larger the number of simulations is, the more adequate the result is. After simulation of 1,000, 10,000, 100,000 runs or what number of runs is chosen, the results are presented as uncertain distributions, from which histograms, average value, standard deviation and other statistical parameters can be determined.

For further reading, see [Benjamin & Cornell 1970] and [Crystal Ball - User manual].

9 Glossary

Hazard	A situation or condition that has the potential for human injury, damage to property, damage to environment, economic loss or delay to project completion.
Risk	A combination of the frequency of occurrence of a defined hazard and the consequences of the occurrence.
Risk acceptance criteria	A qualitative or quantitative expression defining the maximum risk level that is acceptable or tolerable for a given system.
Risk analysis	A structured process which identifies both the probability and extent of adverse consequences arising from a given activity. Risk analysis includes identification of hazards and descriptions of risks, which may be qualitative or quantitative.
Risk assessment	Integrated analysis of risks inherent to a system or a project and their significance in an appropriate context. I.e. risk analysis plus risk evaluation.
Risk elimination	Action to prevent risk from occurring.
Risk evaluation	Comparison of the results of a risk analysis with risk acceptance criteria or other decision criteria.
Risk mitigation measure	Action to reduce risk by reducing consequences or frequency of occurrence.

The definitions indicated above are from [The Engineering Council, 1993] with some modifications and supplements to better suit a construction project.

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