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

Søren Degn Eskesen, Per Tengborg, Jørgen Kampmann, Trine Holst Veicherts

ITA Working Group 2, Research, ITA-AITES, c/o EPFL, Bat GC, CH 1015 Lausanne, Switzerland

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.

Preface

Front page articles in the news on spectacular tunnel collapses during the 1990s focused the public and in particular potential tunnel owners' attention on the inherent risk associated with underground construction works. As a result, risk management became an integral part of most underground construction projects during the late 1990s. However, from discussions in international forums, it became clear that handling and management of risks were performed in many different ways, some more concise than others. Out of the discussions came the idea of establishing international guidelines on tunnelling risk management.

Work on these guidelines began at the meeting of ITA Working group 2 "Research" in Oslo in June 1999. After much study, discussions and investigations, the guidelines were completed in April 2003.

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 guidelines show how risk management may be utilised throughout the phases of a project implementation:

1. Early Design Phase
2. Tendering and Contract Negotiation Phase
3. Construction Phase

The guidelines also contain some typical components of risk management and a short introduction to general risk management tools as well as a glossary of risk terms. Finally, an example of how risk management was carried out for the Copenhagen Metro following principles similar to those presented in the guidelines is included as an appendix.

The practice of performing risk management requires much experience, practical and theoretical knowledge. It is, therefore, not expected that these guidelines will cover every aspects of tunnelling risk management, but it is

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intended to provide some basic knowledge and indicate what is recommended industry best practice for tunnelling risk management. It is hoped that this knowledge will be continuously improved by the use of these guidelines.

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Søren Degn Eskesen
Coordinator, ITA Working Group 2 Research

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.

2. Use of risk management

In keeping with the task of the Working Group, 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 and 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 Fig. 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.

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.

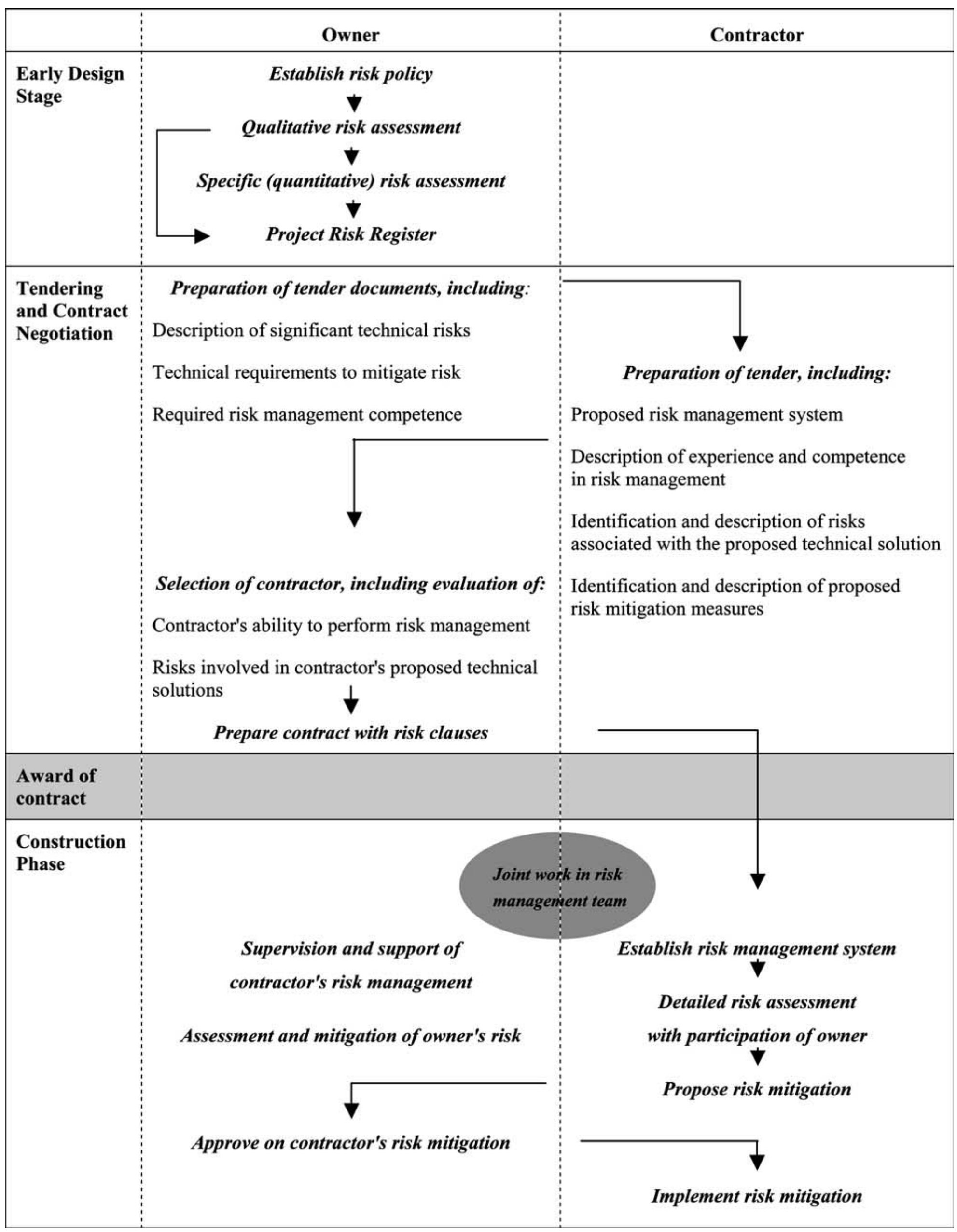

Fig. 1. Risk management activity flow for owner and contractor.

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 *a*s *l*ow *a*s *r*easonably *p*racticable.

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 owner's 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 are 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 a 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 Fig. 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 Fig. 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 Sections 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 Sections 3 and 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 uses as its base 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 five 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.

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.

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.

7.3.2.1. 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.

7.3.2.2. Injury to third parties. When considering injury to third parties, as compared with injury to workers and

Table 2
Injury to workers and emergency crew

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

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

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.

7.3.2.3. 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.

7.3.2.4. 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 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.

7.3.2.5. 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 10 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.

7.3.2.6. 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 consequen-

Table 3
Injury to third parties

	Disastrous	Severe	Serious	Considerable	Insignificant
No. of fatalities/injuries	F > 1, SI > 10	1F, 1 < SI ⩽ 10	1SI, 1 < MI ⩽ 10	1MI	–

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

Table 4
Damage or economic loss to third party

	Disastrous	Severe	Serious	Considerable	Insignificant
Loss in Million Euro	>3	0.3–3	0.03–0.3	0.003–0.03	<0.003

Table 5
Harm to the environment

	Disastrous	Severe	Serious	Considerable	Insignificant
Guideline for proportions of damage	Permanent severe damage	Permanent minor damage	Long-term effects	Temporary severe damage	Temporary minor damage

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

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 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

tial 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.

7.3.2.7. 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.

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

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 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 100 m 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.

For further reading, see Sturk (1998) and Ang and 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 (see Figs. 2 and 3).

For further reading see Benjamin and 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

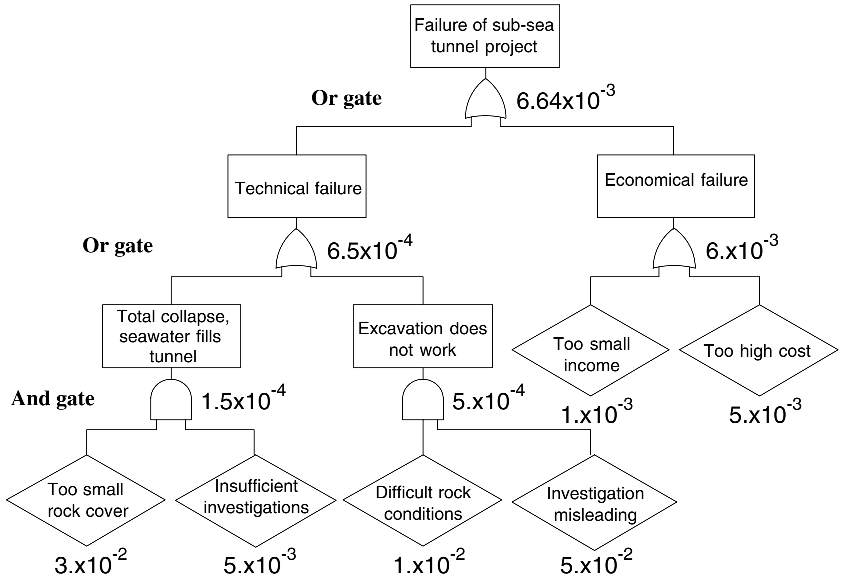

Fig. 2. Example of a fault tree with "and gates" and "or gates" and evaluated probabilities.

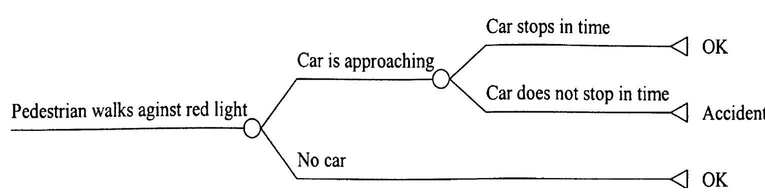

Fig. 3. Principle event tree for the event: pedestrian walks against a red light without watching. Rings, chance nodes and triangles, terminal nodes.

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 Fig. 4.

For further reading see Ang and Tang (1984), Benjamin and Cornell (1970) and Jaselskis and 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.

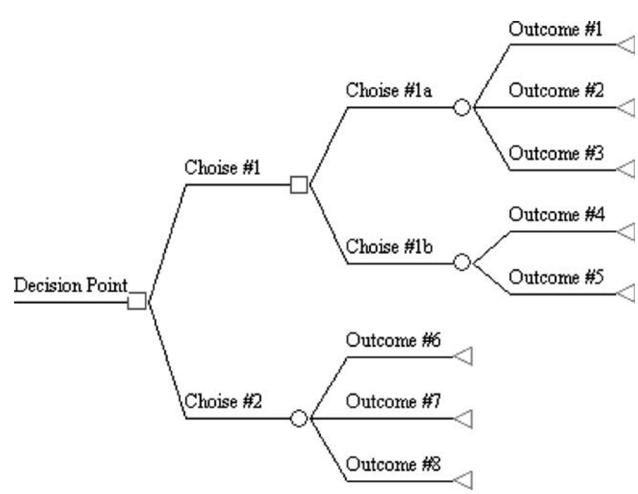

Fig. 4. Example of a decision tree. Triangles, terminal nodes; circles, chance nodes and squares, decision nodes where the decision-maker makes an active choice.

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 (1989) and Lichtenberg (2000).

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 and Cornell (1970) and Crystal Ball – User manual.

Appendix A. Example

Experience with risk management for the Copenhagen Metro.

A.1. Preface

The appendix includes an example on how risk management was carried out following principles similar to those presented in the guidelines. The work has been carried out for the Copenhagen Metro in Denmark.

A.2. The Metro system

The Copenhagen Metro is a new mass transit system that connects the central part of Copenhagen with a new township with travel times of about 7 min, as shown in Fig. 5.

Phase 1 and 2 of the Metro comprises 17 km of double track with 17 stations, of which 8 km and 9 stations are underground. The third phases will add a further 4 km of line and 5 stations to the system, mainly at surface level. The first and second phases of the system opened in October 2002 and in October 2003 respectively and the third phase is under construction with scheduled opening in 2007.

A.2.1. Existing conditions

The geological stratification of the project area may generally be described as follows, from ground level downwards:

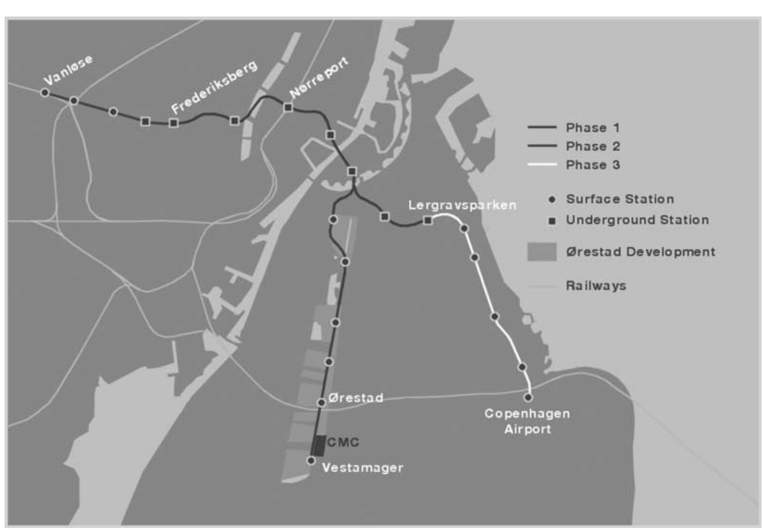

Fig. 5. Alignment of Metro.

- Recent deposits of fill and topsoil generally 2–6 m thickness, in places up to 10 m.
- Quaternary, glacial deposits of tills (clay, sand and gravel) with layers or pockets of meltwater sand and gravel (8–15 m thickness).
- Copenhagen Limestone (35–50 m thickness) divided into 3 stratigraphical sub-units: upper, middle and lower. The limestone contains flint beds up to 25%.

The tunnels and the deeper components of the deep underground stations and shafts are excavated in the upper and middle Copenhagen Limestone strata.

The tunnel alignment passes below the central part of the City of Copenhagen, where many sensitive buildings might be affected by even minor changes in the foundation conditions, caused by either ground settlements or groundwater lowering. The construction of the Metro could, therefore, affect both the stability of buildings and lead to the formation of cracks resulting in structural damage, unless adequate precautions were taken during the design and execution of the works.

Within the construction area, there are buildings spanning a wide age range, from the medieval period to modern times. Many of the 17th and 18th century buildings are founded on timber piles, which cannot tolerate any lowering of the groundwater table, see Fig. 6. Rot and fungus tend to attack the tops of timber piles if these are exposed above the protective effects of the groundwater. Other old buildings are founded on a layer of stone laid directly on fill. This type of foundation is highly sensitive to settlement and to changes in the groundwater conditions.

A.2.2. Tunnels

During the design development, comparative studies were made between TBM, NATM and Cut and Cover tunnelling methods, all of which are considered technically feasible for the conditions in Copenhagen.

For the greater part of the tunnel alignment TBM bored tunnels were selected, because of their minimum impact on the environment, high degree of construction safety and cost effectiveness for the actual length of the tunnels, see Fig. 7.

NATM tunnelling has been limited to lengths where non-circular cross sections are required for excavation in the limestone for the emergency shafts, and for excavation of an underground cross-over cavern, TBM launch chambers, two bifurcation chambers, and cross passages, as shown in Fig. 7.

Cut and Cover tunnelling was limited, too, because of the disturbance it causes to the surface structures, and

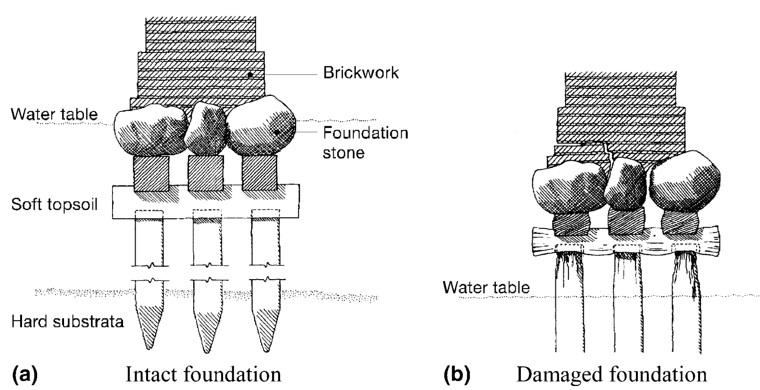

Fig. 6. Typical foundation.

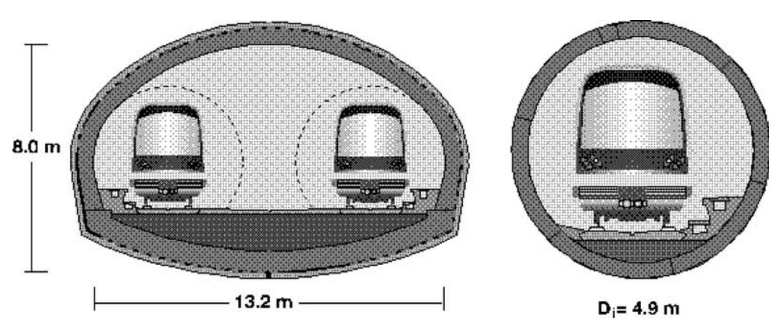

Fig. 7. Cross-section of bored tunnel showing cross-over (left) and running tunnel (right).

Fig. 8. Bifurcation cavern constructed by NATM (left) and running tunnel by TBM (right).

high construction cost. This method was used only where the cover was insufficient for bored tunnelling, see Fig. 8.

A.2.3. Underground stations

The underground station design proposals considered during development of the project covered a wide range extending from 25 m wide underground caverns, through the traditional London Underground type small cavern station, to a variety of cut and cover layouts, including stations with two track levels.

The selected construction method utilised cut and cover construction techniques for the deep station excavation. This method, combined with small diameter single track tunnels, allowed the highest possible level of the station platform, in most cases only 18 m below street level.

The architectural requirements of the station space had a major impact on the structures. The three main requirements were:

- undisturbed overview of the full passenger area (no concealed areas),
- daylight at platform level,
- minimalistic design.

A.3. Tender process and contract basis

The tendering and contracting process was based on EU Council Directive 93/38/EEC following the principle of tendering after negotiations. The objective of the evaluation process was to determine which tender was the economically most advantageous to the Employer. The tenders were evaluated on listed criteria, which were subdivided into the following groups; project, construction, organisation and cost.

The tender documents issued to the pre-qualified Tenderers included a Project Outline indicating a possible solution fulfilling the functional requirements in the tender documents. The Tenderers were not obliged to follow this Project Outline.

The tender evaluation process was performed in stages. Each stage consisted of an evaluation and short-listing of the tenders to eliminate the lower ranked tenders. At each stage the Tenderers not on the short list to the next stage were informed about the weak points in their bids (price, quality, organisation, etc.) noted by the Employer, and they were given the opportunity to change their tender within a certain deadline.

At the last stage, the remaining Tenderers were requested to state their final offer, improving on the technical quality and financial aspects raised by the Employer during negotiations. The Employer then selected the economically most advantageous tender without further negotiations. The Tenderers were informed, in advance, of the tender assessment process and the evaluation criteria, prior to submitting their bids.

The contract was a design and construct contract on a lump sum basis.

A.4. Risk management in early design stage

A.4.1. Construction risk policy and risk acceptance criteria

Management of construction risks was identified as an essential task early in the project. A construction risk policy was therefore established, indicating scope, risk objectives, and risk management strategy.

The types of risk covered are:

1. Risk to the health and safety of workers and third party people, including personal injury and, in the extreme, loss of life,
2. Risk to third party property, specifically normal buildings, cultural heritage buildings and infrastructure,
3. Risks to the environment including pollution, and damage to flora and fauna,
4. Risk to the Employer in delay to the completion,
5. Risk to the Employer of financial loss.

The general objective of the construction risk policy was to reduce all risks covered to a level as low as reasonably practicable, i.e., the ALARP principle. Emphasis was given to minimising overall risk by reducing the likelihood of occurrence of accidents with large consequences, e.g., with several fatalities.

For each type of risk, specific minimum risk objectives were defined in addition to the general ALARP requirement. For example, the general public should be exposed only to an additional risk from construction of the Metro which is small compared to the risk they are exposed to as users of buildings, cars, bicycles, public transport and when walking in the adjacent streets.

The risk management strategy adopted according to this construction risk policy was 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 at each stage.

A.4.2. Qualitative risk assessments

During the early design stage, a qualitative risk assessment of the construction activities expected to be included in the project was carried out covering all types of risk covered by the Construction Risk Policy.

The main purposes of this work were to raise the awareness of all concerned to the major risks involved in the construction, to provide the basis for input regarding management of construction risk in the Tender Documents and to prepare the Client and the project team for the risk aspects prior to the contract negotiations.

The assessment was operated as a top down study. The process of identification relied upon a review of world-wide operational experience of similar projects drawn from the literature with written submissions from partner companies, and discussions with qualified and experienced staff from the project team and other organisations around the world. Keeping in mind that this was a top down assessment, some 40 individual hazards were identified and grouped under the following headings:

1. contractual disputes,
2. insolvency and institutional problems,
3. authorities interference,
4. third party interference,
5. labour disputes,
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.

Likelihoods of occurrence and consequences were assessed according to five-fold classification systems established specifically to suit the requirements and scale of the Copenhagen Metro. In addition to published statistics (in the few instances where these were available), expert judgement drawn from a number of sources within the project team, and staff of collaborating organisations, was used to arrive at the assessments. The level of risk for each hazard was then determined based on the assessed likelihood and the most serious consequence assessed.

Having determined the level of risk for each hazard, the risk was classed as significant or insignificant, using a definition of the significance of risk related to the objectives stated in the Construction Risk Policy.

A.5. Risk management during tendering and contract negotiations

A.5.1. Risk management during preparation of tender documents

In the planning of the tender evaluation process, construction risk aspects were taken into account by identifying this to be a separate aspect to be considered in the evaluation, and the Instruction to Tenderers stated that risk aspects would be one of the evaluation parameters. Furthermore, it was decided that quantitative risk assessment techniques should be used in the evaluation of the individual tenders.

The input to the Tender documents resulting from the qualitative risk assessment described in Section A.4.2 was:

- Modification of the requirements to the construction methods in relation to the risk to third party buildings, identified to be an area of particular concern.
- Provision of requirements to the Contractor's construction risk management.
- Request for information to be included by the Tenderers as basis for the tender evaluation:
  - Envisaged risk reduction measures.
  - Plan for the construction risk assessment work.
  - Information on the tenderer's capabilities in risk assessment work, including references and CV's.

As a basis for the quantification of the risk involved in the projects proposed in the individual tenders, a quantitative risk assessment of the Project Outline was carried out using the framework provided by the qualitative risk assessment described in Section A.4.2 above. The quantification process began with a review of the hazards in the light of the final tender documents. The likelihoods and consequences were then quantified using expert judgement. A risk model was constructed using a Monte Carlo simulator attached to a well known computer spreadsheet program. Only the cost over-runs and the delays were quantified, and the delays were assessed as extensions to the expected critical path. The cost consequences of delays were found using a unit price per week extension.

A.5.2. Risk management during selection of contractor

The system adopted for the assessments of the bids was the same as that for the assessment of the Project Outline. Expert judgement drawn from the project team and the staff of collaborating organisations was used to evaluate the deviations in both likelihood and consequences for each identified hazard when compared to the Project Outline. The resulting total risks were then quantified using the Monte Carlo simulator. In this way, all tenders were evaluated on a consistent basis.

In parallel with this quantification, a qualitative assessment of the risk of damage to third party was carried out. The reason for this was that damage to third party property could be unacceptable according to the construction risk policy without causing a significant financial loss.

The process was complicated in that the tender evaluation procedures allowed each Tenderer the opportunity to modify his bid (technically and financially) after he had been warned that he would be excluded from further consideration. This required the assessments to be reviewed for all the tenders prior to their eventual exclusion.

At each stage of the evaluation, the risk assessment was able to provide a most likely risk cost that could be taken into account in the overall evaluation of the tender together with the tender price, the ''upgrade cost'' estimate and the estimated ''other costs''. The ''upgrade cost'' represented the costs considered necessary to upgrade the tender to the quality required and ''other'' costs were costs such as additional operation and maintenance costs, compared to the Project Outline. Care had to be taken to ensure that technical reservations were not double counted in both the risk and the upgrade costs.

The results of the assessments were presented to the decision makers in tabulation form and as plots. One such plot is shown in Fig. 9 where the total estimated risk cost of each tender (T1-T6) is shown and compared to the risk costs of the Project Outline. The tender price plus upgrade and other costs are shown.

It is evident that the value of risk varies significantly between the individual tenders and that the lowest risk is not necessarily associated with the highest bid price. In the tender evaluation the different types of cost were not added, but used as indicators. In this way it could be concluded that in the case where the estimated risk costs are lower (tender T5) the higher bid price was not fully justified by the reduced level of risk.

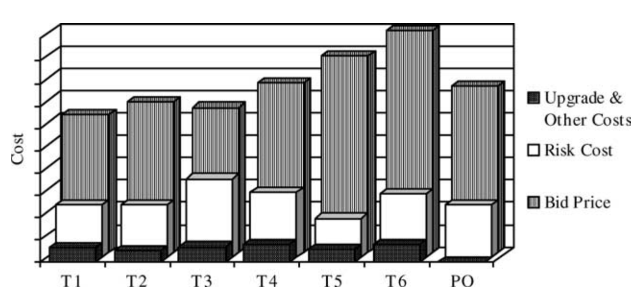

Fig. 9. Risk Costs and Tender Price for Six Tenders and the Project Outline, PO. First Evaluation of the Tenders (schematic).

The tender that was finally selected (T1) shows a level of risk approximately equal to that of the Project Outline. Interestingly, the successful tender was also the lowest bid price, but the effective difference between T1, T2 and T3 in bid price was so small that it would have been difficult to justify the selection of any one of the three without a risk cost estimate. T3 was excluded first. T2 was excluded after receipt of the final bid and a revision of the risk which showed that the risk costs were larger for T2 than for T1.

A.5.3. Risk clauses in contract

The information obtained through the risk assessments carried out was used in the negotiations with the Tenderers in the last stages of the tender evaluation. The most significant aspects were:

- TBM design and operation
- Procedures and measures to be used in prevention of damage to third party property
- Procedures for the Contractor's construction risk management work

Through these contract negotiations, the final text of the Contract was developed, providing a clearer and more detailed definition of the Contractor's obligations. In this way, the risk to the Client was controlled. The resulting contract provisions are described below.

Construction methods with inherent low risk.

The early design stage focused on defining low risk construction methods. This was reflected in the Project Outline issued with the Tender Documents. The selection of the successful Tenderer through the tender evaluation process including the risk assessment described above ensured that only a Tenderer proposing low risk construction methods could be selected.

The construction methods to be used were defined in the Contract. The basis for this was the description included in contractor's tender with modifications resulting from the contract negotiations. The tunnelling was with earth pressure balance TBMs, supplemented with NATM construction and cut and cover tunnels as explained in Section A.2. The stations were constructed using secant pile walls and top down slab construction in most cases.

Provisions to manage building risk.

Provisions to manage building risk coming both from tender documents and as a result of contract negotiations included:

- The Contract defined that the contractor was responsible for prevention of damage to buildings and other third part property. For this to be practicable, a limit was required to define building damage, and so the minor degradation of building decorative finishes were excluded from the range of damage for which the Contractor was responsible. This was done by reference to the categories adopted in BRE Digest 251, "Assessment of Damage in Low Rise Buildings", revised 1995: In listed buildings and buildings to be preserved, only category 0 damage according to this document was not considered to be damage in terms of the Contract. For normal buildings, also category 1 damage was not considered to be damage in terms of the Contract.

- A general pre-contract investigation of all buildings within a 100 m wide zone along the tunnel alignment had been made available to the Tenderers and included in the Contract. In addition, the Client provided detailed investigations of selected sensitive buildings prior to construction. This included the production of a damage schedule, including photographs and registration of existing cracks.
- The Contractor should before construction started in a particular area document that the envisaged construction methods would not cause damage to buildings and other third party property. This included prediction of ground movements and the resulting impact to the buildings and structures. The Contract gave a detailed description of how this documentation should be provided.
- For each construction site, the Contractor devised a monitoring system which would reveal when actual ground and/or building behaviour exceeded predicted limits such that appropriate additional measures could be implemented in due time.
- The Contract defined that drawdown of the shallow ground water table was not allowed. This could be adhered to by a combination of prevention of groundwater inflow to the construction site and recharging. A monitoring system to detect any dangerous groundwater drawdown was implemented by the Contractor.

A.6. Risk management during Construction

The Contract defined the construction risk assessment work to be carried out by the Contractor. There were general requirements for all the construction risk assessments to be carried out for all construction sites and some further requirements to the construction risk assessment for the TBMs.

It was a general requirement to all risk assessment work that it should be completed in sufficient time that any risk reduction measure identified could be implemented.

The general procedure for the construction risk assessment may be described as follows:

- A detailed plan for the work including definition of acceptable risks and classification systems.
- A systematic identification of hazards with qualitative assessment of likelihoods and consequences using the predefined classification system. Classification of the hazards according to their severity.
- Identification of possible risk reduction measures, and decision on implementation of risk reducing measures.

The risk assessment was carried out by the Contractor using expert elicitation and brain storming with participation of the Client's representative.

The TBM construction risk assessment had to start immediately after signing of the Contract with an assessment of the conceptual design followed by an assessment of the detailed design with the purpose to contribute to the design of the TBMs. Furthermore, risk assessment of the TBM operation was carried out – providing input to the operation procedures.

A.7. Lessons learned

A.7.1. At signing of contract

On the basis of the experience with construction risk assessment for the Copenhagen Metro, the following may be concluded:

1. The establishment of a construction risk policy at an early stage in a project enables an uniform attitude and awareness towards risk to be established.
2. It is recommended to identify risk and candidate risk reduction measures as early as possible in the project development. During the early design stage there are several parameters which can be adjusted to reduce the risks, whereas, in the later design stages, several decisions have been frozen, often the alignment and the tunnelling method, and the numbers of parameters in play to reduce the risk are less global and more limited in their effect.
3. The risk assessments were performed as round table discussions with expert judgements. They provided a useful forum for discussion and understanding the risks issues and assisted in maintaining an awareness of the risk issues by the project team throughout the project development and implementation.
4. The risk assessment carried out during tender evaluation provided an important contribution both to the selection of the Contractor and in the development of the final Contract during the negotiations.
5. Requirements to the Contractor's risk assessment work were included in the Tender Documents and further detailed during contract negotiations. It was thus ensured that construction risk assessment was used as a tool from the early design stage to completion of construction.
6. Risk assessment work shall be completed in sufficient time that any risk reduction measure identified can be implemented.

A.7.2. After completion of the project

The risk management system utilised for the Copenhagen metro has contributed by avoiding any major hazards of a technical nature. Particularly the route based risk assessments with risk assessments performed for each tunnel section between stations prior to start of tunnelling draw the attention of all involved parties towards any identified risk and draw everybody's attention towards the risk reduction measures identified as part of the assessment.

No major technical problems occurred during the construction process and we assign this to the use of construction risk management from the early start of the project which assisted in the selection of robust and safe construction methods.

During the construction of the works, the risk management resulted in identification and selection of risk mitigation measures and justification for the implementation of these measures.

The risk management system in our opinion has thus contributed to overcoming some of the challenges in constructing an urban underground mass transit system. However, it did not foresee or solve every difficulty experienced on the project. Although the project was completed meeting the technical quality requirements set for the project, the project was not completed within the time schedule and the budget set out.

Within the first year or so of the construction, severe delays to the time schedule occurred. The main cause of the delay was a long implementation time for establishing a sufficient organisation that was able to handle the detailed design within the design and construct contract requirements. Due to the long implementation time, the detailed design of the temporary and permanent works was completed later than foreseen in the time schedule agreed between the parties. These delays then led to substantial claims arising as a result of the delay in the design and delays to the subsequent construction works.

The risk management system identified some time schedule problems. However, they were not identified in such a way that their severity was acknowledged by the management in time that remedial action could be taken.

A revised time schedule was agreed between the parties approximately two years into the contract and the project was completed within this schedule.

A.7.3. Overall

Risk management is included as an integrated part in the planning and construction of any major underground works. The benefits of risk management can be improved compared to the experience from the Copenhagen Metro by putting more emphasis on general hazards and improving project management's awareness of the importance of risk management. The guidelines as presented now put more emphasis on the general hazards by separating them from the specific hazards of more technical nature.

References

Ang, A.H.-S., Tang, W.H., 1984. Probability concepts in engineering planning and design. In: Decision, Risk and Reliability, vol. II. Wiley, New York.

The Engineering Council, 1993. Guidelines on Risk Issues. London, ISBN 0-9516611-7-5.

Benjamin, R.J., Cornell, A.C., 1970. Probability, Statistics and Decision for Civil Engineers. McGraw-Hill, New York.

Crystal Ball – User manual, Decisioneering Inc.

Jaselskis, E.J., Russel, J.S., 1992. Risk analysis approach to selection of contractor, Evaluation Method. Journal of construction Engineering and Management 118 (4), 814–821, ASCE.

Lichtenberg, S., 1989. The Successive Principle – a New Decision Tool for the Conception Phase, Proceedings. Project Management Institute/INTERNET Symposium, Atlanta.

Lichtenberg, S., 2000. Proactive Management of Uncertainty Using the Successive Principle. Polyteknisk Forlag, Copenhagen.

Sturk, R., 1998. Engineering geological information – Its value and impact on tunnelling. Doctoral Thesis at Royal Institute of Technology, Stockholm.

For further reading

Bielecki, R., 1998. The safety concept for construction of the 4th tube of the Elbe Tunnel in Hamburg. In: Russian Tunnelling Society: Underground City; Geotechnology and Architecture. Conference September 8–10, 1998, St. Petersburg, pp. 82–89.

Einstein, H.H., 1996. Risk and risk analysis in rock engineering. Tunnelling and Underground Space Technology 11 (2), 141–155.

Eskesen S.D., Kampmann J., 2000. Risk reduction strategy in urban tunnelling: experience from the Copenhagen Metro. In: ITA World Tunnel Congress, Tunnels under Pressure, Durban, 2000.

Godfrey, P.S., 1996. Control of Risk – A Guide to the Systematic Management of Risk from Construction. Construction Industry Research and Information Association, CIRIA.

Holst Olsen, T., Lauritzen, E.K., Holm, N., Ladefoged, L., 1997. Practical risk management in construction – experiences from the Øresund fixed link, Danish Landworks, Society for Risk Analysis – Europe Conference, New Risk Frontiers, Stockholm.

Isaksson, M.T., Reilly, J.J., Anderson, J.M., 1999. Risk mitigation for tunnel projects – A structured approach. In: Alten, et al., (Eds.), Proceedings Challenges for the 21st Century. Balkema, Rotterdam.

Kampmann, J., Eskesen, S.D., Summers, J.W., 1998. Risk assessment helps select the contractor for the Copenhagen Metro System. In:d ITA World Tunnel Congress, Tunnels and Metropolises, Sao Paulo, Balkema.

Reilly, J.J., 2000. The management process for complex underground and tunnelling projects. Tunnelling and Underground Space Technology 15 (1), 31–44.

Norwegian Tunnelling Society, 1992. ITA Recommendations of Contractual Sharing of Risks. second ed., March, 1992.

Smith, D.J., 1997. Reliability Maintainability and Risk. Butterworth Heinemann, Donald Lamont, ISBN0 07506 37528.

Stille, H., Sturk, R., Olsson, L., 1998. Quality systems and risk analysis – New philosophies in underground construction industry. In: Franzén, T., Bergdahl, S.-G., Nordmark, A., (Eds.), Proc. Underground Construction in Modern Infrastructure, Stockholm, June 1998. Rotterdam, Balkema.

Tengborg, P., Olsson, L., Johansson, J., Brantmark, J., 1998. System analysis of the Hvalfjördur tunnel. In: Franzén, T., Bergdahl, S.-G., Nordmark, A., (Eds.), Proc. Underground Construction in

Modern Infrastructure, Stockholm, June 1998. Rotterdam, Balkema.
Tonon, F., Bernardini, A., Mammino, A., 2002. Multiobjective optimization under uncertainty in tunnelling: application to the design of tunnel support/reinforcement with case histories. Tunnelling and Underground Space Technology 17 (1), 33–54.

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.