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# Quality in tunnelling: ITA-AITES Working Group 16 Final report ☆

Claudio Oggeri [a,*,1], Gunnar Ova [b,1]

[a] Dept. of Georesources, Tunnelling and Underground Space Center, Politecnico of Turin, Corso Duca degli Abruzzi 24, 1029 Torino, Italy
[b] Selmer Skanska AS, St Olavsg 25, 0107 Oslo, Norway

**Abstract**

Quality in tunnelling means knowledge. Knowledge is necessary to answer correctly to the requirements of the Design that has been prepared for an underground work, planned for a solution in civil, environmental or industrial fields. Knowledge is necessary to learn and "copy" better what the previous Designers have done to find new solutions for tunnel construction. Knowledge is necessary to spread all over the technical world both the reasons of failures and the keys for success. Experience, good contracts, professionality, self responsibility and simple rules are the basis to reach the objectives fixed in the Design, that is to perform the underground work following the Quality procedures. The Working Group (WG) No. 16, appointed by the International Tunnelling Association (ITA) council during the annual meeting in Oslo on 1999, defined the main topics in Milan on 2001 and closed in Amsterdam on 2003 this document, which is aimed to give a comprehensive contribution for a good behaviour in the various stages of tunnelling. This is not a handbook, because each single phase is not analyzed in extreme detail, but it allows one to go through the interacting activities of the involved parties. It is not so easy to write about generics of Quality without the knowledge of what goes wrong: this was the main difficulty that the Working Group (WG) has encountered during its effort to give good suggestions. The members of the WG hope however that the culture of spreading of knowledge will reach the people involved in tunnelling, thus contributing to one of ITA aims, that is the contribution for a common language in the practice of tunnelling. It is necessary to promote a link between Committents or Contractors on one side and the national and international organizations, working groups and the Universities on the other, in each field of activity, aimed to a continuous and updated collection of references, because only this link will provide an enormous base of lessons learned directly from case histories. The difficulties due to the uncertainties of the geological characters can determine huge consequences and each effort should be done to define the position of the tunnel, the excavation and support methods, the environmental and safety effects, the time and cost of the alternative solutions. The purpose of this document is to encourage all the involved parties to develop and maintain good organization and communications and to put each stage of a work in a common layout.


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* Corresponding address: ITA AITES, c/o EPFL, BatGC, CH1015 Lausanne, Switzerland. Tel.: +41 21 69323 10; fax: +41 21 69341 53.
*E-mail address:* secretariat@ita-aites.org (C. Oggeri).

[1] Co-authors and Editors for the work made by WG16, whose members are acknowledged, and listed at the end of the paper.

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## 1. Introduction

### *1.1. Summary and structure of the report*

The recommendations put forward in this report are aiming to give practical guidelines to the various parties engaged in tunnelling projects during the different stages of a project. Since the basis for a successful tunnelling project is often related to careful planning and management rather than isolated inspections and tests, this report focuses mainly on quality management measures, including iterative processes with the objective of securing adequate and updated quality plans and procedures at any stage. Project prerequisites and risk assessment are dealt with in different sections of the report, recognizing the importance of these topics.

The report has been arranged according to different project phases and give specific recommendations for each phase (Table 1). For practical reasons the Working Group (WG) has chosen to handle procurement as a project phase, even though the procurement activities can be related to all stages of a project. It should be noted that the different project phases described are not completely separated from each other. The need to identify interactions between phases and between project participants is crucial to the success of any tunnelling project.

Conclusions and recommendations are given for each project phase in the respective sections.

### *1.2. Objectives and scope of work*

The Working Group has adopted the following objective for the work:

> To give recommendations on how to achieve Quality in Tunnelling and how to identify, evaluate and specify Quality Management measures to be taken by all parties in the Conceptual Planning, Procurement, Design, Construction, Operation and Maintenance phases of underground projects involving tunnels.

The WG supports the use of international standards and guidelines for Quality Management Systems such as ISO 9000 with updates (ISO standards on quality), internationally accepted forms of contracts and agreements, but feels that specific attention should be paid to topics relevant to tunnelling. The management systems should be utilized as tools adapted to the particular features of tunnelling. Thus, the report contains recommendations on ISO related topics, such as allocation of responsibility, communication, etc., but also specific recommendations on the necessary prerequisites needed to achieve quality in various phases of an underground project.

Reference to and use of updated recommendations produced by international or national sister organizations (ISRM, ISSMFE, IAEG etc.) and other professionally developed documents (such as the Eurocodes by European Committee for Standardization) is encouraged.

The professional tools used for implementing quality procedures are not covered in this report as each company/organization can adopt the most suitable procedures when establishing the project quality plan. However, the WG has found it important to stress the need to specify the interaction between Employer (could be Employer, Owner, Client, Host Government), Engineer (could be Engineer, Designer, Consultant) and Contractor (could be Contractor, Concessionaire).

### *1.3. Definitions – "key words"*

The meaning of *"Quality"* was defined in ISO 8402-1994 (replaced by ISO 9000:2000) as "The totality of features and characteristics of a product or service that bear upon its ability to satisfy stated or implied needs". As it is difficult to know, and particularly in advance, what the specific needs are, it is of great importance that these are expressed for a project.

In tunnelling the "stated needs" of the Employer could mean the construction of a tunnel in accordance with the technical quality defined by the Employer (i.e. technical specifications), within the estimated budget and predefined time schedule or programme. The "implied needs" are multifold and could be respect for laws and regulations, safety aspects, environmental protection, energy savings and sustainability of the works. It is of fundamental importance that the prerequisites are continuously updated and met both during construction and the operation phases.

*"Quality Management"* means "all those systematic actions that are necessary to provide adequate confidence that a product or service will satisfy given quality requirements". The ITA recognizes that it is difficult to completely assure quality in tunnelling, especially by third-party organisations. For this reason it is recommended the adaptation of "quality management" to tunnelling projects rather than quality assurance rules. Suggestions for comprehensive approaches are given in the report rather than prescriptive routine control and testing activities (see Fig. 2 and Table 2).

With regard to the ISO 9000 regulations for accreditation and certification, the certification itself may not be a practical quality requirement. It is acknowledged that many employer/client bodies, engineers/consultants and contractors consider that the ISO 9000 certification may go beyond their limits of affordability. However, the client and his contractors should strive to comply with the requirements of the ISO 9000 regulations in the formulation and achievement of the quality goals that have to be reached.

Bearing in mind that quality, defined as the sum of procedures and control tools that allow for the achievement of goals in terms of set parameters and the result of the planned actions, is connected to other technical and organisational tools, links with other ITA Reports, such as Contractual Practices, Subsurface Planning, Tunnelling Risk Management and Maintenance and Repair, should be considered.

### *1.4. Organisation – working group members*

The Working Group has been working actively since the Oslo ITA-AITES Congress in 1999, calling for contributions in several occasions, mainly during the annual symposia. The working group members have been appointed regularly over the years and have all contributed to the discussions and the preparation of this report. The members of the group represent the different parties generally involved in tunnelling, employer/clients bodies, consultant/engineer bodies, researchers and contractors. A list of the working group members who have compiled, or made contributions to this report, is found in Chapter 10. The WG has been meeting at the annual ITA congresses and has been conducting work sessions between congresses. A Draft Report was submitted in the beginning of 2001, and comments received on this draft have been taken into account in the final report.

The WG has always been open to suggestions, and every effort has been made and will be made to take into account the corrections.

## 2. General recommendations

### *2.1. Project prerequisites*

In the early stages of the project, and before any detailed agreements are made with the consulting bodies and construction companies, the client or implementing organization should establish project prerequisites such as:

- Internal organisation with defined responsibilities including organisational access to the top management or decision-making body, minimum staffing requirements etc.
- Project budget and detailed budgets for the work to be carried out at any given time.
- Approved scope of work for the work to be carried out at any given time.
- Time limitations for the project phases and the work.
- Legal competence, including environmental and public relations/awareness.
- Contractual competence.
- Procurement competence.
- Competence on evaluating the performed work at any stage.
- Determination of all the obligations relative to contractual matters.
- Determination of necessary competence concerning geological conditions and geotechnical behaviour in the various stages of the project, from the planning to the construction.

Knowledge is crucial when it comes to dealing with uncertainties and the risk associated with those uncertainties. Results from site investigation have a direct influence on estimates of cost, time, choice of equipment, *professional quality of staff* and safety conditions, especially when tunnelling in difficult conditions is foreseen.

### *2.2. Risk allocation – principles*

Uncertainties in tunnelling projects arise from the inability to study the complete structure and behaviour of the rock and soil formations in such detail that all possible scenarios can be contemplated. It should be emphasized that tunnel failures have been the result of various reasons such as insufficient site investigation, inadequate evaluation at the planning stage, *project understaffing*, mistakes during construction and operation phases.

An inventory of inherent risks for the project phases should be undertaken for all tunnelling and underground projects. Risk assessment should be made for:

- Rock and soil conditions versus the stability, physical properties and seepage.
- Construction methods versus progress, rock/soil conditions, environment and safety.
- Equipment versus suitability, capacity, energy consumption, environmental and safety aspects.

The consequences on the total project cost and financial matters should always be included in risk evaluations.

Site investigations and geological exploration and their use in design optimisation, coupled with well matched construction techniques, can prevent most kinds of collapses. The design cannot only be based on a deterministic approach for the evaluation of a risk, a probabilistic approach that takes into account the uncertainties in the geological, geotechnical and construction techniques and external constraints will enable the project management to optimize the final design and define the technical, administrative and financial management of the risk.

It is recommended that detailed paragraphs dealing with risk allocation should be included in all contracts or agreements, and that risk is distributed by taking into consideration both technical and financial aspects.

Contractual procedures should be simple and the role of the various parties should be made extremely clear, both from a technical and financial point of view. Excessive legal and bureaucratic complexity should be avoided, but specific attention should be given to those contractual aspects that deal with the information obtained on the natural ground conditions.

### 2.2.1. Risk analysis and control

Among the aims of Quality procedures the "risk assessment" has a significative role. It should be underlined that a "risk analysis" is different than a "risk assessment", and not always necessary, because it increases the cost of the design and does not contribute proportionally to the actual handling of the risk. Risk assessment, as far as the Quality procedures are concerned, is aimed to identify which risks are foreseen by the design, which risks are undertaken by the contractor and who undertakes any further risks.

As a guideline the following key steps should be taken to define the risk occurrence related to unknowns and unforeseeables during planning and design:

As a guideline the following key steps should be taken to define the risk occurrence during planning and design:

- identify any hazards,
- assess risks (likelihood and consequences),
- use engineering and other means to eliminate risks (already included in the design),
- identify actions (countermeasures) to handle the unforeseen risks,
- assess any residual risks (the uncertainties which have not relevant consequences, including secondary risks),
- give approximate estimate of the costs and benefits of alternative risk mitigation options or strategies,
- allocate responsibilities for the unforeseen risks,
- select and implement any beneficial actions aimed to reduce the uncertainties.

Design should not be based on the most extreme conditions even though this could protect the parties from most of the possible risks. The design should however take into account any possible extreme conditions in order to complete the construction sequence using:

- modelling of the consequences (in terms of techniques, times and costs) that the occurrence of geological unpredicted situations would have on tunnel construction. It means to model different scenarios related to geological situations which are difficult to be studied;
- demonstration of the relative cost-benefit that might result if sufficient preliminary geotechnical investigations and the appropriate design are carried out in order to narrow down the spectrum of possible risks;
- a predefined monitoring plan, aimed in particular at checking the extreme conditions, specifying criteria for the analysis and evaluation of measurements and the establishment of procedures for the use of data;
- verification that the design has considered the technical criteria for intervention in order to overcome the extreme conditions during construction (given that the technical means are the contractor's responsibility), together with the definition of the administrative responsibilities and procedures.

Risk sharing is one of the step that Quality procedures would identify. Risk associated with ground conditions is related to the conditions being different from was expected or foreseen. This particular risk is considered to be the highest risk that contractors and owners are exposed to and is also considered to be the major reason for tunnelling projects to falling into disarray. Traditional forms of contracts provide clauses that deal with change in ground conditions, and the client body generally carries the risk for these. Many new generation contracts provide clauses where the contractor bears the risk of cost overruns due to ground conditions. The risk carries in these cases will include those of cost overruns due to unforeseen conditions. Contractors could however expect a premium for the acceptance of such risk. In these types of contract the accuracy of preliminary and subsequent site investigations during design and construction becomes even more important, whereas changed ground conditions will remain beyond contractors responsibility. In each case clear definition of "boundary conditions" between the expected and actual ground conditions should be specified, and as a consequence, all the related differences in costs and progress for construction (see Fig. 4).

## 2.3. Allocation of responsibility – project manager

The experience and the opinion are that successful planning is the key to a successful project and that adherence to the plan is essential in order to develop and achieve the quality goals set. Decision making, based on the best information available and the transfer of information both upwards and downwards in an organisation, in a format understood by all, are key issues in the process. The importance of timeous decision-making cannot be stressed enough.

It is recommended that the owner/employer/client should create a position of Project Manager for each project at the commencement of the conceptual planning phase and that this position remains throughout each phase of the project until the project is completed. The person/s appointed to this controlling position must be thoroughly conversant with the breadth of potential problems in tunnel design and construction. It should be carefully evaluated, whether this person should be the same through all phases of the project, or whether it should be changed.

A job description for the position should be prepared in writing by the owner/employer/client stating the responsibilities and the subsequent mandate given to the project manager to carry the project through into the next phases. The project manager should report directly to a senior executive of the implementing body who jointly will identify the quality goals to be set. In addition, a resourcing organogram should be prepared, showing different positions (both internal and external) with job descriptions, timing/programme, budget/costs, reporting procedures and responsibilities.

Detailed and resourced programs of activities during the different phases, showing key dates for the different requirements, should be established. Performance in accordance with the program should be monitored for each resource on a regular basis, without involving too many audits and auditors (see Fig. 1).

It is also recommended that the implementing body appoints an independent and periodic verification of the quality issues for the project and that this appointment is made in the early stages of the conceptual planning phase so that assistance in the identification of the quality goals and monitoring process can be obtained.

Quality audits should be performed of both the implementing body as well as within the consultant's/contractor's organisations, but repetition of the same auditing operations should be prevented. In tunnelling, where the final result often follows a series of iterative processes, audits should also be performed of adherence to project prerequisites and the handling of derived project and design parameters. Further reference to auditing is made in other sections of this report.

Depending on the type of work, the owner should define his expectations by a functional description of the project. The geotechnical information/description of the project shall be independent of construction methods and tender and procurement procedure. Based on this, risk exposure for tenderers/bidders and investors can be defined. This first phase is fundamental because it provides the tools for investors to assess the degree of risk, but can also assist the owner in preventing speculative offers/actions. Careful monitoring during construction and final commissioning by an external engineer is in some instances, like in Italy, required by law.

Items related to responsibilities and risk allocation include, but are not limited to, the following; technical and financial feasibility, environmental impact studies, design issues, financial planning, construction budget/costs and time for construction.

### 2.4. Quality goals

There is a direct, linear relation between project quality and project cost. In order to obtain a well functioning tunnel or underground structure, all project stages are of fundamental importance; the stage of knowing the geological and geomechanical characteristics, the planning stage, the stage of choosing the machinery and method of excavation, the installation of lining and rock support, and the organisational and financial coordination stage. As far as Quality Systems are concerned, an analysis of the numerous problems that occur in a tunnel, independent of the adoption of Quality System procedures, show how these may not be resolved automatically by Quality Systems.

Quality Systems should reflect the various stages and assess the influence on the final result, mainly focusing on those aspects where the interpretation becomes decisive in the technical choices.

Tunnelling and underground projects are usually of significant financial value and are generally considered high risk in terms of final cost and time for construction/delivery. In addition, tunnel construction often requires multinational input for both funding and technical capacity. Performance to the set quality goals therefore becomes a critical issue.

When it comes to the quality issues, it is not considered necessary to maintain a uniform approach for the duration of a project. Some issues might turn out to be more important than others and experience shows that, during the course of construction, some issues may well be abandoned without harm to the project.

Research into the appropriate local legislation and regulations for such matters as health and safety, the protection of the environment and socio-economic consequences, as well as technical standards to be achieved should be carried out. These can then be compared to best international practice, which can be adopted to suit the particular project and then the quality goals can be set accordingly.

All phases of a project and all organisations/groups of organisations involved should have a set of quality goals for the work to be performed. Quality goals should be aimed at giving the project added value with regard to cost, time, improved performance/physical properties and could be set relative to "soft parameters" like improved competence or educational standards for involved parties, environmental aspects, safety standards or benefits for the public in general. When quality goals are determined, these should be related to the factors of success for the project and a strategy on how to achieve this should be included in the Quality Plan. Compliance and the degree of success in achieving the set goals should be communicated to all project members/companies.

It is recommended that requirements and detailed instructions for quality control for the design and the construction work should be specified in the contract. It is important that procedures for the registration and communication of items such as test results are specified. A project procedure including owner/employer, engineer/designer and contractor for lines of communication and the responsibilities of each party for handling such information should be drawn up. The continuous process of evaluating, for instance, test results and any subsequent changes to the design and/or construction methods should be adequately defined and described.

Table 1

LAYOUT OF THE ADAPTED QUALITY SYSTEM FOR TUNNELLING

**STEPS FOR THE LIFETIME OF A TUNNEL**
⇓

| QUALITY ITEMS ⇓ | General planning | Design | Financing | Procurement | Characterization | Monitoring | Construction | Approval | Claims and controversies | Operation | Maintenance | Installations | Statistics |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Management responsibility | Authority and mandates for involved people | | | | | | | | | | | | |
| Quality planning | Definition of procedures for the various activities and co-ordination | | | | | | | | | | | | |
| Contracting | Administrative, legal and technical rules | | | | | | | | | | | | |
| Control and inspections | All the tests, approval, inspections, verifications | | | | | | | | | | | | |
| Document control | Issue, control and approval of documents | | | | | | | | | | | | |
| Purchasing And Contractors | Control of materials and contractual works | | | | | | | | | | | | |
| Non conformities | Problem definition and notifications | | | | | | | | | | | | |
| Corrections and preventions | Accurate definition of problems and planning for preventive and remedial actions | | | | | | | | | | | | |
| Audits | Independent check of the organization and methods | | | | | | | | | | | | |
| Training and information | Internal and external education | | | | | | | | | | | | |
| Data control and elaborations | Data processing of all phases; economical, statistical, technical, measurements | | | | | | | | | | | | |

This is a general layout of all the possible stages of an underground work (1st row) linked to all the specific actions of quality plans (1st column). Depending on the specific case, an interacting matrix can be implemented following the arguments listed in the various rows.

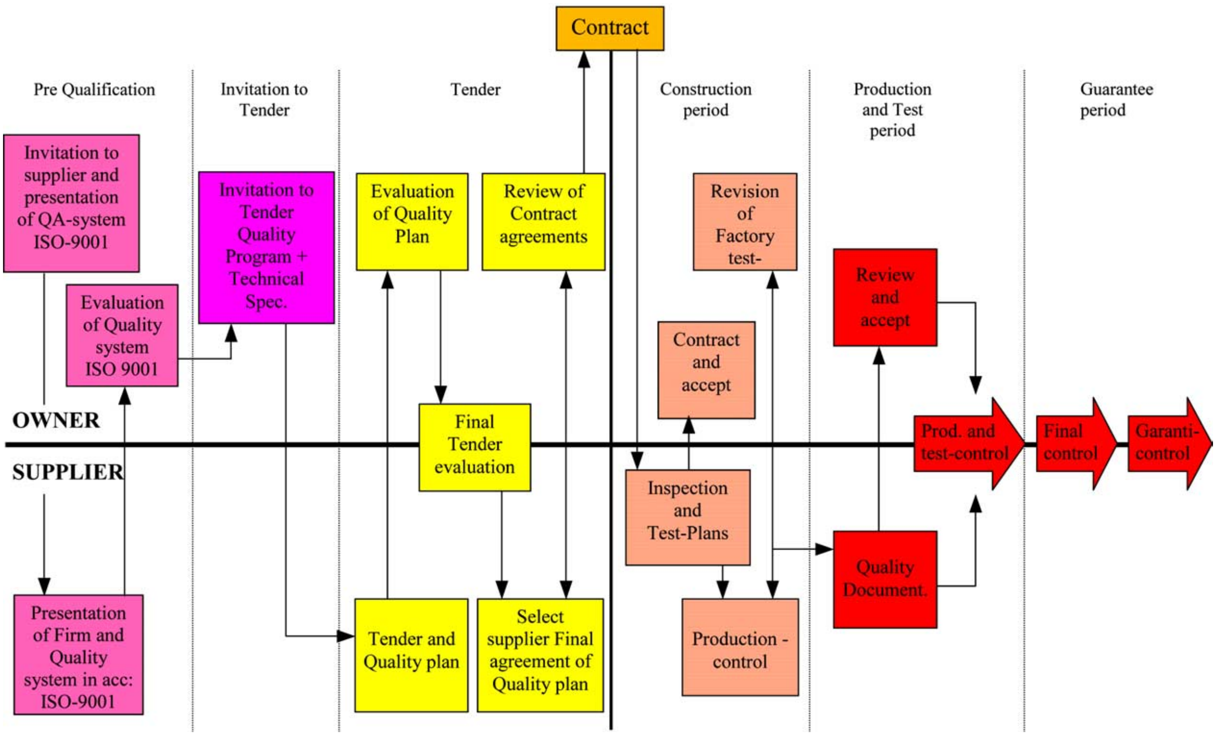


Fig. 1. Flow sheet of quality activities. Courtesy Swedish National Road Administration.

It is recommended that implementing bodies and contractors make available technical data and statistics from the construction phase and communicate such data to international bodies and universities. By doing so, objective views on the state-of-the-art of methods used and case histories could be obtained, all in line with a generally recommended quality goal regarding the transfer of knowledge.

Methods for procuring, constructing, maintaining and operating private/public infrastructure are numerous. They range from lump-sum contracts for the construction of a designed facility, to complex transactions involving ownership transfer, equity financing and novel revenue features. Understanding and adapting available contract options is crucial for the success of a project. The owner should be aware of how his precise requirements are best served and of the practical considerations associated with different contract strategies.

The details of appropriate methods of financing and remuneration, risk allocation, the nature of the different parties' obligations/responsibilities and the ownership structure are matters specific to the individual projects.

It is possible to resume what have been described in terms of benefits of the application of Quality as follows:

- Good organization and relationship.
- Definition of needs and constraints of the work.
- Design adapted to needs and constraints.
- Control on the evolution of design stages and selection of appropriate contracts.
- Evaluation of risks and allocation of responsibilities.
- Ability to perform modifications to details.
- Historical records of the design and of the performed works.
- Reciprocity for communications and problem-solving attitude.

## 3. Conceptual planning

The conceptual planning phase is defined as "the period of a project which commences when the request is made to prepare estimates of feasibility, cost, viability and delivery options and ends when approval is given to proceed with the project into the design phase" (Table 2).

### *3.1. Organisation – allocation of responsibility*

The importance of timeous decision making is emphasised again. The client body is expected to have established the general decision making process. If this process does not exist, it should be established upon commencement of the conceptual planning phase.

### *3.2. Competence and communication*

Recognising that many tunnelling and underground projects make use of 'State-of-the-Art' technology, it is necessary to provide effective communication lines and a continuous upgrading of competence within the

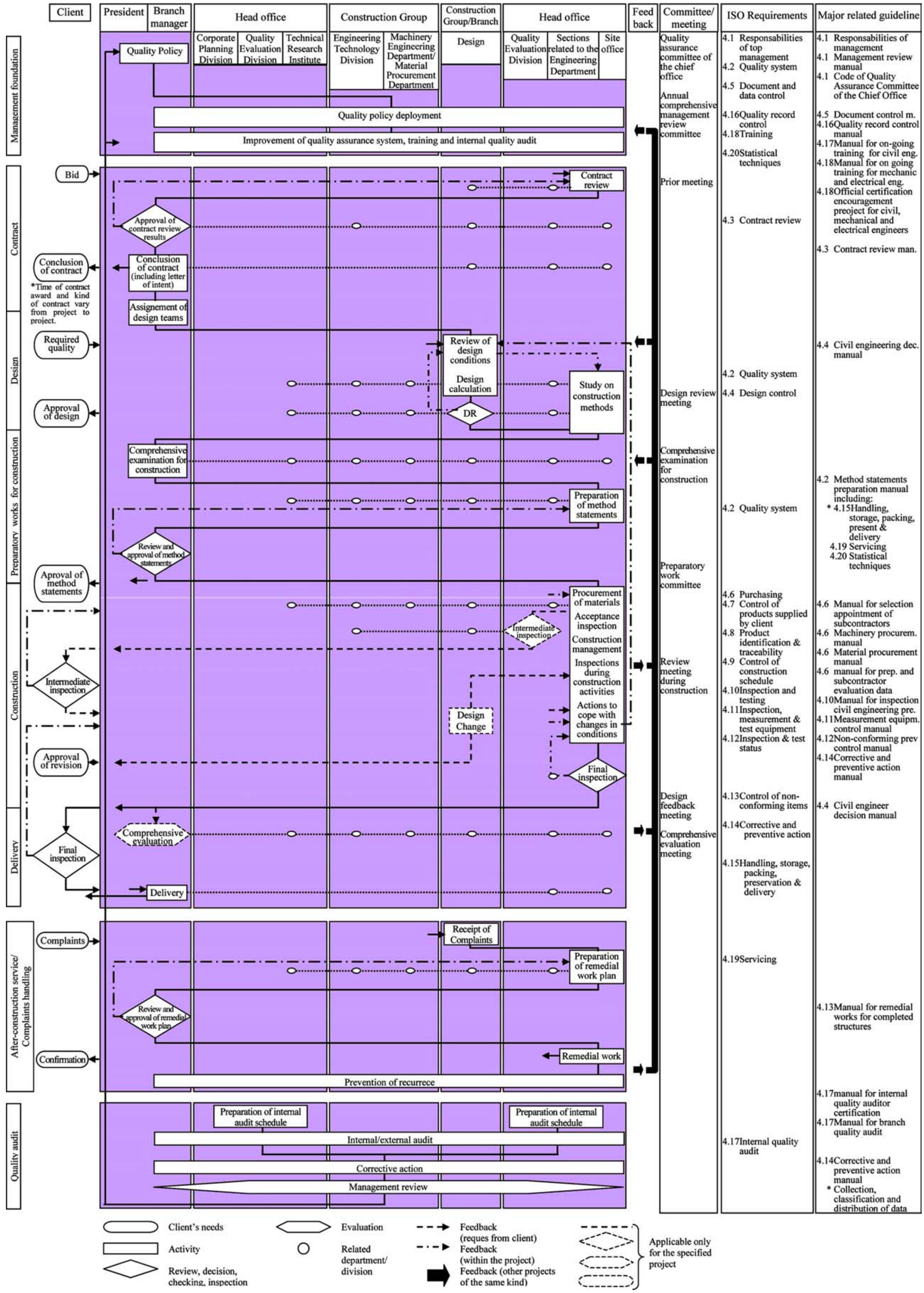


Fig. 2. Example of flow chart for quality assurance system (for design/build civil engineering projects, Kaijima Corp., Japan).

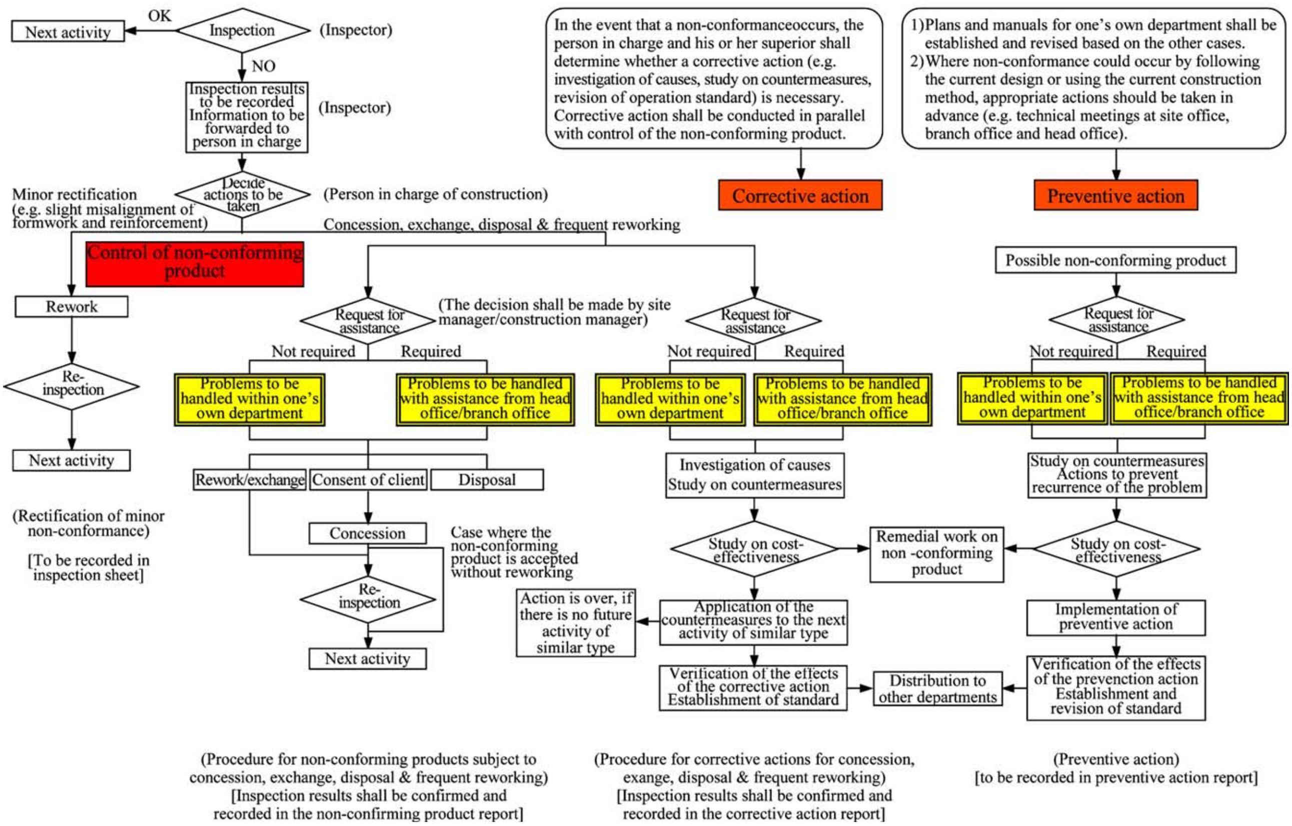


Fig. 3. Procedure for the handling of non-conformances (courtesy of Kaijima Corp., Japan).

participating bodies/companies. Thus the following measures should be established:

- Competence levels for the various project participants.
- Procedures for the regular monitoring and reporting of successes and failures.
- Procedures for the circulation of information. These should include regular meetings between all the involved disciplines, progress meetings and reporting to the decision making body.
- Description of project iterative processes including testing, evaluation and possible design and construction changes/modification, definition of responsibilities and mandates for the respective project parties (as described earlier).
- Documentation/Procedures for project modifications.
- General guidelines for procedures ensuring contract and project knowledge (Contractual Review).
- Procedures ensuring that the extent of inspection and monitoring is known.
- Education of all persons involved in the project in the quality issues and goals to be achieved.

### 3.3. Time schedule

It is recommended that the time schedule includes not only the dates of the final submission of the work, but also the dates of the intermediate stages, as appropriate. Specific time allowance should be allocated for review of critical inspections and testing.

### 3.4. Special recommendations

The phase of the conceptual planning of a tunnel is very important, since it is at this stage that the most serious project risks and constraints are identified, alternative solutions are examined and costs are evaluated.

It is recommended that during the conceptual planning phase, particular attention should be paid to the following:

- *Risk identification and evaluation*: It is of vital importance to identify all the possible risks related to a specific tunnel alignment. All possible alternative alignments should be examined and their risks identified and evaluated.
- *Investigation of surface and sub-surface conditions*: This is the key factor to tunnelling and the main cause for disputes, delays and "changed condition" claims. The investigation of rock/ground conditions should start at this stage, and include at least satellite and aerial mapping if appropriate, geological surface mapping, seismic risk analysis (where appropriate) and the collection of all available geological and

geotechnical data. The investigation of the rock/ground conditions usually continues at the design phase and is linked to the project risk evaluation.

- *Clarification of project constraints*: Constraints such as funding, laws and regulations, environmental restrictions, interference with other existing projects, possible public reaction, land expropriation and necessary licenses should be identified.
- *Establishment of design criteria*: The Design Criteria clarify the requirements of the tunnel owner (Client's needs). The more clearly these requirements are stated the more easily quality is achieved and costs controlled.

The Design Criteria should *inter alia* include tunnel cross-section, which for transportation tunnels takes into account vehicle envelope, pedestrian sideways, drainage, ventilation, electromechanical facilities, aerodynamics, permanent lining, etc. Other factors are tunnel safety including accident prevention measures, fire fighting methods, type of fire, escape routes, rescue organization, etc. Environmental impact studies on groundwater/ground conditions, noise, air pollution, fauna/flora, social/town planning structures should be included as well as location of tunnel portals, tunnel drainage and other facilities.

- *Selection of Designer/Consultant including Consulting Fees*: It is recommended that bidding on tunnel planning and design works should be avoided. Instead, the selection of a designer should be based on:
  - Proven experience in similar projects.
  - Qualifications and experience of design team.
  - Diversity of disciplines in the design team.

It is recommended that geological studies, seismic risk analysis and geotechnical evaluation studies are assigned to the same consulting firm, whereas the geotechnical site exploration works could be carried out either by the same or by a different entity.

It is recommended that prior to signing contracts for planning and design, an evaluation of professional requirements should be conducted. The result of such an evaluation should be in writing and compliance should be checked and verified. Professional requirements should include adequate and available resources amongst senior personnel with documented competence. Planning and design contracts should include paragraphs for the transfer of knowledge in cases where the client body needs further and defined competence.

Since tunnelling and underground projects are usually characterized by a long duration, it is recommended that planning and design contracts should contain paragraphs that will provide for sufficient continuity within the consulting organisations.

It is recommended that the fees for tunnel project design, during all stages of design, should not be a prefixed total sum. In addition, the fees should not be related to the project cost estimate neither directly related to the actual project cost.

- *Quality Control Plan*: It is recommended that a Quality Control Plan for planning/consulting services should contain the following:
  - Design coordinator responsible for the coordination of all the involved disciplines
  - Team leaders for the various design disciplines
  - Design phases

It is recommended that a Project Appraisal Report is compiled at the beginning of each design phase. This report should review the current status of the project and identify the necessary actions/steps to be taken by either the client or the designer.

- Time schedule of planning phases
- Communication/reporting

It is recommended that regular meetings between the Project Manager and the designer's project coordinator are specified in the Quality Control Plan. It is good practice to prepare these meetings in advance and to encourage the participation of members of the respective teams of both parties. Thus, information is circulated more easily. Minutes of these meetings should be kept in writing.

All queries, ambiguities and uncertainties can be resolved during these meetings. Both parties should be aware of the usefulness of these meetings, provided that a spirit of co-operation prevails. The designer must always remember that the scope of his work is to meet the Client's needs. In turn, the Client must recognize that only through his clear statements and prompt and timeous decisions the final goal can be achieved.

- Documentation/Design Modification Records
- Allocation of Responsibilities
- List of Key Elements of the Relevant Design Criteria.

The list should serve as a checklist of the works to be carried out.

- List of Laws and Regulations to be taken into account during the planning stage and any licenses which need to be obtained.
- Conceptual Planning Review

It is recommended that internal reviewers from the client body carry out the design review. They should have similar experience and professional competence as that demanded from the designer. If the client does not have such personnel, then a Technical Advisor should be appointed for this purpose. The internal reviewers should act as 'suppliers of services' to the Project Manager making appropriate recommendations only.

- Approval Procedure

If during the design phase the procedures are followed and meetings held at regular intervals, it is unlikely that the final submission of a Conceptual Planning Report will be rejected. However, in many cases the reviewers may comment on the report. It is recommended that the Project Manager obtains the response of the designer to these comments, within a specified time, and only afterwards makes a decision on the approval of the design.

- Conceptual Planning Audit

It is recommended that an independent Conceptual Planning Audit is carried out, if the size and the importance of the tunnel justify it, and also if the Client feels that the internal review is not adequate. Such an audit should focus on the following:

- Fulfillment of project prerequisites and design criteria.
- Identification and evaluation of all possible risks.
- Adequacy of the performed studies.
- Investigation of all external constrains.
- Conclusions and recommendations for the next design phase.
- Compliance by the designer with regard to the client's requirements.
- Evaluations concerning project economy/feasibility, technical constrains, project time schedule.

## 4. Procurement

The procurement phase is defined as "Those stages of a project when necessary prerequisites have been defined and agreements and contracts are being established for the planning, design, construction and operation phases of tunnelling and underground projects".

In general, it is recommended that planning, design, construction and operation services are contracted based on national or international approved standards.

The client body should have the competence to perform evaluations and quality audits to secure compliance with the necessary competence requirements that have been defined for the planning, design, construction and operations (Table 2).

### *4.1. Allocation of responsibility*

Two issues are related with the "Allocation of Responsibility", which should be dealt clearly in all contracts:

1. Who has the authority to decide on changes (especially design changes during construction).
2. Risk undertaking during construction. The expected geological/ground conditions should be clearly described in the contract. If the encountered conditions during construction are different, the contract should describe the procedure for the verification of changed conditions and who will, then, undertake the responsibility.

The various stages of planning and design contracts should be defined in the contract time schedule. It is of vital importance that the client body's reaction/response time with regard to altered prerequisites, design reviews or evaluations are specified.

Project milestones and decisions that depend on conditions revealed during geological mapping/soil investigations and during construction should be well defined in the contract time schedule. The responsibilities of the client body, designer and contractor in the iterative processes of testing/inspection – evaluation – design modification – construction method modification should be clearly stated in the contract.

A framework for Quality Audits and Audit Plans should be given in the contract. Design audits should focus on design criteria – establishment and updating, methodology, results from design reviews, third party verifications and official approvals, resources and competence.

Audits of construction should include the physical prerequisites – construction methods, evaluation of performed work, quality control, resources and competence.

If not specified in the underlying contract standards, possible risk and subsequent allocation thereof should be defined in accordance with the specific type of contract. Risk should be identified and evaluated for rock/ground conditions, environmental impact, safety, methods and equipment. It is important that risk identified and evaluated during the planning and design phases should be brought forward to the construction phase and subjected to further evaluations by the competent professionals and the prequalified contractors. The need for third party verifications by professional and official bodies should be considered.

Assistance from external legal and technical professionals on the allocation and evaluation of risk should be considered. Risk allocation should be based on the principle that the most competent party should bear the major share of the consequences.

It is recommended that neither design nor construction contracts should be agreed before a joint meeting between the parties has been arranged and an evaluation of the physical and contractual aspects connected to the above specified fields of risk assessment has been carried out. Conclusions from such a meeting should be in writing and be made available to the relevant parties.

### *4.2. Competence and communication*

It is recommended that Quality Plans for the planning, design, construction and operation phases are established by the client body and that similar requirements are passed on to all involved in the further development of the project. The Quality plans, in addition to relevant requirements of systems like the ISO 9001 standard, should describe measurable quality goals for the work.

It is recommended that, prior to signing the contracts, an evaluation of the professional requirements should be conducted. The results of such an evaluation should be in writing and compliance should be verified. Professional requirements should include adequate and available resources amongst the design and production planning personnel as well as an adequate and competent staff for the construction activities. It is equally important that the contractors provide skilled operators and workforce. Requirements of suitable and well maintained machinery and equipment should also be verified.

Programs for continuous education is a key factor to success within any organisation or company. Tunnelling and underground projects are suitable for 'on the job' training since most large projects make use of 'state-of-art' technology in one or more fields. It is recommended that educational programmes be established within all organisations and companies, and that the goals and requirements of the detailed education plans are specified in the contracts.

Contracts should include paragraphs concerning the transfer of knowledge, especially in cases where the client body needs further and defined competence.

Since tunnelling and underground projects are usually characterised by a long duration, it is recommended that contracts should contain paragraphs that will provide for sufficient continuity within the consultant's and the contractor's organisations. Requirements to back-up and reserve machinery and equipment should also be specified in construction contracts.

It is recommended that requirements and detailed instructions on the quality control of the design and the construction work should be specified in the contracts including the establishment of Quality Plans, Inspection and Test Plans identifying all control and verification activities. Special emphasis should be placed on the design and activities related to rock and ground conditions (stress monitoring, rock- and ground support, shotcreting, etc.) and environment related topics (hydrology, hydraulics, seepage) (see Fig. 5).

The need for third party verifications should be considered when evaluating topics like stress monitoring, critical rock-/ground support, issues related to the environment and conditions calling for changes in methods or equipment. The requirements or guidelines for third party verifications should be given in both the design and construction contracts. The construction contracts should specify any actions to be taken when the given physical properties are exceeded or otherwise not being fulfilled (regular or ad hoc reviews – external professional assistance, e.g. dispute review boards should be considered).

### *4.3. Time limitations*

It is generally acknowledged that tunnelling and underground projects are in a continuous state of development throughout the project phase prior to commissioning. When sub-surface conditions are uncertain or not adequately investigated, time should be allocated to provide necessary evaluations and possible changes in construction methods or the physical design.

It is recommended that a method for the handling of the consequences of altered construction methods and design should be specified in the construction contracts, reference is made to the above paragraphs on iterative processes. As previously stated, the planning capacity within the contractor's organisation should be well documented.

It is equally important that discipline is established in relation to given time limits. Continuous reporting of progress relative to fixed milestones is crucial to any project and the requirements and methods of reporting should be given in all contracts.

### *4.4. Financial aspects*

Financial constraints in relation to the client body's estimated total cost as well as to the contractor's ability to handle altered conditions can have many adverse effects on the total quality of the project development. It is recommended that financial capacities are well documented for both contract parties before construction contracts are signed.

Experience has proved that financial constraints or the desire to accept low bids for planning and design work can lead to many adverse effects on the total quality of the project. As stated earlier, it is recommended that planning and design contracts should not be awarded on the basis of a fixed total sum, but on the basis of a split of competence and price.

### *4.5. Contract forms*

During recent years different contract forms have evolved. The recommendations of this report generally reflect the 'traditional' parties in tunneling projects with Client, Designer and Contractor acting as separate bodies.

However, the principles of the report should be applicable even to new contract forms, like BOT and EPC Turnkey contracts, given that the Client body is supplied with competent and independent expertise to evaluate fulfillment of project prerequisites, design criteria and the physical properties relative to specified functions.

## 5. Design

The design phase is defined as "the period of a project which is embodied after approval is given to proceed with the Project into the construction phase, when the conceptual planning is evaluated from various aspects such as cost, viability and quality."

The design of a tunnel is usually carried out in stages that are often related to the type of the construction contract. For example, there are "design-and-build" contracts or "build only" contracts. In either case the first stage of the design, at an engineering report level, leads to bidding and the preparation of contract documents. The final design is carried out at a later stage either by the Contractor or by the Client. These two stages of tunnel design are crucial for the achievement of quality.

Most cases of tunnel non-quality, especially in terms of cost and time, are attributed to the changes to the engineering report during the final design. The most common reason for the changes is the uncertainties connected to the ground/rock conditions. It is true that tunnels are characterized by a number of particular features, such as the geological medium through which the structure is built, the variety of construction methods and technologies, the involvement of various scientific disciplines, the sharing of responsibility for the construction risks, the variety and complexity of construction contracts, etc.

In light of this, the formulation of a Quality Management System for the design of a tunnel is not a straight forward process and should be adapted to every particular case. The recommendations of the following paragraphs give only an outline of the main factors to be considered (Table 2).

### 5.1. Allocation of responsibility

As stated earlier, it is recommended that the Project Manager is responsible for the entire project including the design. A division of responsibilities between the project manager and an independent design party should be avoided. If an independent design consultant and/or design department within the Client body is to review a tunnel design, they should act as consultants to the project manager.

Likewise, the consulting firm (contractor of design services) should appoint a Project Design Coordinator. The job description of such a position should include coordination of the design team, communication with the Client's Project Manager, assignment of tasks to various design teams, work progress control in accordance with contract requirements, reporting to the Client and the top management of the consulting firm, meetings with the design teams.

Further allocation of responsibilities is good practice, for both the Client and the Consultant. All parties involved should know who is responsible for what. Experience has shown that the allocation of responsibilities for a specific project is a practical and flexible alternative to an organogram.

All studies, reports and drawings should state the names of the designers and those carrying out the design checks. The use of more than one design team in tunnel design is generally unavoidable, and usually involves a variety of scientific disciplines. It is recommended that the number of design team interfaces is reduced to a minimum.

The Project Manager or the Project Design Coordinator is responsible of ensuring that all design teams are involved in the preparation of the relevant plans. The staff members who are responsible for implementing the necessary actions should be identified by name. It is important to ensure that the procedures for the design team interface control are clear and the persons responsible for the implementation are named.

### 5.2. Design input – communication

#### 5.2.1. Review of conceptual planning

The Conceptual Planning studies should be reviewed at an early stage of the tunnel design and all constraints, risks, applicable statutory and regulatory requirements are listed and taken into consideration for the next design steps. Particular emphasis should be given to the adequacy of the available geological and geotechnical information.

The basis for adequacy and approval of the conceptual and final design should be clearly stated for the benefit of, in particular, the design consultant. This will form part of the design input.

#### 5.2.2. Contract review

Any contract related to tunnel design should be reviewed upon commencement of the design in order to identify the design conditions. This might include applicable specifications, standards and criteria, construction methods and policy, key dates, method of payment, any particular requirements of the Client, etc. A list of the main contract provisions is made by all the involved parties and circulated to the personnel engaged in the design activities.

#### 5.2.3. Design criteria

It is again emphasized that the establishment of Design Criteria for each tunnel clarifies the Client's requirements and it is an essential prerequisite to a good tunnel design. An indicative list of tunnel design criteria is as follows:

- Methods of analysis of both temporary and permanent lining.
- Load cases and load combinations.
- Construction sequence.
- Applicable safety factors.
- Materials.
- Standards and regulations.
- Drainage and sewage.
- Environmental requirements (portals, groundwater, pollution, toxic compounds, etc.).

- Ventilation/fire fighting.
- Electromechanical facilities.
- Deliverables (design output).

*5.2.4. Verification of design input*

The Project Manager or the Project Design Coordinator is responsible for the collection and evaluation of all the design input requirements. Any ambiguities and conflicts regarding these requirements should be resolved with those who are responsible for imposing them. It is important to have all the design input documented.

Finally, a list of all the design goals should be drawn comprising all the above design requirements.

*5.2.5. Relations with client body*

Regular meetings should be held between the Client's Project Manager and the Consultant's Design Coordinator with the participation of representatives of the involved design teams. These meetings should be prepared in advance. The design progress, design team interfaces and the Client's requirements should be kept in writing and constitute a part of the design input.

*5.3. Design output – control and verification*

*5.3.1. Output contents*

The design output should meet all earlier mentioned input requirements and, in particular, conform to design criteria, regulatory requirements and contract provisions. An important element in the design output is the description of the rock/ground conditions and the way these influence the tunnel excavation and support. This is addressed further in Section 5.5 of this report.

A typical tunnel design output should contain the following:

- Technical description of the project.
- Calculations.
- Drawings.
- Specifications.
- Bills of quantities.
- Tender documents and Contract conditions (design for bidding purposes).

It is recommended that all types of documents are standardized according to type and format, e.g. standard calculation sheets, drawing size and layout, reference numbers, etc. The calculations should follow a logical sequence with sufficient explanations on the real conditions, how these are modeled, what assumptions are made, the method of analysis, the geotechnical parameters used in the analysis and how these were derived and, the standards used.

All computer programs used in the analysis should be fully documented and sufficient information supplied on the program input and output.

*5.3.2. Design check/review/verification*

All calculations and drawings should be checked regarding assumptions and input parameter accuracy, the suitability of modeling and method of analysis, compliance with standards, consistency of calculations, drawings and reports, dimensional accuracy, satisfactory interface coordination and constructability. It is recognized that it is not feasible to check the accuracy of all the calculations, but sample checks should be made.

If an innovative method of design is adopted, then cross-checking with other methods is advisable and a more detailed design review is necessary. All documents should state the name of checker and date of the check.

It is recommended an independent design check by a third-party consultant only if the size and importance of the tunnel justifies it. However, the checker should have at least the same qualifications as those of the designer.

*5.3.3. Revisions/design changes*

A procedure should be established for handling the revisions of any part of the design. This could include the following:

- Request for revision and relevant documentation.
- Authorization of revision/change.
- List of the parts of the design that are influenced by the revision.
- Procedure for the distribution of information to the involved design teams.
- Names of the staff authorized to implement the revisions.
- Procedure for document filing and updating with revised reports and drawings.

The request for tunnel design changes requires special attention, when made at the construction stage, since it usually has significant consequences on the costs and construction time schedule. For this reason it is recommended that special provisions should be made in the contract documents to handle requests for design changes.

Similar provisions should be made in the consulting service contracts. Design changes requested by the Client body might involve significant additional design work and influence the design time schedule. The relevant cost and delays should be agreed on by the Client and the Consultant. Reference is made to Section 4 – contractual provisions for iterative processes leading to design and construction modifications.

*5.3.4. Final design verification*

All checks, reviews and examinations carried out at the various design stages should be listed and signed off by the persons authorised to do so. However, it is recommended that the Project Manager should ultimately be responsible for the final design verification. He must be fully satisfied that all the necessary checks, examinations and design reviews have been carried out and that all major prerequisites of the Client body are fulfilled. Thus the final Design Verification should bear the signature of the Project Manager.

#### 5.3.5. Design quality control plan

The design quality control plan should incorporate all the points mentioned in Sections 5.1, 5.2 and 5.3. Key elements of the plan should be (see Fig. 3):

- Design criteria/basis for the design (listed or with reference to identified documents).
- Procedures for contractual review.
- Procedures for design control and final verification.
- Detailed description of the various design elements and degree of verification (Control Plan, tabular form).
- Procedures for design review.
- Procedures for design changes
- Procedures for non-conformances of the design

### 5.4. Development of competence

The education and training of the staff involved in tunnel design is very important. Tunnelling requires specialized knowledge based on advanced technology, not only on the theoretical methods of analysis, but also on the practical construction methods and technologies. For this reason it is recommended that a global approach to the professional development of the tunnel design staff is adopted. Indicative recommendations are the following:

- On the job training of personnel. This might involve rotational relocation from one team to another in order to increase knowledge and experience and to refresh interests.
- Collective training through specialised lectures or seminars.
- Encouragement of publications on tunnel design, construction and performance.
- ITA particularly recommends the participation in the international tunnelling conferences, where experiences are exchanged and specialists meet.
- Regular visits of the design team staff to tunnel construction sites.
- It should be stressed that an absolute prerequisite of a good tunnel design is the knowledge of and experience on tunnel construction.
- Library – archives – manuals.
- The consulting firms are advised to maintain a library accessible to all design staff with bibliographical references relevant to tunneling. The library must also contain complete series of relevant Standards (as applicable), Laws and Regulations.
- Finally, as a minimum requirement, all computer programs used in the tunnel design must be documented with their manuals.

### 5.5. Special recommendations

The underground structures are characterized by an inherent degree of uncertainty due to the surrounding ground or rock mass. The objective of the design is to reduce this uncertainty but at the same time to maintain a balance between uncertainty and construction cost. Thus, the issue of "geotechnical risk" becomes a major factor in tunnel design.

Another important consideration for a tunnel design is its link to the excavation method and construction. The phases of excavation, the equipment used for the various support measures, the timing of the entire excavation sequence and particularly that of the application of support measures are part of the tunnel design.

In this sense the following special recommendations for a tunnel design can be outlined.

#### 5.5.1. Geological – geotechnical risk

The best available scientific knowledge should be used in order to set up an accurate geological model for the tunnel site. The inevitable uncertainties concerning the ground/rock conditions should be identified and stated clearly in the design reports. The construction contract should then take care of the relevant risks. A concept that is worthy of consideration, is that of the Geotechnical Baseline Report. Risks associated to conditions consistent with or less adverse than those described in the Baseline Report are allocated to the contractor and those significantly more adverse than the Baseline Report are accepted by the owner.

In order to have the anticipated conditions clearly defined, the baseline statements should be described in quantitative terms that can be measured and verified during construction.

#### 5.5.2. Rock mass classification

The quality of rock mass and the relevant geotechnical parameters should be evaluated for every single tunnel case in order to reduce the geotechnical risk. It is preferable that the parameters used should be measurable, such as those suggested by the various rock classification systems (RMR, Q, GSI, etc.).

However, the indiscrete use of rock mass classification systems for contractual purposes and specifications should be avoided especially for weak rocks or fault zones.

#### 5.5.3. Guidelines for construction quality control

Tunnel design should specify in detail the necessary quality control to be applied during construction. An indicative list of the relevant topics is as follows (see Fig. 6):

- Rock mass classification.
- Detailed sequence and timing of excavation and application of tunnel support measures.

- Monitoring of stresses and deformations and relevant limits for emergency steps and remedial measures (design and construction modifications).
- Material specifications (shotcrete, rock bolts, etc.).

## 6. Construction

The construction phase of a project is defined as "the period of a project's development that commences with the award of the construction contracts and terminates with the commissioning of the structures" (Table 2).

### *6.1. Organisation – allocation of responsibility*

The establishment of a Quality System for construction management is very important for both the Client body and the Contractor.

#### *6.1.1. Client body*

It is recommended that the Project Manager of the Client body maintains the overall responsibility. At an early stage and prior to the commencement of construction the Construction Supervising Authority/Board is established. Depending on the size of the project this could be a small or a larger team. It is usually to the benefit of the project to have a strong supervision consisting of experienced personnel.

It is recommended that all works performed by the contractor are supervised and checked. The Client body is advised to bear the cost of the supervision in order to minimize the final time schedule and project cost overruns.

If deemed necessary, the Client body could employ a Quality Control consultant to assist with the technical issues. However, the authority of the construction supervision should be the responsibility of the Client and its Resident Engineer.

The Client's Resident Engineer is responsible to the Project Manager. A detailed job description should include the quality goals to be attained, frequency of reporting to the Project Manager, limits of authorization to handle contractual non-compliances by the contractor, resources allocated (personnel, vehicles, laboratory equipment, etc.).

All inspections of works should be documented and signed by the inspector. The inspection forms should comprise a short description of the performed works, items and quantities, time of application, compliance or not with the contract provisions, key remarks for the attention of the supervisor or the next shift inspector.

It is recommended a clear definition of the responsibilities and authority of the key inspection staff. Particular attention should be given to the following issues:

- Responsibility for rock classification.
- Extent of authority to handle design change requests.
- Handling of contract non-compliances.
- Responsibility for monitoring and surveillance.
- ITA recommends that the instrumentation is installed by the contractor, but the monitoring and evaluation of the tunnel behavior is performed by the Client's supervising team.
- Emergency procedures.

The inspection staff should be fully aware of the contract provisions and technical specifications. A complete contract review should be carried out by the Resident Engineer and the Supervisors. A list of the main items will be attached to the Construction Quality Control Plan.

#### *6.1.2. Contractor*

A basic activity in the early stages is to conduct a *contract review* which should include all technical as well as administrative requirements. In long duration projects and with a number of construction stages it is of vital importance that the contract review should be conducted prior to the commencement of these stages. It is recommended that the contract review should be conducted at planned stages and includes the various functions of the management and the production personnel.

Based on the early preparation for the work and the initial contract review, the contractor should set up an *organisation* that provides for sufficient allocation of the resources and competence. The allocation of responsibility is directly related to the planning of the works. For this reason, the Contractor's organization chart, job descriptions and qualifications of the key personnel is recommended to be subject to approval by the Client body.

The demands for specific *competence* (knowledge, experience, ability) should be evaluated prior to signing a contract. It is the responsibility of the contractor to secure an ample supply of competence throughout the construction phase. Identification and availability of back-up personnel should be regularly determined.

The *allocation of responsibility* should at least cover the following fields of activities:

- Supply of materials and parts.
- Evaluation and approval of suppliers and subcontractors.
- Equipment maintenance and repairs.
- Adherence to defined construction processes and procedures.
- Quality control of materials and works.
- Rock mass classification.
- Characterisation of tunnel support categories.
- Evaluation and handling of non-conformances. Preventive measures.
- Requirement for design changes.
- Handling of emergencies.

Table 3
Quality aspects related to tunnel collapses (Vlasov et al., 2001)

| | | Type | Phenomenon | Cause | Remedial measures |
|---|---|---|---|---|---|
| 1 | Ground collapse | Ground collapse near the portal | During the excavation of the upper half section of the portal, the tunnel collapsed and the surrounding ground slid to the river side | Ground collapse was caused by the increase of pore water pressure due to rain for five consecutive days | • Installation of anchors to prevent landslides<br>• Construction of counter-weight embankment which can also prevent landslide<br>• Installation of pipe roofs to strengthen the loosened crown |
| 2 | | Landslide near the portal | Cracks appeared in the ground surface during the excavation of the side drifts of the portal, and the slope near the portal gradually collapsed | Excavation of the toe of the slope composed of strata disturbed the stability of soil, and excavation of the side drifts loosened the natural ground, which led to landslide | • Caisson type pile foundations were constructed to prevent unsymmetrical ground pressure.<br>• Vertical reinforcement bars were driven into the ground to increase its strength. |
| 3 | | Collapse of the crown of cutting face | 10 to 30 $m^3$ of soil collapsed and supports settled during excavation of the upper half section | The ground loosened and collapsed due to the presence of heavily jointed fractured rock mass at the crown of the cutting face, and the vibration caused by the blasting for the lower half section (hard rock) | • Roof bolts were driven into the ground in order to stabilize the tunnel crown.<br>• In order to strengthen the ground near the portal and talus, chemical injection and installation of vertical reinforcement bars were conducted. |
| 4 | | Collapse of fault fracture zone | After completion of blasting and mucking, flaking of sprayed concrete occurred behind the cutting face, following which, 40 to 50 $m^3$ of soil collapsed along a 7 m section from the cutting face. Later it extended to 13 m from the cutting face and the volume of collapsed soil reached 900 $m^3$ | The fault fracture zone above the collapsed cutting face loosened due to blasting, and excessive concentrated loads were imposed on supports, causing the shear failure and collapse of the sprayed concrete | • Reinforcement of supports behind the collapsed location (additional sprayed concrete, additional rock bolts)<br>• Addition of the number of measurement section<br>• Hardening of the collapsed muck by chemical injection<br>• Air milk injection into the voids above the collapsed portions<br>• Use of supports with a higher strength |
| 5 | Distortion of supports | Distortion of tunnel supports | During excavation by the full face tunneling method, steel supports considerably settled and foot protection concrete cracked | Bearing capacity of the ground at the bottom of supports decreased due to prolonged immersion by ground water | • Permanent foot protection concrete was placed in order to decrease the concentrated load.<br>• An invert with drainage was placed. |
| 6 | | Distortion of lining concrete due to unsymmetrical ground pressure | During the excavation of the upper half section, horizontal cracks ranging in width from 0.1 to 0.4 mm appeared in the arch portion of the mountain side concrete lining, while subsidence reached the ground surface on the valley side | Landslide was caused due to the steep topography with asymmetric pressure and the ground with lower strength, leading to the oblique load on the lining concrete | • Earth anchors were driven into the mountain side ground to withstand the oblique load.<br>• Ground around the tunnel was strengthened by chemical injection. Subsidence location was filled. |

Table 3 (*continued*)

| | | Type | Phenomenon | Cause | Remedial measures |
|---|---|---|---|---|---|
| 7 | | Distortion of tunnel supports due to swelling pressure | Hexagonal cracks appeared in the sprayed concrete and the bearing plates for rock bolts were distorted due to the sudden inward movement of the side walls of the tunnel | Large swelling pressure was generated by swelling clay minerals in mudstone | • Sprayed concrete and face support bolts on the cutting face were provided to prevent weathering.<br>• A temporary invert was placed in the upper half section by spraying concrete. |
| 8 | | Heaving of a tunnel in service | Heaving occurred in the pavement surface six months after the commencement of service, causing cracks and faulting in the pavement. Heaving reached as large as 25 cm | A fault fracture zone containing swelling clay minerals, which was subjected to hydrothermal alteration, existed in the distorted section. Plastic ground pressure caused by this fracture zone concentrated on the base course of the weak tunnel section without invert | • In order to restrict the plastic ground pressure, rock bolts and sprayed concrete were applied to the soft sandy soil beneath the base course.<br>• Reinforced invert concrete was placed. |
| 9 | Adverse effects on the surrounding environment | Adverse effects of vibration due to blasting on the adjacent existing tunnel | During the construction of a new tunnel, which runs parallel to the side wall of the existing portal, cracks appeared in the lining (made of bricks) of the existing tunnel | The voids behind the existing tunnel loosened and the lining was distorted due to the vibration of the blasting for construction of the new tunnel | • Steel supports and temporary concrete lining were provided to protect the existing tunnel.<br>• Backfill grouting was carried out.<br>• Excavation was carried out by the non-blasting rock breaking method and the limit for chemical agent was set to mitigate the vibration. |
| 10 | | Ground settlement due to the excavation for dual-tunnel directly beneath residential area | Considerable distortion of supports occurred in the embankment section. Although additional bolts were driven into ground and additional sprayed concrete was provided, ground surface settlement exceeded 100 mm | Since the soil characteristics in the embankment section were worse than expected, the ground settlement was considerably increased by the construction of tunnels following the dual-tunnel | • Pipe roofs were driven from inside the tunnel to reduce ground surface settlement. |

Summary table of different conditions for tunnel collapses, caused by geological unforeseen conditions, inadequacy of design models or support systems.

Fig. 6. Collapse due to a sinkhole in the crown of loosen material in a tunnel supported by steel arches and shotcrete.

- Health, safety and environmental protection measures.
- Communication and amicable resolution of disputes with the Client's representative.
- Reporting to both the Client and the top management of the company.

### 6.2. Communication and development of competence

Tunnelling and underground projects in many ways represent a situation of continuous education. Given that basic competence requirements are determined, a refinement of the project management systems and upgrading of the required/formal knowledge should be conducted. It is recommended that the contractor's organisation establishes education plans for the various functions or parts of the organisation.

Tunnelling projects are well suited for "On the Job Training." Such training could preferably be directed towards construction methods and the operation of equipment. In establishing the programs, necessary coordination with the client/designer and equipment supplier is essential.

The communication of all the involved personnel of both the Contractor and the Client is vital during the construction phase. The Client's supervising team should hold regular meetings preferably on a weekly basis to discuss the progress of the work and whether the set quality goals have been obtained or not. If delays or contract non-conformances are registered on a regular and systematic basis, then preventive and remedial actions should be discussed and implemented.

Similar meetings should be held by the Contractor with the participation of the Site Manager and all Section Foremen and Supervisors.

Regular meetings should also be held between the Client's and the Contractor's representatives. The main topics for discussion should be the progress of work, the conformity to the technical specifications, the applicability of the design provisions, the Contractor's response to the Client's requirements, the regularity of payments, and the resolution of any responsible problems. These meetings should be conducted in a spirit of cooperation. The job of the site personnel is to implement the provisions of the contract.

Any arguments or disputes arising from different interpretations of the contract clauses should be referred to a higher level. If necessary, a permanent panel of experts, with representatives from both parties, should be appointed in order to objectively review the overall progress of the works. The conclusions of such a panel should be taken into consideration by both parties.

### 6.3. Construction quality plan

A basic part of the construction management system is the Construction quality plan. The plan should give guidelines for all important functions and activities. It is recommended that quality plans be established, continuously refined/developed and thoroughly communicated within the organization. The contents and practice of quality plans may vary within the tunnelling and underground community – but the essential parts to be treated should be:

- Establishment and communication of quality goals.
- Contract review, control of drawings and specifications.
- Organization, administration, and document handling.
- Description of construction processes and procedures.

It is recommended that construction methods and processes, including equipment requirements, should be evaluated and approved by competent personnel, and if desired or required, by a representative of the Client or a third party. If a process is innovative, a testing program prior to production should be conducted.

This type of validation of a process or procedure should also aim at supplying the production personnel with sufficient competence as well as at determining the amount of documentation needed to verify the results. As the amount of technical documentation often represents a point of conflict between the client and the contractor – a validation process can contribute to a common understanding.

- Inspection and test plans.

It is recommended that verification activities conducted by the client or third parties be clearly specified in the plans. Test results requiring evaluation by others and that such evaluations may introduce constraints on the progress shall be highlighted. Reference is made to previous discussion on iterative processes leading to design and construction modifications.

- Evaluation and qualification of suppliers and subcontractors.
- Handling of non-conformances and follow up of preventive measures.
- Handling of design and project changes. A detailed procedure will provide necessary guidelines for any contract updating.
- Systems follow-up and improvement based on audits and management review.

The contractor's management should genuinely be committed to the establishment and development of the quality management system for a project. A basic part of the system is the quality plan. The concept of management review should be adopted in all major tunnelling and underground contracts. Items to be evaluated are:

- Quality goals – current performance and effectiveness of the management/quality system.
- Non-conformance – statistics, determination and effects of preventive actions.
- Evaluation of processes and procedures both technical and administrative.
- Educational plans.
- Audit plans with results from both external and internal audits.

### 6.4. Special recommendations

Experience has shown that during construction certain issues have direct impact on the quality goals and in the following these special recommendations are emphasized.

#### 6.4.1. Quality control and quality testing

Adherence to procedures for control and testing is respected by all personnel right from commencement of construction. A management commitment explicitly stated in writing will facilitate the adherence to relevant procedures.

#### 6.4.2. Design applicability and design changes

It has been emphasized throughout this report that design changes during construction cause chain reactions and normally have implications on the project cost and completion time schedule. It should be made clear that generally no major design changes will be allowed during construction, except for minor adaptations to the applied construction method and equipment.

It is recommended that clear and strict clauses should be included in the contract with the aim of minimizing any requests for tunnel design changes by the contractor. However, it is recognized that the in-situ adaptation of the design to the real rock/ground conditions might be necessary. As discussed earlier, provisions for such conditions should be included in the contracts (Table 3).

#### 6.4.3. Construction documentation

Detailed, accurate and timeous data recording is very important in tunnelling. These records facilitate the back analysis of the tunnel performance and the causes for possible failures, assist in the future maintenance of the tunnel but are also the main source of information for the resolution of future disputes and claims.

Thus, a complete record of all relevant construction data should be kept by the Contractor and a copy of it given to the Client at regular intervals, as specified.

The recorded data should include the geological mapping of tunnel face, roof and sides with all the relevant geological, hydrological and geotechnical information, sequence and method of excavation and support measures with respective timing, installation of instrumentation and measurements, as-built drawings, any special operation and maintenance requirements. The construction data should be subject to document control procedures in order to eliminate any malpractice of data alteration or loss of data.

#### 6.4.4. Environmental considerations

The construction of a tunnel generally causes less environmental disturbance than other projects of comparable size. The organisation and layout of the construction activities should take care of the environment. The disposal areas must be carefully selected in order not to cause public reaction. If the waste disposal is permanent, the design must make provisions for the complete rehabilitation of the environment. The use of chemicals and toxic compounds should be approved by the Client and relevant authorities. Dissolution of nitrous compounds may have adverse effects on ground- and surface water and the consequences should be assessed.

## 7. Operation and maintenance

The operation and maintenance phase is defined as the period after the works have been commissioned.

As far as this stage is concerned, it is necessary to evaluate particular conditions that require special attention in order to establish effective quality procedures. As a part of the commissioning it is necessary to conduct a formal acceptance of the structural properties as well as the various technical installations.

It should be underlined that the Operation and Maintenance concepts should be evaluated at an early stage of the design and any an eventual *Operation and Maintenance Manual* be prepared with the cooperation of the Contractor.

The operation phase involves the regular inspections of linings and installations and the checking of the regular operating conditions of the tunnel as planned in the design stage. The maintenance, intended as either restoration or significant modification of the linings and the installations, cannot always follow the same acceptance criteria as new tunnels, because the standards evolve with time and it is impossible to expect all old tunnels to comply with the new standards (safety, cracking of lining, etc.). In case of technical problems for adaptation, limitations for use should be introduced.

The main expenditures of the operation phase are due to installation operations, safety facilities, maintenance needs and insurance fees.

From the contractual point of view, the term maintenance is normally used to refer to the various tasks involved with the upkeep of the physical structure of the facility as opposed to the day to day running of its duty. The term operation is understood to encompass the latter.

The ultimate purpose of an operation/maintenance contract is generally to ensure the facility performs the way intended and to the standard required by the owner and the law. At such, it seeks to attract the commercial interest of the operator in the life cycle cost of the project, motivating the operator to consider the future maintenance costs of a project as it carries out its design and construction obligations (Table 2).

### *7.1. Organisation. Allocation of responsibility*

It is recommended that the owner of a tunnel or underground structure establishes an organisation that is well suited for and competent to evaluate and conduct repair works and improvements. Public transportation structures should have an organisation that is qualified for daily operations and maintenance. The responsibility for the structure's fulfillment of national or otherwise valid safety regulations should be clearly defined.

The owner's organisation (or the concessionaire) should have access to all design prerequisites, design parameters, rock or soil characteristics (as measured) and all test and inspection data. If the organisation does not have expertise in the fields of structural analysis or installations design, contracts should be established to provide for instant assistance.

It is recommended that the physical condition and the inherent risk of failure is calculated or otherwise verified at regular intervals with respect to structural conditions (rock, soil, support- and lining structures), environmental aspects within and outside the structure (water, smoke, seepage of chemical compounds) and the functioning of the technical installations. The responsibility for this checks lies mainly to the Owner, who also sets for the relevant safety criteria. For public transportation structures the safety level of the daily operation should be assessed at regular intervals. Preventive actions and necessary repair work should be identified.

In addition to a regular inspection plan, the organisation should establish an inspection aimed at examining the physical conditions and prerequisites, operation and maintenance procedures as well the organisation's ability to handle operational and safety aspects.

The inspection plan should include the survey of lining conditions, eventual progressive damages and evaluation of repair reports and significant monitoring data.

### *7.2. Development of competence*

The owner's organisation should establish a plan for the continuous education of its personnel in order to provide necessary competence for the daily operation and maintenance. External expertise should be sought, if not available within the owner's organization. This could be true for particular monitoring in which the use of instrumentation is a specialistic way.

Transfer of knowledge from design and construction should be conducted according to approved plans and, as stated earlier, according to contract specifications. Internal communication and motivation should be based on available statistical data and experience from the operation as well as project and design prerequisites and data from construction and testing.

It is recommended that the owner's organisation establishes a library containing all relevant technical information as well as relevant laws and regulations. It is fundamental that each tunnel has its own record/data base.

### *7.3. Time aspects*

The text that follows should rather have a different title than "Time Aspects" e.g. "Operation Criteria".

It is obvious that external requirements and prerequisites change during the lifetime of an underground project. Methods for structural and geotechnical analysis have been refined over the years. Any underground project should be re-examined with respect to structural conditions when considered necessary or when applicable technical standards are revised (see Table 2).

The effects of environmental impacts (landslides, floods, earthquakes, etc.) shall be assessed. Technical and traffic regulating installations should be subject to similar evaluations (see Table 1).

Cost estimates should be carried out with the aim of determining the most cost effective scheduling of maintenance, repair works and improvements.

### 7.4. Special recommendations

#### 7.4.1. Operational tools for large scale and critical projects with extensive public use or involvement

The following aspects are recommended for the Operation and Maintenance stages:

- Records of complete documents regarding site investigations, planning results, design assumptions and analyses, "as built" drawings and technical specifications, test records, instrumentation monitoring, statistical data.
- Identification of the involved professional people and organisations.
- Summary tables with information about geological decisions, selection of support systems/structures and the materials used for waterproofing, injections, additives etc.
- Provisions for Safety.
- Environmental monitoring with regard to interference with wells, springs, flammable gases, accidents with fires, etc.
- Monitoring of the critical areas, portals, crossing of faults etc.

The tunnel becomes a product with some data that can no longer be modified (geology, excavation method) and with others that can be updated and modified (monitoring, conditions of the linings, hydrogeological regimes, conditions of the installations, conditions for use, etc.).

It is necessary to have three operational instruments:

1. *Approval test* (Pelizza et al., 2000). The test results from the construction stage constitute the basis for the observations as the tunnel is commisioned/consigned. The results should give the qualitative and quantitative indications of the measurements that have been carried out measuring displacement, load and hydrogeological conditions.
2. *Operation and inspection procedures*. A Manual with the visual inspection and instrumental monitoring plan should be prepared by the Owner following the indication of the Designer to function for the type of works and the final lining. The frequency and the extent of the inspections should be stated. The installations should be verified regularly and any anomaly noted.

The responsible parties for the inspection and monitoring are usually the field Engineers appointed by the Committent; they can have both a technical and an administrative role.

3 *Maintenance procedures*. The maintenance and substitution or adjustment interventions should be planned to minimise disturbance of the use of the tunnel. The interventions when it comes to repair works for the linings vary considerably depending on the type of damage and the reasons for 'failure'. The maintenance and repair interventions should also be verified through adequate testing procedures.

It should be differentiate between "maintenance" and "repair" works. The maintenance should be prescribed in the Operation Manual and it should be regular, whereas the repair is necessary in case of damage or in order to prevent damage or failure. Recommendations for the necessity of repair works should be included in the Evaluation Report of the Inspection and Monitoring.

Finally, communication with external organisations is strongly recommended and should be encouraged (for example with universities) as far as relevant statistical data are concerned (frequency, cause and repair interventions) in order to validate the maintenance measures and procedures.

#### 7.4.2. Approval tests

The approval test has the purpose of verifying and certifying that the tunnel has been excavated according to regulations and established technical specifications in agreement with the contract, design modifications and approved procedures. The approval test should above all be accompanied by instrumental tests, whose amount and type is decided according to the specific situations.

In general this procedure will lead to a "*final commissioning certification*" or "**approval certification**".

The structural test, considering the type of work here dealt with and the consequent impossibility of completely inspecting it when finished, should be performed during the construction phase.

The commissioning certification procedures should include:

- Type of tunnel and its conformity to general (state) technical and safety criteria (or requirements).
- Verification of those who are involved in the works and the administrative procedures.
- Examination of the constructed project and verification of the conformity of the works.
- Verification of the technical reports.
- Verification, when it is possible, of the results of any legal and technical claims; these claims seldom are re-

Table 2
Practical quality assurance in tunnelling example of tables

| Tunnelling stage: Geological and topographical surveys | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Definition of directions and interconnections | Uses, functions, future trends | Inadequacy of informations | Appropriate preliminary studies | |
| Design and characterization | Study of geometry and formations. Installations for geophysical surveys and drilling | Geology, hydrogeology, geotechnics, type of work, occurrence of gas and karst. Technical references. Adequate timetable | Wrong characterization and inadequate geometry for traffic evolution | Preliminary studies and investments | |
| Financing, procurement and contractual phase | Evaluation of alternatives | Basic elements for choices of suitability of the work | Incomplete evaluation of the whole project Possible increase of controversies | Evaluation of alternatives | Accurate balance between investments for investigations and risk mitigation |
| Construction and monitoring | External and underground controls and investigations | Details of rock and soil formations, definition of profiles and geometries. Adequate timetable | Unexpected conditions, difficulties for supplying of construction materials | Training, appropriate site inspections | Great delays if inadequately considered |
| Operation and maintenance | Verification of changes in conditions | Change of conditions, both for designed and involved aspects | Difficulties in the operation; excess of cost for maintenance | Record of data | |
| **Tunnelling stage: Hydrogeology and environment** | **Step of the work** | **Concerned elements** | **Negative effects** | **Actions** | **Notes** |
| Work planning | Evaluation of influences on the environment including water sources | Natural and modified conditions, at short and long time scale. Special awareness for subsea tunnelling. Location of landfills | Water pollution, settlements, vibrations, traffic | Severe regulations and studies | Basic decision stage |
| Design and characterization | Investigations and simulations | Water flow, modifications of traffic conditions, influence on stability | Undesired damages to structures and natural resources | Adequate investments for studies | |
| Financing, procurement and contractual phase | Detailed description of constraints | Adequate estimates for rock support. Environmental consequences, for example ground water table, vegetation | Additional or new costs | Allocation of responsibilities, delays | External costs |
| Construction and monitoring | Application of methods for reduction of damages | Water quality, dust and vibration controls. Muck disposal | Nonconformities, claims | Procedures for prevention and mitigation | Critical phase for claims |
| Operation and maintenance | Constant control of environmental parameters | Analysis and mitigations | Increase of pollution, loss of credibility | Respect of traffic limitation and regular maintenance | |

Table 2 (*continued*)

| Tunnelling stage: Design and construction concepts | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Selection of the geometry of the work and of installations | Type of the work, size and shape, profile. Use of reamer TBM | Inadequacy of the methods or type of work | Experience and lessons learned from similar cases. Adaptability of the project parameters | Discussions and agreements with external parties. |
| Design and characterization | Selection of parameters and design methods | Overburden, water, faults, settlements, accessibility. Evaluation of landslides and rock fall | Accidents, damages, instability, delays and additional cost | Revision of the design and risk assessment | Fundamental step of the whole process |
| Financing, procurement and contractual phase | Detailed description of costs and supplies | Complete knowledge of alternatives; Selection of the appropriate type of contract | Difficulties for the relationship with the involved parties; Resolution of contract | Prepare detailed contracts and establish severe economic constraints | In this step economics, regulations and engineering must agree completely |
| Construction and monitoring | Selection of construction method (traditional or mechanized) and site measurements; landfilling or rock waste recovery | Selection of equipment, personnel, instrumentation, organization of the personnel and phases. Particular conditions for microtunnelling and subsea crossing. Control of blasting cross sections | Surface occupation, vibrations, dust, settlements, stability of landfills | Detailed and daily control by the field engineers | Fundamental step of the whole process. Daily discussions and claims. |
| Operation and maintenance | Provisions for future works | Provisions for future work. Performance of the installations | Difficulties for maintenance and inspections | Provisions of the state of the tunnel after long periods of use | |

| Tunnelling stage: Rock support and reinforcements | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Type of support elements and reinforcing techniques | Geologic formations. Surface tunnels. Works in urban areas | Inadequate support | Further verification in design. Vibration and noise | Coordination with surface structures in urban areas. |
| Design and characterization | Detailed description of type, quantity and time for adoption of support and eventual reinforcing elements | Calculation methods, mechanized equipment. Organization of the operative timetable. Rock burst. Prevention of sink-holes and water inflow | Inadequate support | Observational methods; lessons learned | It is a fundamental stage for stability and safety |
| Financing, procurement and contractual phase | Consideration of the alternatives | List of costs | Delays and additional costs | Refine design | |
| Construction and monitoring | Installation of the support and preliminary or late reinforcing element; measurements. Particular attention for urban areas and surface tunnels | Equipment, type of support, type of reinforcing, verification of adequacy of used support systems. Techniques for face reinforcement | Failures, collapses, subsidence | Observations and measurements; respect of the design | Fundamental phase of the whole process |
| Operation and maintenance | Evaluation of long term behaviour | Stability | Failures | Periodic monitoring, careful to new external conditions | |

| Tunnelling stage: Sealing and linings | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Objective of the drainage and type of final lining | Hydrogeology of the formations | High stresses on linings; excess of drainage | Detailed studies. Monitoring of stresses and piezometric conditions | |
| Design and characterization | Detailed selection of materials. Proved experience for precasting firm | Rock and soil parameters; Type of geosynthetics; quality of the concrete. Heavy stresses due to water pressure | Inadequacy of the choices | Experience from similar cases | |
| Financing, procurement and contractual phase | Preparation of dedicated report | Influences on the surrounding environment | Claims, delays and extra costs | Allocation of responsibilities | Several claims with external parties. |
| Construction and monitoring | Proper installations. Selected procedures for mechanized tunnelling, both in small and large diameter | Choice of materials, organization of the work | Unexpected flows and subsidence | Prevention; special materials. Fast countermeasures | |
| Operation and maintenance | Regular controls | Verification of damages and measurements | Degradation of linings | Planning of works | |

| Tunnelling stage: Excavation and construction equipment | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Selection of equipment | Safety, increase of mechanized phases, organization | Inadequacy of the machinery; Delay due to mechanical problems. Contract's renegotiation. Resolution | Verification of similar cases, adequate organization | The choice of the equipment is the most important feature which determines the evolution of the work. |
| Design and characterization | Selection of methods and reuse of waste | Geometry, power, pollution, organization of phases | Limitations for space, inadequacy of safety devices. Training of personnel | Preliminary adaptation to the tunnel conditions | |
| Financing, procurement and contractual phase | Evaluation of important investments (TBM) | Detailed knowledge of equipment and work organization | Large loss of time and increase of costs | Adequate consideration for the machinery suppliers and maintenance | |
| Construction and monitoring | Power supply, proved organization in particular for mechanized tunnelling | Geometry, phases, velocity of advance. Anti-detonating devices. Treatment of EPB-Slurry shield muck | Safety of personnel, delays, increase of costs | Adoption of well tested equipment with preliminary field tests | |
| Operation and maintenance | No influence | No influence | No influence | No influence | |

Table 2 (*continued*)

| Tunnelling stage: Installations and safety | Step of the work | Concerned elements | Negative effects | Actions | Notes |
|---|---|---|---|---|---|
| Work planning | Type of work | Traffic, geometry, regulations. Preventive actions | Consequences at each level of damage, both in construction and operation | Prevention; quick counter-measures | Fundamental for the modern acceptance of the work. |
| Design and characterization | Choices of ventilation, lighting, escapes | Access, length, secondary installations. Amount of personnel in the tunnel | Inadequacy of installations. Controversies | Select the heavy operation conditions | Very high responsibility. |
| Financing, procurement and contractual phase | Consideration of present safety standard | Technical requirements for installations | Inadequacy of regulations | Important investments, also in training and communications | |
| Construction and monitoring | Verification of good materials and equipment | Acceptability tests. Rescue devices and procedures | Nonconformities. Suspension of the construction | Detailed field controls | This is the crucial phase for the effective safety of the workers. |
| Operation and maintenance | Regular functioning of the equipment | Respect of updated regulations and procedures. Rescue devices and procedures | Accidents, at each level | Prevention, periodic tests and increase of performance | This is the crucial phase for the effective use of the structure. |
| Tunnelling stage: Monitoring, maintenance and statistics | Step of the work | Concerned elements | Negative effects | Actions | Notes |
| Work planning | Report of the statistical data of the tunnel | Measurements, used materials, new works | Problems for the use of the structure | Periodic adaptation of the structure | Adequate organisation, data base, planning of maintenance works. |
| Design and characterization | Selection of adequate measurement types and indication of future work requirements | Materials, alterations, pollution | New costs | Indication of methods for periodic inspections | |
| Financing, procurement and contractual phase | Contract details | Data base of the tunnel. Periodic controls and repairs | Unappropriate allocation of costs | Clear definition of contract roles | |
| Construction and monitoring | Use of corrected procedures and materials | Phases and adopted materials | Loss of technical documents and unexpected damages | Complete record of each tunnelling phase | |
| Operation and maintenance | Organization of roles | Measurement and maintenance planning | Degradation of the work | Adequate investment for the improvement of operational conditions of the work | |

For each underground work it is suggested to resume in a series of tables the various interacting phases, both as time evolution and actions are concerned to determine a direct or indirect influence on the success of the work. The result of these tables should be a pragmatic tool. A simple example from whom any adaptation is possible, is shown in the following.

Fig. 4. Diversion in road tunnel, conventional tunnelling (Bolzano, Italy, courtesy S.Tua, Soc.It. Condotte d'Acqua).

Fig. 5. Hydroelectric tunnel, mechanized tunnelling (Bormio, Italy, C. Oggeri with permission of M.Concilia, SELI).

solved prior to the commissioning of a tunnel. In that case they should not be dealt with in such a final approval report; any substantial modification to the original project should be verified.

- Examination of the statistical data of a construction type, including any deduced from the quality plan.
- Examination of the materials used in the construction.
- Examination of the instrumentation measurements carried out during the work and those performed during use of the tunnel.
- Examination of any extraordinary situation.

*7.4.3. Operation and inspection procedures*

These procedures are in particular dedicated to safety when a tunnel is used for the transport of goods or people.

The procedures should include:

- the availability of a general plan for the use of the tunnel (permitted traffic, working personnel) and of the safety (escape routes, fire extinguishing systems, smoke detectors),
- management of geotechnical, hydrogeological and environmental instruments,
- management of safety installations and systems,
- information for the users and for the operating personnel,

- acquisition of statistical data,
- periodical inspection plan of the tunnel in working and non-working conditions of both structures and installations.

*7.4.4. Maintenance and repair procedures*

The maintenance stages should include:

- the availability of a technical manual in which the construction details of the various sections of the tunnel, the encountered geological formations and problems;
- an examination of the available monitoring equipment;
- an examination of the results from the previous inspection stages and any remedial interventions already carried out;
- a detailed inspection through non-invasive techniques (photographic, thermographic and georadar surveying) or even invasive techniques (core drillings and destructive tests);
- maintenance and remedial interventions;
- entrusting of the works to specialised companies;
- testing of the performed interventions.

The repair procedures are part of a detailed design, as they involve sustantial modification of the actual situation. For this reason, design documents should list all the specific stage for the works.

## 8. Conclusions

*8.1. Updating*

Quality is a concept that is constantly evolving. There are unique features in tunnelling due to the great number of involved parties, both in minor and in major projects and due to the non-repeatable nature of tunnels. However, the trend of the concept of quality, in this field, is towards both a good planning / management and suitable technical results.

In December 2000 the ISO committee introduced a revised version of ISO 9000:2000 series for quality management systems based on management principles:

1. Customer focus.
2. Leadership.
3. Involvement of people.
4. Process approach.
5. System approach to management.
6. Continual improvement.
7. Factual approach to decision making.
8. Mutually beneficial supplier relationships.

These principles are defined in ISO 9000:2000 "Quality management systems – Fundamentals and vocabulary", and in ISO 9004:2000 "Quality management systems – Guidelines for performance improvements".

It would be useful to correlate these points to the different aspects of tunnel construction and especially to the operation and maintenance phases in order to create a proper standard management approach to these operations.

Operation and maintenance of the tunnel can easily be connected to some of the previous points:

1. Customer focus

It is not possible to do anything without considering the customer aspect; both the client who pays for the construction of the tunnel and the general public who at the end use the tunnel should be considered as "customers".

It is of primary importance to consider the customer's needs and satisfaction to plan the operation mode of the tunnel and to decide how and when to carry out the maintenance works, i.e.: not to plan the maintenance of road tunnels during holiday periods

2. Leadership and
3. Involvement of people

It can be useful to define in advance the various responsibilities for the different areas or aspects of the work to ease the solution of possible problems during operation phase or during emergency repairs.

4. Process approach

Definition of procedures for the various activities and co-ordination.

5. System approach to management

Scheduling the maintenance in advance, from the building phase, to be able to operate before real damages occurs to the structure and installations, to be able to allow a continuous functioning of the structure.

6. Continual improvement

The maintenance phase in itself is based on the idea of a continuous improvement and should be approached with such a goal in mind.

7. Factual approach to decision making

All decisions should be converted into interventions on the basis of correction and prevention criteria, following the experience obtained from data control and statistics processing.

8. Mutually beneficial supplier relationship

New materials, new construction technologies and the special requirements for underground works should always be compared, in order to improve safety and usability standards.

Energy savings can also be obtained moving by a simple and rational planning towards a correct organization of transportation, the development of railroads and roads systems etc.

*8.2. Summary of recommendations*

Quality is the sum of the client's needs and expectations and the level of performance achieved by satisfying the needs, whether delivering a service or a structure.

In tunnelling there are two levels of quality as far as performance is concerned. One is related to the use and efficiency of the underground structure, and this is taken into account during the planning and operation phase. The other is related to the characteristics of the works, and this is taken into account during the design and construction phase.

Quality goals as far as expectations are concerned are linked to the adherence to the construction programme, keeping within foreseen costs and limiting the number of claims.

These desired features can be fulfilled through well planned and controlled stages (Muir Wood, 2000):

- planning during which the effective needs are highlighted;
- progressive investigation and monitoring;
- well defined preliminary design;
- correct choice of the type of contract, conditions of contract, financing and procurement procedures, depending on the type of project;
- well considered design with verification of both the technical and economical aspects;
- appointment of consultants and auditors for all the phases including the commissioning and approval.

In general if the scheduled actions, the design requirements, the indications of the investigations and the contractual rules are observed, a good result for the work is possible.

Each involved party should estimate and describe the uncertainties and risks that are connected to their responsibilities such as the owner for the planning and for the tender and the project manager for the coordination and financing.

These responsibilities should be assigned taking due cognisance of the type of contract/contract conditions and national laws and regulations. Eurocode 7 on Geotechnical Design is an example of detailed technical recommendations for the geotechnical investigation and design.

The final objective for quality in tunnelling is to limit the number of uncertainties, whether these are related to communication, allocation of risk, technical or financial issues.

Procedures should be activated in order to guarantee the transferring of experiences and knowledge, for example by exchange of informations with universities and other independent cultural associations.

## 9. Working Group Members May 1999 – March 2003:

| | | | | |
|---|---|---|---|---|
| Jindrich Hess | Metrostav | Prague | Czech R | WG Tutor |
| Kai A Sorbraten | Vannkraft Ost | Lillehammer | Norway | Former WG Tutor |
| Claudio Oggeri | Politecnico di Torino | Torino | Italy | Animateur |
| Renato Arfé | Cavet | Bologna | Italy | |
| Gunnar Ova | Selmer Skanska AS | Oslo | Norway | Former Animateur |
| Vasso Stavropoulou | Consultant | Athens | Greece | Vice Animateur |
| Ulrika Hamberg | Vagverket | Stockholm | Sweden | |
| Tina Helin | Skanska International | Lima | Peru | |
| Takahiro Aoyagi | Kajima Corporation | Tokyo | Japan | |
| Takashi Fujita | Kajima Corporation | Tokyo | Japan | |
| Karl Kuhnhenn | BUNG GmbH | Heidelberg | Germany | |
| Mike Trissler | | Uhmlanga Rock | South Africa | |
| Jiri Belohlav | Metrostav | Prague | Czech R | |
| Joe Kellogg | Kellogg Corporation | Denver, CO | USA | |
| Gerard M. Letlatsa | LHTP | Maseru | Lesotho | |
| Ntsoeleng Mohale | MCG | Maseru | Lesotho | |
| Weining Liu | NJTU | Beijing | China | |
| Maeng Doo Young | Kistec | Seoul | South Korea | |
| Vanjia Keindl | Ministry of Environmental Protection and Physical Planning | Soel | South Korea | |
| Hae-JinOH | CHEIL Engr. Co | Soel | South Korea | |

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| | |
|---|---|
| Sir Alan Muir Wood | United Kigdom |
| Ola By | Norway |
| G. Mazzoleni | France |
| Jean Paul Godard | France |
| Francois Vuilleumier | Switzerland |
| Harald Wagner | Austria |

## 10. Report Summary

The recommendations of the report on Quality in tunnelling are aimed to give practical guidelines to the various parties engaged in tunnelling projects during the different stages of a project. Since the basis for a successful tunnelling project is often related to careful planning and management rather than isolated inspections and tests, this report focuses mainly on quality management measures, including iterative processes with the objective of securing adequate and updated quality plans and procedures at any stage. Project prerequisites and risk assessment are dealt with in different sections of the report, recognizing the importance of these topics.

The report has been arranged according to different project phases and give specific recommendations for each phase. For practical reasons the WG has chosen to handle procurement as a project phase, even though the procurement activities can be related to all stages of a project. It should be noted that the different project phases described are not completely separated from each other. The need to identify interactions between phases and between project participants is crucial to the success of any tunnelling project.

The Working Group has adopted the following objective for the work:

> To give recommendations on how to achieve Quality in Tunnelling and how to identify, evaluate and specify Quality Management measures to be taken by all parties in the Conceptual Planning, Procurement, Design, Construction, Operation and Maintenance phases of underground projects involving tunnels.

Reference to and use of updated recommendations produced by international or national sister organizations (ISRM, ISSMFE, IAEG etc.) and other professionally developed documents (such as the Eurocodes by European Committee for Standardization) is encouraged.

The meaning of *"Quality"* is *"The totality of features and characteristics of a product or service that bear upon its ability to satisfy stated or implied needs"*.

In tunnelling the "stated needs" of the Employer could mean the construction of a tunnel in accordance with the technical quality defined by the Employer (i.e. technical specifications), within the estimated budget and predefined time schedule or programme. The "implied needs" are multifold and could be respect for laws and regulations, safety aspects, environmental protection, energy savings and sustainability of the works. It is of fundamental importance that the prerequisites are continuously updated and met both during construction and the operation phases.

*"Quality Management"* means *"all those systematic actions that are necessary to provide adequate confidence that a product or service will satisfy given quality requirements"*. It is difficult to completely assure quality in tunnelling, especially by third-party organisations. For this reason it is recommended the adaptation of "quality management" to tunnelling projects rather than quality assurance rules. Suggestions for comprehensive approaches are given in the report rather than prescriptive routine control and testing activities.

All along the project a coordination of activities is necessary in order to reach significative results for:

technical features
economical results
contractual agreements
environmental effects
safety standards

All these goals can only be obtained by means of high professionality, self responsibility, clear requirements.

The rational development of scheduled activities is one of the main instrument for success. Other suggestions for good results show the importance of knowledge of state of the art and of case histories which have given problems.

As the non-quality is clear when:

1. time for providing the work are exceeded
2. new costs alter the budget
3. claim within the involved parties occur without resolution
4. controversies between the project parties and external arise
5. accidents and failures determine loss of lives or goods

the quality procedures should coordinate each action aimed to:

1. a good knowledge of the geologic formations
2. evaluate the interaction between the tunnel structure and the surrounding environment
3. evaluate any development on a long time base

Uncertainties in tunnelling projects arise from the inability to study the complete structure and behaviour of the rock and soil formations in such detail that all possible scenarios can be contemplated. It should be emphasized that tunnel failures have been the result of various reasons such as insufficient site investigation, inadequate evaluation at the planning stage, mistakes during construction and operation phases.

An inventory of inherent risks for the project phases should be undertaken for all tunnelling and underground projects. Risk assessment should be made for:

- Rock and soil conditions versus the stability, physical properties and seepage
- Construction methods versus progress, rock/soil conditions, environment and safety
- Equipment versus suitability, capacity, energy consumption, environmental and safety aspects

The consequences on the total project cost and financial matters should always be included in risk evaluations.

Site investigations and geological exploration and their use in design optimisation, coupled with well matched construction techniques, can prevent most kinds of collapses. The design cannot only be based on a deterministic approach for the evaluation of a risk, a probabilistic approach that takes into account the uncertainties in the geological, geotechnical and construction techniques and external constraints will enable the project management to optimize the final design and define the technical, administrative and financial management of the risk.

It is recommended that detailed paragraphs dealing with risk allocation should be included in all contracts or agreements, and that risk is distributed by taking into consideration both technical and financial aspects.

Contractual procedures should be simple and the role of the various parties should be made extremely clear, both from a technical and financial point of view. Excessive legal and bureaucratic complexity should be avoided, but specific attention should be given to those contractual aspects that deal with the information obtained on the natural ground conditions.

Among the aims of Quality procedures the "risk assessment" has a significative role. It should be underlined that a "risk analysis" is different than a "risk assessment", and not always necessary, because it increases the cost of the design and does not contribute proportionally to the actual handling of the risk. Risk assessment, as far as the Quality procedures are concerned, is aimed to identify *which risks are foreseen by the design, which risks are undertaken by the contractor and who undertakes any further risks.*

### 10.1. Quality goals

In order to obtain a well functioning tunnel or underground structure, all project stages are of fundamental importance; the stage of knowing the geological and geomechanical characteristics, the planning stage, the stage of choosing the machinery and method of excavation, the installation of lining and rock support, and the organisational and financial coordination stage. As far as Quality Systems are concerned, an analysis of the numerous problems that occur in a tunnel, independent of the adoption of Quality System procedures, show how these may not be resolved automatically by Quality Systems.

Quality Systems should reflect the various stages and assess the influence on the final result, showing above all those aspects where the interpretation becomes decisive in the technical choices.

Tunnelling and underground projects are usually of significant financial value and are generally considered high risk in terms of final cost and time for construction/delivery. In addition, tunnel construction often requires multinational input for both funding and technical capacity. Performance to the set quality goals therefore becomes a critical issue.

When it comes to the quality issues, it is not considered necessary to maintain a uniform approach for the duration of a project. Some issues might turn out to be more important than others and experience shows that, during the course of construction, some issues may well be abandoned without harm to the project.

Research into the appropriate local legislation and regulations for such matters as health and safety, the protection of the environment and socio-economic consequences, as well as technical standards to be achieved should be carried out. These can then be compared to best international practice, which can be adopted to suit the particular project and then the quality goals can be set accordingly.

All phases of a project and all organisations/groups of organisations involved should have a set of quality goals for the work to be performed. Quality goals should be aimed at giving the project added value with regard to cost, time, improved performance/physical properties and could be set relative to "soft parameters" like improved competence or educational standards for involved parties, environmental aspects, safety standards or benefits for the public in general. When quality goals are determined, these should be related to the factors of success for the project and a strategy on how to achieve this should be included in the Quality Plan. Compliance and the degree of success in achieving the set goals should be communicated to all project members/companies.

It is recommended that requirements and detailed instructions for quality control for the design and the construction work should be specified in the contract. It is important that procedures for the registration and communication of items such as test results are specified. A project procedure including owner/employer, engineer/designer and contractor for lines of communication and the responsibilities of each party for handling such information should be drawn up. The continuous process of evaluating, for instance, test results and any subsequent changes to the design and/or construction methods should be adequately defined and described.

It is recommended that implementing bodies and contractors make available technical data and statistics from the construction phase and communicate such data to international bodies and universities. By doing so, objective views on the state-of-the-art of methods used and case histories could be obtained, all in line with a generally recommended quality goal regarding the transfer of knowledge.

Methods for procuring, constructing, maintaining and operating private/public infrastructure are numerous. They range from lump-sum contracts for the construction of a designed facility, to complex transactions involving ownership transfer, equity financing and novel revenue features. Understanding and adapting available contract options is crucial for the success of a project. The owner should be aware of how his precise requirements are best served and of the practical considerations associated with different contract strategies.

The details of appropriate methods of financing and remuneration, risk allocation, the nature of the different parties' obligations/responsibilities and the ownership structure are matters specific to the individual projects.

It is possible to resume what have been described in terms of benefits of the application of Quality as follows:

- Good organization and relationship
- Definition of needs and constraints of the work
- Design adapted to needs and constraints
- Control on the evolution of design stages and selection of appropriate contracts
- Evaluation of risks and allocation of responsibilities
- Ability to perform modifications to details
- Historical records of the design and of the performed works
- Reciprocity for communications and problem-solving attitude

### *10.2. Summary of recommendations*

Quality is the sum of the client's needs and expectations and the level of performance achieved by satisfying the needs, whether delivering a service or a structure.

In tunnelling there are two levels of quality as far as performance is concerned. One is related to the use and efficiency of the underground structure, and this is taken into account during the planning and operation phase. The other is related to the characteristics of the works, and this is taken into account during the design and construction phase.

Quality goals as far as expectations are concerned are linked to the adherence to the construction programme, keeping within foreseen costs and limiting the number of claims.

These desired features can be fulfilled through well planned and controlled stages:

- planning during which the effective needs are highlighted;
- progressive investigation and monitoring;
- well defined preliminary design;
- correct choice of the type of contract, conditions of contract, financing and procurement procedures, depending on the type of project;
- well considered design with verification of both the technical and economical aspects;
- appointment of consultants and auditors for all the phases including the commissioning and approval.

In general if the scheduled actions, the design requirements, the indications of the investigations and the contractual rules are observed, a good result for the work is possible.

Each involved party should estimate and describe the uncertainties and risks that are connected to their responsibilities such as the owner for the planning and for the tender and the project manager for the coordination and financing.

These responsibilities should be assigned taking due cognisance of the type of contract/contract conditions and national laws and regulations. Eurocode 7 on Geotechnical Design is an example of detailed technical recommendations for the geotechnical investigation and design.

The final objective for quality in tunnelling is to limit the number of uncertainties, whether these are related to communication, allocation of risk, technical or financial issues.

Procedures dealing with planning, control and how to deal with changes to set procedures and design can ensure that the end product is such that client satisfaction can be achieved, time and cost overruns limited and resulting claims minimised. At the same time proper procedures can ensure that knowledge is transferred not only between parties during the project phases but to parties after completion of a project, including for instance universities and other independent organisations.

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## Glossary

*Short glossary*

| | |
|---|---|
| Adit | The entrance of a tunnel into the mountain slope. |
| Approval engineer | Engineer authorized to verify the fulfillment of technical requirements during or after the construction of the work. |
| Arbitration | A procedure for the resolution of a dispute, administrated by an arbitral team. |
| BOTT | The build-operate-train-transfer is a type of contract under which the concessionaire designs and provides the works ready for operation and then operate and maintain the works.After the concession period the works are taken over by the project owner, following the training of the new operators. |
| BOT | The build-operate-transfer is a type of contract under which the concessionaire designs and provides the woks ready for operation; after the concession period the works are taken over by the project owner. |
| BOOT | The build-own-operate-transfer is type of contract under which the concessionaire designs and provides the works ready for operation, and then owns, operates and maintain the works during the concession period.At the end the works are revert to the project owner. |
| Concessionaire | Society or group who has been given the rights to design the work. |
| Concession period | The period during which the concessionaire has the responsibility for the operation of the project. |
| Consultant | A professional who carries out services or studies for a client, a contractor, a concessionaire or a owner. |
| Contract | The set of documents which constitute the legal and technical agreement between the parties for the design, construction and operation of a work. |
| Contractor | Society or group whose tender has been accepted and who is responsible for providing the works. |
| Conventional method | The drill and blast method traditionally adopted in hard rock formations. |
| DB | The design-build is a type of contract under which the contractor provides the design and the construction of the work. |
| DBFO | The design-build-finance-operate is a type of contract under which the concessionaire obtains financing and design, and provides the works for operation, and then operate and maintain the works during the concession period.At the end of the concession period the works are taken over by the project owner. |
| EPC | The engineering-procurement and construction contract is an agreement under which the contractor provides the works ready for operation by the client, and may include financing parts of the works. |
| Final support | The lining that surround the section of the tunnel, usually made of casted concrete, precasted segments, masonry or sprayed concrete |
| Geotechnical characterization | The investigations and the tests aimed to find direct values or indirect correlations with the geotechnical parameters of the geological materials and of the geological formations. Also the carrying out of the geomechanical classifications. |
| Monitoring | The measurement plan and operations aimed to obtain a continuous or periodic survey of geotechnical, structural or hydrogeological parameters. |
| Pilot tunnel | Small section tunnel driven for detailed investigation or for preliminary reinforcement or for safety reasons. |
| Performance certificate | The technical report in which the approval engineer or a certifying body declares that the contractor has performed all obligations under contract. |
| Preliminary support | The methods for supporting the rock or soil excavation: usually they consist of bolting, sprayed concrete, wire mesh, steel arches. |

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| Portal | The final structure or completion of the adit of the tunnel. |
| Profile of the tunnel | Both the longitudinal and lateral sections of the tunnel, referred to topographical and geological conditions. |
| Quality assurance | Actions oriented to verify the fulfillment of quality requirements. |
| Quality management | Organisation methods aimed to coordinate parties and procedures during a project. |
| Reinforcement | All the technical actions aimed to ameliorate the geotechnical conditions of the formations, both before and during the excavation: drainage, grouting, nailing etc. |
| ROT | The repair-operate-transfer is a type of contract under which the concessionaire repairs an existing work and then operate and maintain it during the concession period. The work is the taken over by the owner. |
| Shield | Mechanical equipment for the tunnel excavation in soil formation (EPB shield, slurry shield, mix shield etc.) |
| TBM | Mechanical equipment for the tunnel excavation in rock formation (open TBM, shielded TBM). |
| Tender | The set of documents which allow the various competitors to submit to the employer (owner or committent) the respective proposals for the work. |
| Tests on-after completion | The tests which are required to be carried out to verify the technical performance of the structures and installations. |
| Turnkey | The type of contract under which the contractor designs and provides the works, ready for operation. |
| Waste | The rock debris or soil material produced by the excavation of tunnel (mucking). It can be disposed in landfills or partially re-used. |