OPTIMIZATION OF OPERATION AND MAINTENANCE ACTIVITIES AND COSTS FOR ROAD TUNNELS BASED ON EXPERIENCE

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Summary

Major tunnels in marine and aggressive environment are today typically being design for a service life of 100 or even 120 years through specific construction requirements to structures and installation with due respect to the later on operation and maintenance phase, the far longest period in a tunnel's lifecycle. However, years of practical experience from the operational phase shows many difficulties in obtaining the assumed optimum service as original design for due to many reasons. The paper deals with the basic ideas and principles behind implementation of a modern management system for tunnels to optimize operation and maintenance activities and costs ensuring the day-to-day traffic, safety and service level for road users in an optimal way.

***Keywords**: Operation & Maintenance, Tunnel Management System, Life Cycle Costs*

1. Introduction

1.1 Objectives

The overall objectives of operation and maintenance works are to maintain the specified safety and service level, ensuring the day-to-day traffic at all time in the tunnel area and to optimise expenditures taking environmental effects and traffic user inconvenience into account.

Professional and well organised planning of operation and maintenance activities is therefore necessary. For existing and new tunnels regular inspections and monitoring schemes including introduction and implementation of systematic operation and maintenance activities form the basis to meet the objectives and in order to ensure the specified lifetime of the structures and installations.

Modern tunnel management requires and involves a large number of activities and skilled people from many entities all with different responsibilities and tasks that need to cooperate such as the owner, the operator, consultants, contractors, authorities, emergency entities and tunnel users. This emphasizes the importance that the optimisation of activities and costs for the future operational phase starts years before the inauguration of a road tunnel by involving many experts with different backgrounds, objectives, demands, requirements and roles for operating a road tunnel.

The far longest period in a tunnels lifetime is the operational phase. It is thus of utmost importance to take all the tunnel operation and maintenance requirements into account during the planning, design and construction of a tunnel. From experience it is well known that the best outcome of future cost-effective operation and maintenance activities and tasks come by the involvement of experts on O&M from the initial planning phase.

Nowadays it is commonly used to create a Tunnel Design and Safety Consultation Group (TDSCG) which will meet regularly during the conceptual and detailed design phase. This group can ensure both operational and safety requirements and aspects by adequate consultation. An essential part of the work of the TDSCG is to ensure that the design engineers have a proper understanding of how the tunnel will be operated.

This paper considers the use of experience gained from systematic administration and operation of road tunnels especially in aggressive and marine environment through almost 40 years in Denmark and combines it with the international experience from working and implementing management systems for several major infrastructure projects abroad covering both new and existing tunnels, bridges and marine structures.

1.2 Experience based operation and maintenance

Based on years of experience by implementing and operating a systematic approach for operation and maintenance activities of major tunnels, bridges and marine structures, undergoing constantly technological improvements, and including the extensive experience gained from repair, rehabilitation and renewal of structures and installations in recent years, it is possible to evaluate the actual condition and thus estimate a reliable range of expected residual life for most common tunnel elements and components.

Realistic lifetime considerations are constantly being taken into account during budgeting and choice of strategy for operation, maintenance, repair and rehabilitation activities. By considering overall lifetime costs for different strategies, it is possible to make a technical - economical optimization of the activities over a certain time period and thus in the long run minimize the total costs for operation, maintenance, repair and rehabilitation to be paid by the owner or tunnel operator during the service life of a tunnel.

2. Planning of Operation and Maintenance Activities

2.1 General

There are two main activities when creating a good technical and economical monitoring system for planning of operation and maintenance activities. The first is to define, establish and implement an inspection system. The second is to develop and implement a Tunnel Management System (TMS) as a tool for handling all the information of the tunnel from i.e. inventory data, archive documents, and inspection data entered into a database ending up with i.e. elaboration of necessary work orders and storing of feed-back from site related to execution of the actual work.

By organising these two activities it is possible to obtain outputs concerning:

- Needs for operation and maintenance
- Need for repair and replacement
- Prediction of deterioration and consequences
- Options for repair
- Ranking and optimization of limited resources
- Estimates of overall costs and budgets

Data input from experience to these processes will be an essential part of the management system.

The SCADA (Supervision, Control And Data Acquisition) system is normally an integrated part of or linked to the TMS and used as an important monitoring tool to obtain reliable information of the present condition of especially the M&E installations for future planning of operation and maintenance works. ITS or Traffic Management Systems are normally integrated in the SCADA system.

2.2 Inspections

The Danish inspection system is based on data from 4 different kinds of inspections, all with separate activities, but of course with inter-relations between them.

The following types of inspections recommended to be carried out are shortly presented below:

• Roadman Check is an inspection performed daily or once a week as a part of the regular inspection of the highway network. The inspection is a visible check from the inspection van of any sudden damage or failure. The objective is to detect any abnormal situation and report it to the maintenance organisation immediately. The Roadman Check is performed by a Contractor in Denmark.

• Routine Inspections are inspections to be carried out with short intervals, monthly or quarterly. This type of inspection is always as a minimum carried out at the same time as execution of the planned maintenance work. The purpose of the inspection is to ensure that the structures and installations fulfil their function and that no damage or other factor that increases risk has arisen. Extended routine inspection may be necessary because of special circumstances, i.e. after severe traffic accidents, heavy rainfall or high water level. Reporting is done on pre-printed forms and handed over to the maintenance organisation. The Routine Inspection is in Denmark performed by a Contractor.

• Principal Inspections are carried out with predefined intervals normally between 1 to 6 years. It is a visual inspection of all accessible components of the tunnel carried out by technicians or engineers to evaluate and report the condition of each tunnel component including signs of damages and proposal for possible remedy and expected costs. Principal Inspections are in Denmark performed by the owner's staff or Consulting Engineers.

• Special Inspections are a more thorough inspection carried out when the principal inspection has shown damage or sign of damage that could not directly be evaluated. The report describes the consequences with respect to extent, cause and possible repair strategy including strategies with costs recommended to be followed by the tunnel owner. Special Inspections are always performed by Consulting Engineers in Denmark.

All the inspection data are entered and stored in the TMS for planning of future systematic operation and maintenance activities.

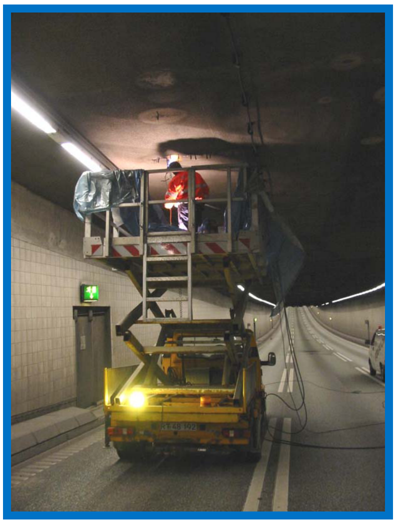

***Fig. 1** Special Inspection* ***Fig. 2** Routine Inspection* ***Fig. 3** Roadman Check*

2.3 Systematic Maintenance

Systematic maintenance can be divided into several types of activities, which are not specific for each tunnel. The problems are more or less the same regardless of country, type of tunnel and the organisation behind the administration. Some systems are well thought-out and contribute to the overall safety. Other forms of maintenance can be based on uncoordinated activities and do not necessarily give the safety needed.

Tunnel operation and maintenance activities are recommended to be systematic and planned maintenance dividing it into two groups:

• Preventive maintenance as periodic and/or condition based maintenance
• Corrective maintenance as breakdown based maintenance

Periodic maintenance can be calendar based and/or operation time based.

Preventive maintenance is for tunnels recommended to be planned, organised and performed periodic to prevent operational breakdown. Experience shows that maintenance based on preventing damages to components and systems is safer and more economic than maintenance based on repairing damages. Preventive maintenance is also recommended to be performed as calendar based maintenance for both existing but also new road tunnels from the start, when one is not accustomed to other routines, and as such contributes to the introduction of a systematic planned maintenance system.

Condition and operation-time based maintenance is recommended to be used as supplementary activities. It is a part of a periodic and condition based maintenance system that inspections are carried out in which components and also the entire system are evaluated in order to determine when and to what extent major interventions such as replacement are necessary.

Corrective maintenance means that maintenance measures are carried out after an operational breakdown or accident has occurred. It is not possible to plan or make any specific budgets for this type of maintenance. If a defect or failure affects traffic safety or cause user inconvenience then immediate rehabilitation is required. Otherwise, the rehabilitation may be postponed to the regular maintenance intervals.

2.4 Operation and Maintenance Activities

The time intervals for execution of operation and maintenance activities can be e.g. monthly or bi-monthly depending on the traffic flow and the outcome from inspections. For existing road tunnels and especially as a start for new tunnels in the first 1 to 5 years the following scheme is recommended based on experience:

- Monthly or bi-monthly tunnel washing and cleaning activities
- Quarterly regular routine maintenance activities including routine inspection of all main components
- Principal Inspection of all structures and installations after 5 years

Based on the experience during the first years the intervals may be adjusted also considering the need for corrective maintenance.

Preventive maintenance activities for tunnels are most convenient planned to take place during the hours with low traffic intensity i.e. night hours minimizing the disturbances and impact on traffic flow and permitting easy access to the tunnel for the O&M staff. Planned activities during the night hours are seen more and more for urban tunnels world wide.

For road tunnels typical preventive operation and maintenance activities are normally considered for and comprise:

• Tunnel washing and cleaning of structures, pavement, buildings etc.

• Operation, maintenance and control of mechanical systems in the tunnel as i.e. ventilation, drainage, pumps, basins, fire fighting systems, emergency escape doors and doors for SOS stations etc.

• Operation, maintenance and control of electrical systems in the tunnel as i.e. power supply and distribution systems, UPS systems and emergency generators, tunnel lighting systems, fire and heat detection, tunnel control facilities as local PLC, remote SCADA etc.

• Operation, maintenance and control of ITS components and elements as i.e. cameras for IDS and CCTV, SOS stations, Information panels and VMS, radio systems, cross - over barriers and stop/turning barriers outside tunnel, queue warning and height detection systems etc.

• Operation, maintenance and control of M&E installations for Toll Stations, Portal and Service Buildings

• Routine Inspection of main components and elements to determine and evaluate the condition and need for future repair or replacement

Corrective maintenance is very difficult to plan for as the works from i.e. operational breakdown are normally informed through alarms from the SCADA system to the operators PC. These alarms are commonly divided into two groups:

• Technical alarms, most often to be postponed to regular maintenance periods

• Alarms that affect traffic and tunnel safety requiring immediate action

By organising operation and maintenance activities in a planned, periodic and effective system it is from experience possible to minimize the volume of corrective maintenance activities.

2.5 Repair of structures and installations

It is the experience that sooner or later preventive maintenance can no longer postpone a repair work, where one or more structural components or installations must be repaired or replaced.

Repair works are best divided into minor or major works where minor repair works are planned limited project works with a duration of a few weeks and a budget in the range of 0.1 - 0.5 million Euros. It is the experience that minor repair and rehabilitation works seem to be inevitable for i.e. tunnel walls, ceilings, pavement and joints starting few years after the inauguration of a tunnel.

Major repair is generally most likely to appear first after 20 to 25 years in operation. For concrete structures in aggressive and marine environment the deterioration in reality starts just after the castings are completed where every minor defect, crack and failure will be detected during the first principal inspection or within the first year of the liability period. The damages are monitored continuously until the functionality of the element in question need to be repaired or replaced before making to much damages to other components and installations.

For M&E installations major repair or replacement works are often seen necessary after just 5 to 10 years after the inauguration. It is the experience with optimal preventive maintenance to postpone the replacements until 20 to 25 years for most common tunnel equipment and installations.

When a major repair is necessary, several methods of carrying it out shall be investigated. For each of the proposed methods the technical details must be specified. If the method affects the traffic flow, a proposal for dealing with the traffic during the repair period must be elaborated and included. The proposal can vary from no action at all to replacement of the entire structure or component. In addition to a technical evaluation, traffic and economic evaluations are also done using i.e. road user costs covering the inconveniences to road users.

2.6 Tunnel Management System

Tunnel management and administration procedures require a large number of interrelated activities such as tunnel inventory data, inspections, assessment of damaged components and structures, allocation of funds for repair and maintenance, elaboration of works orders for operation and maintenance works etc. with the objectives of ensuring the day-to-day traffic, the defined service level in the safety concept for the tunnel and to maintain the structures and installations in an acceptable condition using the lowest possible amount of funding. To assist the management in these activities a computerized Tunnel Management System (TMS) is needed.

A TMS can in principle support the management and operator as a tool to:

• Plan necessary preventive operation and maintenance activities including programme, staff and materials needed
• Generate cost analysis for planning works, quality control and record historical data for works completed in the tunnel
• Optimise tunnel maintenance, repair or replacement activities
• Provide technical feedback on the tunnel and installed systems

It is recommended that a TMS includes a set of manuals describing codes, guidelines and procedures to be followed for all activities including the use of software modules. Furthermore, a database for storing of data and a set of computer tools for processing the data in the database is needed.

Numerous Tunnel Management Systems have been developed in different countries with a variety of success. The experience is that it is beneficial for a modern tunnel management organisation to develop, implement and optimise an innovative, sustainable and cost-effective tailor made computerized management system on its own. This ensures a useful complete and functional system available at all time to assist the owner in fulfilling the objectives taken into appropriate account the experience and knowhow from the owner or operators staff.

Alternatively, there is a huge market for purchasing standard computerised Administration and O&M systems. Such systems are seldom very useful in complying with the objectives outlined from the authorities, owner, operator, road users and emergency entities.

If the system shall be developed as a web-based system or a PC based system using lap-tops depends on the complexity and constraints in administrating and operating the tunnel. It is in this respect of utmost importance that the TMS can be developed, compiled and integrated into other computerised systems in the tunnel such as SCADA.

3. Operation and Maintenance Costs

3.1 General

Broad international experience shows that a substantial part of operation and maintenance costs are introduced and determined by decisions made from the initial planning phase as conceptual design to the design and construction phase of a tunnel project. Unfortunately, those involved in these phases of a project frequently have only limited experience of those factors effecting maintenance costs. The longest period in a tunnels lifetime, the operational phase, only has a minor level of influence on the overall future maintenance costs even the staff is highly skilled and has many years of experience in tunnel management. This indicates that the tunnel operators in many cases will have to live with these non cost effective conditions premade by others and try to do the best optimisation of the operation and maintenance activities and related costs on sometimes inappropriate and inadequate circumstances.

PIARC has estimated the level of influence on the operation and maintenance costs at the different phases of a tunnel project as shown in figure 4.

Influence of operation and maintenance costs by:	Level of Influence
Planning and design - (including design manuals)	60 - 80 %
Construction	10 - 30 %
Operation	10 - 30 %

Fig. 4 *Relation between Level of Influence and Operation and Maintenance Costs. PIARC, WG1, 2005*

Experience from consultancy of a broad variety of tunnels under different conditions verify the PIARC figures as being very realistic and the situation the operators have to deal with for many years.

3.2 Cost distribution based on experience

Experience in Denmark and abroad including several international studies show that the overall normal operation and maintenance costs most likely seem to be in the range of 0.8 - 1.0 % of total construction costs per year for the first 10 to 15 years after a tunnel is operational. The costs will then typically increase up to 1.0 - 1.5 % per year ending up typically around 2.0 % per year of total construction costs after 25 to 30 years in operation.

Expenses and costs for normal operation and maintenance activities are from experience most likely covered and distributed into the following groups:

- Energy and electrical power supply (25 %)
- Tunnel washing and cleaning (15 %)
- Operators, consultants, 24 hour staffing and emergency crew (10 %)
- Preventive maintenance works (45 %)
- Corrective maintenance and impact from accidents (5%)

After being in operation more than 15 years the effect of needs for renewal and rehabilitation of tunnel equipment and installations will start to have an impact on the budgets. It is foreseen that an increase to 1.0 - 1.5 % of construction costs per year can be expected for normal operation and maintenance costs after year 15. Taking into consideration the lifetime estimations for the structures and installations experience shows that an increase of yearly costs for normal operation and maintenance could be even 2.0 % from year 25. This figure may include minor repair works.

In addition costs for both minor and major repair/renewal/replacement works of M&E installations, structural components and elements must be foreseen starting after 25 - 30 years in operation. Especially tunnel equipment and installations will need replacement. Principal and Special Inspections will reveal more information on cause, extent and costs for remedial works.

Costs for major repair/rehabilitation/renewal works must be added but kept on a separate long term budget. A long term budget adding these costs can be prepared on basis of the principal and special inspections and later optimised including a certain strategy choosing the time for most cost-effective execution.

3.3 Lifetime considerations from experience

Lifetime considerations are constantly taken into account during budgeting and choice of strategy for operation, maintenance and repair/rehabilitation works for tunnel structures.

More than 50 years of experience with road tunnels in Europe shows that modern and new tunnel equipment and installations are not to be considered as having a lifetime of more than 15 to 20 years mainly due to rapid technological development, so that most installations become obsolete before they are worn out. Especially equipment for SOS stations, CCTV cameras, IDS systems, PC for monitoring and control, software, UPS stations have a very short lifetime in the range of 10 - 15 years. Systems for ventilation, lighting and traffic management are considered to have a lifetime of 25 - 30 years before replacement is necessary.

Tunnel structures are design to have an estimated lifetime for normally 120 years. However, experience from many countries shows that immersed and bored sub-sea tunnels will need major repairs of vital components such as expansion joints, pavement, ramp structures, fire protection of tunnel, emergency doors, tunnel walls and ceilings etc. much before the designed service life is accomplished. The extent of repairs depends mainly on the functioning of the implemented maintenance system, the impact from traffic and environment on the structure.

Based on more than 40 years of experience in Denmark with durability of concrete repair of major infrastructure projects in aggressive and marine environment using special mortar, shot-concrete or in-situ cast concrete for the repair, experiences show, it is not reasonable and realistic to require a durability of more than 50 years. In a few cases it is seen that a major repair has not even obtained 10 years of lifetime, but this is always due to a mix of failures starting from the investigation and inspection of cause and extent, over the design phase to the later execution and supervision of the work. Most commonly experience show a lifetime for a major repair is in the range of 20 to 30 years postponing an actual replacement or renewal to take place hereinafter.

4. Optimization

4.1 Life Cycle Costs

From experience it is recommended to consider the philosophy of Life Cycle Costs (LCC) wherein the Net Present Value Method is used as a tool for the economic evaluation and optimisation process for repairs. For example it makes very little sense to make a short term cost cut in the budget that later on leads to a much higher maintenance and repair costs within a few years time.

The use of LCC is from experience very helpful for optimisation of individual as well as programmes for combined measures of a tunnel. LCC criteria can be used to decide between different operation, maintenance, repair and replacement strategies using optimisation models to support the decisions. For example a criterion can be that a replacement is preferred when a repair costs exceed 50 % of the replacement costs.

4.2 Net Present Value Method

In Denmark and abroad where BMS or TMS systems have been implemented, gained experience shows, it is beneficial to use the "Net Present Value Method" for economic evaluation and optimisation of funds, giving the net present value of executing, or postponing each strategy including direct and indirect costs to society within a certain time. The time-horizon is preferable set in the range of 25 to 40 years as prediction of consequences becomes more uncertain with much longer forecasts. The strategy with the lowest net present value is the economic optimum for the tunnel.

When comparing several strategies for more than one tunnel and with limited budgets the optimum strategies to follow are found as the ones with lowest net present values and where the cheapest strategies for society to postpone the works by 1 year are found and excluded in the first place.

In a present value calculation, the costs of repairs and traffic inconveniences, traffic diversions, traffic noise and pollution, operation and maintenance costs are calculated year for year within the chosen time-horizon. The timing of each cost is based on experience of lifetime of each repair and the time at which the repair is carried out. The annual amount is then discounted back to the initial year using a given discount rate. In this way the present value of each year's expenditure is obtained. In the net present value calculations, the residual value is normally discounted and deducted from the cumulative discounted costs.

4.3 Repair Strategies

Several relevant repair strategies should always be investigated for each tunnel. To make an economic comparison between strategies, they must result in the same increase in the value of each tunnel structure. If a strategy involves a rehabilitation of the structure in the form of strengthening or extension, the value of the improvement shall be assessed, and a similar improvement must be included in the other strategies if they are to be compared.

The full range of relevant strategies may normally be divided into three types:

1. Make a thorough repair now bringing the tunnel structure back to "as good as new" condition
2. Make some superficial repairs now in order to postpone the time for the major repair or replacement works
3. Do nothing now, wait until the tunnel is no longer safe for use, then replace the structure

Input for each strategy comes mainly from the inspections performed.

4.4 Budgeting

It is recommended to elaborate two types of budgets. A short time budgeting is done for a 5 or 10 years period and a long time budgeting for 25 or up to 40 year period covering operation & maintenance, minor repair, rehabilitation and replacement costs for both structures and M & E installations. It is the experience that longer periods are not recommendable due to the consideration and implementation of too many uncertain and unrealistic parameters and data.

Costs for the budgets are estimated as a percentage based on experience from operation and maintenance activities adding the costs for repair, rehabilitation or replacement as found from the optimization process using the net present value method.

It is important to emphasize that it is necessary to adjust the strategies every time when the parameters and basic data changes and thus make new calculations. Optimisation programmes are best fully integrated in TMS and thus easily done by the use of PC.

4.5 Experience from low budgeting

From experience it is known that it is economical beneficial in the long run to perform preventive maintenance for the structures and installations rather to repair or replace them shortly after. This requires a complete up-to-date information level on resources needed for budgeting, condition assessment of structures and installations from inspections including systematic planning of operation and maintenance activities. By this way it is always possible to estimate the actual costs needed for the next year or several years ahead, and more important, describing the consequences for the decision-makers if the budgets will be low.

5. Lessons learned

5.1 Design of new tunnels

The gained experience is today commonly used in the design of repair, rehabilitation, replacement and new tunnels, but also in the daily operation and maintenance of existing structures. During the last 10 to 15 years standards, codes, guidelines and manuals have been revised and up-dated continuously with the latest experience for further use when establishing specifications and construction requirements in tender documents.

Inspection routines, manuals and monitoring systems as SCADA are frequently up-dated with the latest news on procedures and instructions for obtaining the optimum lifetime at minimum costs ensuring that the traffic safety is maintained at all times according to the safety concept applied.

In Denmark for example the lessons learned from the major repair and rehabilitation work during 1999 to 2001 of the immersed Limfjord Tunnel (inaugurated 1969) has lead to new thinking in the design of the immersed Guldborgsund Tunnel inaugurated in 1988, and later in the construction of the immersed Øresund Tunnel, inaugurated in 2000. Major changes have been made in the design and construction of the elements, mainly in casting technique, concrete technology and improvement of waterproofing systems. The Øresund tunnel segments were i.e. casted in one process and without applying any external waterproofing system. In this case the owner has chosen a strategy with full confidence in the concrete density and expects a lifetime of 100 years for the main structure.

All our experience in Denmark gained during more than 40 years will definitely be used during the planning, conceptual and detailed design, procurement and contracting of i.e. the 18 km coming Femern Belt crossing linking Denmark and Germany together with an immersed tunnel or bridge solution carrying both rail and road and all other tunnel structures under planning, design and construction where danish engineers are working worldwide. The experience will i.e. be reflected in the service life design of the overall tunnel structure.

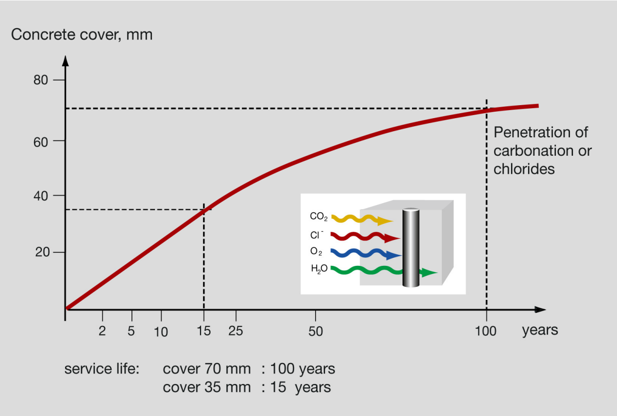

***Fig. 5** Service life design of concrete cover of structures*

***Fig. 6** Preparing embedded corrosion sensors for monitoring of reinforcemnet*

6. Conclusion

For road tunnels it is the experience that a well organised, systematic and planned operation and maintenance system fully implemented from the first day the tunnel is taken into operation forms the basis for all tunnel operation activities and will ensure:

• Cost-effectiveness in all operation and maintenance activities by optimization of preventive maintenance works to be carried out and at the same time reducing the amount of corrective maintenance works to a minimum

• Optimise the expected lifetime for both installations and structures to minimize repair costs

• Minimize the impact, influence and disturbances on traffic flow while carrying out operation and maintenance works

• Safety aspects for road users are taken care off in the most optimum way while using the tunnel thus minimizing occurrence of incidents, accidents and catastrophes

The basis for the whole process is using the experience gained from the past of costs, lifetime and durability and to combine it with a useful and appropriate TMS, SCADA and inspection system and not to forget a good portion of sound engineering judgement at all times.