

Improvement of QRA for tunnel safety by comparing QRA used in other engineering fields

C.J. Soons, J.W. Bosch, P.H.A.J.M. van Gelder & J.K. Vrijling

Delft University of Technology, Faculty of Civil Engineering, Delft, the Netherlands

ABSTRACT: During the last 10 years in the Netherlands, Quantitative Risk Assessment (QRA) is being applied to assess the safety level of tunnels. Due to this relatively short period of time, one expects that improvements in QRA applications for tunnel safety, can be made. For this purpose, a comparison is made between the application of QRA-modelling in other engineering fields (land reclamation (dikes), aviation, chemical and nuclear industry), in which it is being applied for decades. The focus in this research lies on the completeness and the uncertainties of QRA-modelling for tunnel safety. But first, it is researched whether QRA-modelling actually is an applicable tool for assessing tunnel safety. It can be concluded that (i) human factors, (ii) probabilities of failure and (iii) self rescue processes must be investigated further. Currently, the QRA-model cannot be used as a Quantitative Risk Management tool (QRM), which would be of additive value.

1 INTRODUCTION

The attention for tunnel safety has increased due to the Alp fire accidents (Mont Blanc, Gotthard tunnel etc) and raised questions concerning the safety level of tunnels. The Quantitative Risk Assessment (QRA) was used as a tool to appoint the safety level of a tunnel. Since the Alp fires EU Directives are set, and also in the Netherlands legislation regarding tunnel safety will be compulsory in May 2006.

Nowadays, Dutch local governments are requesting an assessment of the safety level, otherwise no construction permits are granted. However, due to the lack of legislation, no standard QRA-model or input is available. As a result, the most heard complaint is that the output can be influenced by the designers of the models to comply with the set standard by each local government.

In this paper it will be investigated in what way the QRA can be valued as an effective method for assessing tunnel safety, by determining (i) whether the QRA can be considered complete and (ii) what are the most uncertain parameters, requiring more research. To provide answers, a comparison is made to other engineering fields also using QRA-modelling. One should keep in mind that QRA-modelling is the only method available to carry out quantitative risk analysis.

Before the comparison is described, the applicability of QRA-modelling in tunnels is expounded in chapter 2. In chapter 3, the current application of QRA in tunnel engineering is described, followed by the

comparison of the use of QRA in other engineering fields in chapter 4. In chapter 5, conclusions regarding the use of QRA-modelling and the improvement of the QRA-model for tunnel safety are determined.

Literature research and interviews have been carried out. The remark must be made that all recipients spoke on personal title and not in name of their company. Their names and dates of interview, as well as the abbreviations, are listed in the Literature of this paper.

2 APPLICABILITY OF QRA-MODELLING

The applicability of QRA in tunnels depends on three issues: (i) acceptability of QRA, (ii) aim of using QRA and (iii) benefits & limitations of QRA.

2.1 *Acceptability of QRA*

Apostolakis (Apostolakis, 2004), professor in nuclear engineering at Massachusetts Institute of Technology, has a long history within the probabilistic risk assessment discipline. He observes a pattern of progress in the application of the QRA method.

- Phase 1. The safety community is very sceptical about the usefulness of this new method.
- Phase 2. Engineers and decision makers become more familiar with the technology, and they begin to pay attention to the insight produced by QRA. Typically, the decision makers first pay attention to the “negative”

insights, i.e. those that reveal failure modes of the system that had not been identified previously.

Phase 3. Confidence in QRA increases as more safety analysts use it and they begin to pay attention to the “positive” insight. Due to the gained insight some previous safety measures/requirements may become less strict because (i) they do not contribute to safety (advanced insight) or (ii) CBA shows that they contribute a very small amount compared to the corresponding costs. Entering phase 3 requires a cultural change within safety management.

It can be said that the acceptability of using in tunnel safety is still in phase 2. In general, only in the nuclear power industry QRA-modelling has reached phase 3.

2.2 Aim of using QRA

There are various reasons/motivations to execute a quantitative or qualitative analysis. These can be put into four categories (Morgan and Henrion, 1992);

- (i) substance-focused motivations
- (ii) position-focused motivations
- (iii) process-focused motivations
- (iv) analyst-focused motivations.

Researching these categories shows that in tunnel safety, QRAs are mostly used with the following motivations:

- I) Illuminating and providing insight on a general area of policy concern for a variety of interested parties. (substances-focused)
- II) Developing insight and understanding; useful to policymakers who have to decide on specific well defined policy issues. (substances-focused)
- III) Generating answers and justifying (in situations, one is expected) the actions taken on the basis of the scientific and technical specifics of the problem. (position-focused)

2.3 Benefits & limitations of QRA

In general, applying QRA-modelling has several benefits but also limitations. QRA-modelling for tunnel engineering can be seen as a good match, because:

- It uses an integral approach (station/tunnel), in contrary to f.i. aviation.
- It implements human factors, although the values used are under discussion.
- It provides the possibility to make decisions on the cost-effectiveness of the safety measures by performing sensitivity analysis.

- It addresses large hazards in a structural manner and it ensures risks are reduced to appropriate levels, cost effectively.

Unfortunately, the QRA is not yet being used as a communication tool for risks in tunnel engineering. This is mainly caused by intransparency and uncertainties. For the public and most stakeholders, the model is still a black box. Due to the many uncertainties, the output tends to vary substantially. This doesn't enlarge trust in the reliability and keeps the focus on the output figure instead of on the whole method. To improve this, the following should be done:

- Clarify that the QRA does not provide “the” safety level of a project/installation etc, but provides a framework in which the safety should be sought.
- Make the QRA reproducible with a uniform set up to improve understanding.
- Use it together with the traditional safety models (deterministic approach).

Lack of data can also be considered as a limitation in QRA, resulting in difficulties in estimating probabilities.

QRA is currently applied just before the construction stage to gain a construction permit. But in the, upcoming, Dutch legislation for tunnel safety (Tunnel-safety, 2003, 2005), the use of risk analysis is imposed to determine the safety level. Risk analysis should be applied before (i) the design stage (simple risk analysis), (ii) the construction stage (QRA) and (iii) the exploitation stage (update QRA).

When decisions have to be made in the design stage regarding safety measures, a QRA is a useful tool to use. At this point the design can be influenced by the outcomings of the risk analysis.

When looking at Quantitative Risk Management (QRM) it is noticed that there is:

- No link between the initial conditions (design stage) and the actual conditions (exploitation stage). Therefore the base of several safety documents is incorrect. (Safety Case)
- No steering tools are incorporated in the QRA-model.

2.4 Conclusion of applicability of QRA

It can be concluded that QRA-modelling is applicable to tunnel engineering. The acceptability of the application of QRA is in phase 2. It is an useful tool which can provide better insights and understanding to the executives on subjects of political concern. Several benefits and limitations (communication and uncertainties) have been identified.

The limitations need to be investigated further. In the following two chapters it is described how this is dealt with, in other engineering fields.

3 APPLICATION OF QRA TO TUNNEL SAFETY

Due to the Alpes tunnel fires the focus on tunnel safety has increased. EU-directives are drawn for road and rail tunnels. Also Dutch legislation for tunnel safety is drafted (compulsory around 2007). Then, the use of scenario analysis and QRA will be compulsory to assess the safety level of tunnels. Several foreign tunnel projects (UK, SE, DK) have been researched in what manner safety is being dealt with. The focus lays on the adapted safety approach, the input of the QRA-models, the uncertainties in the model and the applied criteria.

Although not yet compulsory, QRAs are carried to determine the safety level of the Malmö City tunnel (SE), the Copenhagen mini metro (DK) and in the London Underground (UK).

Several reasons were put forward by the respondents:

- (i) input in decision-making process (SE, DK)
- (ii) documentation of safety process (SE, DK)
- (iii) ensure all risks to be identified (DK)

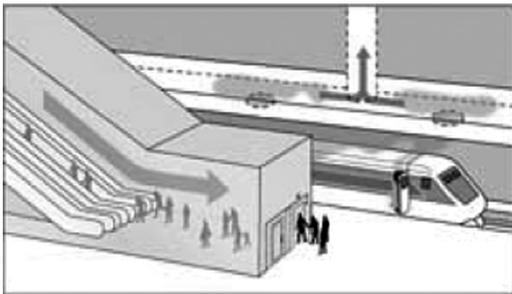


Figure 1. Safety measures in Malmö City tunnel (smoke discharge and overpressure in escape route sealed with glass) (SE).

- (iv) business planning tool (UK)
- (v) input in CBA (UK).

The London Underground Limited (LUL) reviews the QRA of each tubeline every year. The LUL uses it both in the exploitation stage and if new tubes are constructed or renovated. In Copenhagen and in Malmö, QRAs are applied in the construction stage and just before operation.

Scenario analysis is always realized first, before a QRA is executed, by applying the event tree approach. All studied projects use a Safe Haven approach. This is an integral approach to prevent the train/metro from stopping in a tunnel, instead it must drive up to the next station. The three main safety aspects are (i) to prevent a train to depart while having a disturbance, (ii) to prevent a train to stop inside the tunnel and (iii) an exploitation model insuring the next station B is free while departing from station A.

The focus of the safety approach is prevention, but self-rescue also takes up a large part. The LUL applies self-detrainment (lead out of tunnel by personnel), because of the unprotected third rail in the tunnel.

In all risk analyses for tunnel safety an integral approach is applied; this means that the whole system (tunnel/station/wagons/users/) and all possible scenarios are assessed. The consequences for several stakeholders can be researched for each scenario. The input of QRAs can be split up in three:

1. organization (driver, operator, passengers, maintainer, logistics, schedule etc.)
2. transportation (type of vehicle, fire load, driverless or not etc.)
3. infrastructure and technology (e.g. track, escape path, detection systems etc.)

The most uncertainties regarding the input of the QRA are:

- 1) Probabilities of technical systems (no/few testing, no SIL-level)

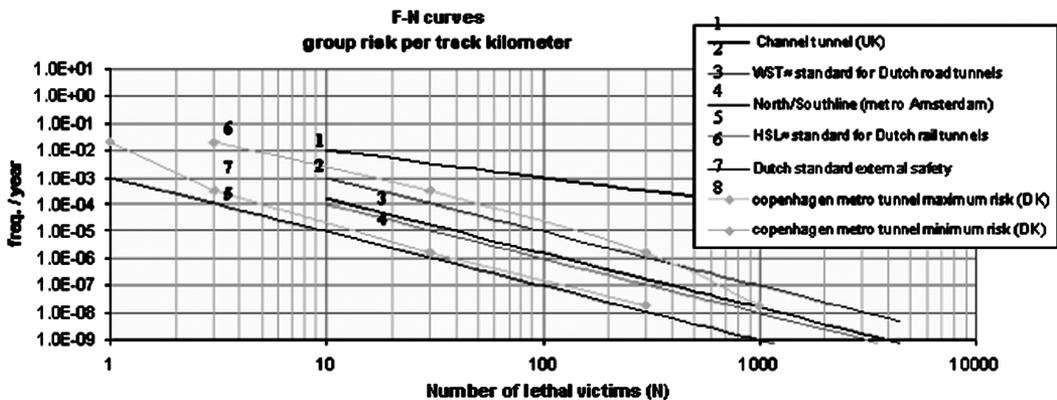


Figure 2. FN-curves of tunnels.

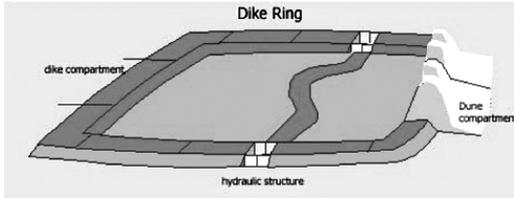


Figure 3. Dike ring schematization.

- Inconsistent level of detail
 - Simple way of modeling (no distribution function of uncertainties, number only)
 - no record keeping.
- 2) Human failure frequencies are subject of discussion (not always implemented)

Due to a lack of legislation, the criteria applied in the Netherlands are variable, as can be seen in figure 2. The resulting safety level of the Copenhagen mini metro is also drawn in this figure. The LUL applies individual risk criteria.

4 APPLICATION OF QRA IN OTHER ENGINEERING FIELDS

In other engineering fields, like the chemical process industry, the nuclear power industry, the aviation industry and for land reclamation (dikes), the QRA-method has been widely spread for decades. It is said that these engineering fields are more experienced in the use and application of QRA, and no problems are observed. To learn lessons from this knowledge, a comparison is made between the use of QRA in these engineering fields and in tunnel engineering.

In each paragraph of this chapter, the safety approach is described of one of the four engineering fields, together with the input used and the criteria set. The research is focused on the Netherlands.

4.1 Flood risk in the Netherlands

More than half of the Netherlands lies below sea-level, and therefore it is protected by a large system of dikes, dunes and hydraulic structures. Due to a storm surge in 1953, flooding the south-eastern part of the country and killing 1853 inhabitants, standards were set.

The standards evolved in the past 50 years. Initially (1950s), standards were based on the exceeding frequency (sufficient height of dike compartment to withstand extreme water heights). In 2000, a new approach was developed by TAW (TAW, 2000; Vrijling, 2001), incorporating (i) the whole dike ring, see figure 3, (ii) all failure mechanisms of dikes and (iii) all uncertainties in a systematic and controllable manner. In follow-up, the project “Safety in the Netherlands mapped” was initiated (VNK, 2005), calculating the risk of all 53 Dutch dike rings.

The safety approach focuses on prevention, while it is an irredundant system. Politics tend to shift this focus to the limitation of consequences, because evacuation suddenly needs to be investigated. This may be considered a less appropriate approach considering the induced consequences in New Orleans. To determine the flood scenarios of a certain area and the possible consequences, the scenario analysis method is applied. The QRA is executed to determine the dike height and serves as input of a cost-benefit-analysis (CBA).

Flood risk is assessed in an integral manner with the dike ring approach. The probability of failure of a dike ring is a summation of the failure mechanisms of each dike/dune compartment and all hydraulic structures. Therefore a schematization needs to be made, incorporating the dike ring parameters.

The input of the model can be divided into two parts;

1. Dike ring failure:
 - Dike ring: hydraulic structures, material, ground layers, state of dikes and dunes etc.
 - Wave conditions (wind, water height, period etc.)
2. Consequences (lethal victims and economical damage)
 - Flood scenarios
 - Flood characteristic
 - Inhabitants
 - Available infrastructure
 - Available time to flee
 - Utilization of soil.

In the model, human factors only explicitly incorporated, like to close a sluice.

Uncertainties in the new VNK model are:

- 1) Variability of nature, in matter of time (e.g. water height) and space (e.g. thickness of a subsurface clay layer).
- 2) The model used by schematizing physical models of a dike.
- 3) Statistical uncertainty, due to limited amount of data.

The safety levels expressed in design water heights are established for each dike ring. For the Randstad, economically of utmost importance, design water heights with an exceeding chance of one in 10.000 years were adopted, see figure 4. For the less populated and economically less important areas, higher exceeding frequencies were adapted.

4.2 Aviation

In 1966, PanAm Airlines placed an order to build the Boeing-747, at that time the largest commercial jet in operation. Boeing engineers felt that it would be important to look at the safety systems of the plane in a different manner than they had in previous aircraft designs. Fault tree analysis was chosen, which provided a systematic assessment of the technical systems



Figure 4. Dike rings in the Netherlands together with exceeding frequency (VNK).

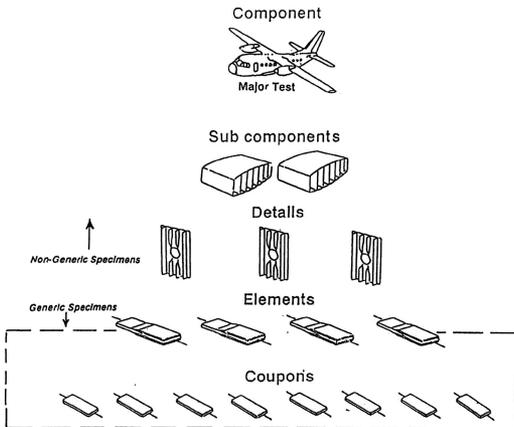


Figure 5. Elements of an aircraft (EASA).

of the airplane (Keller and Modarres, 2005). In aviation this was the beginning of the use of risk analysis.

QRA-modelling is only applied in the design stages of an airplane by the manufacturer, which is obligatory in international legislation. The governing regulations for the design are the Certification Specifications of Large Airplanes (CS-25), set by the European Aviation Safety Agency (EASA). In the United States the FAS is used.

In the exploitation stage, the maintenance manual is of importance. It is produced by the manufacturer for customer support and contains all maintenance tasks that have to be executed to ensure an acceptable safety level.

The safety approach in aviation focuses on prevention and the most technical systems are redundant. QRA is used in the design stage to: (NLR, Airbus)

- (i) get insight into complex systems
- (ii) determine tasks in maintenance plan
- (iii) guarantee the safety level of an airplane.

The input of the QRA only consists of technical systems of which the probabilities of failure are known (engine, propeller, propulsion system) and no human factors are incorporated (EASA). The probabilities of failure of these aircraft components are determined

by extensive testing and also an up to date worldwide failure database.

There are no uncertainties in the QRA-model applied according to CS-25. The uncertainties in the QRA model arise when the whole airplane is assessed including (i) parameters of which the impact on safety is unknown, e.g. cabin safety equipment installations and (ii) human factors. Uncertainties will also rise if the integral approach of transporting passengers is applied.

In aviation, the same as in tunnels, people are transported. Big difference is the fact that in aviation no integral approach is being applied. Air traffic control does “control” the airplane during flight, but this is not assessed by a QRA. Therefore it is not surprising that more uncertainties are discovered in QRA-modelling for tunnel safety, in comparison to aviation safety.

The probability of failure of an airplane with catastrophic consequences is smaller than $1 \cdot 10^{-9}$ /flight hour.

4.3 Chemical power industry

In 1980 the COVO study (Lees, 1996) (Rotterdam Rijnmond) was executed to determine whether it is possible to carry out a QRA in the chemical process industry. The conclusion was positive. In the 1980s, a safety approach for the chemical process industry was developed in the Netherlands, according to the quantitative risk assessment approach (Ale and Uijt de Haag, 1999). People from the government and from the industry developed a safety approach together (Coloured Books) and reached agreements on the used probabilities, as described in the Purple Book (CPR, 1999).

The safety approach is focused on prevention and the technical systems are redundant. Due to the implementation of the Seveso directive in Dutch legislation (that is the BRZO directive in 1999), every 5 years a QRA must be executed to determine the safety level of a certain plant.

The input of the model can be split up into two parts; (i) probabilities of failures and (ii) diffusion model of dangerous substances. The use of the probabilities per substance set in the Coloured Books is compulsory.

The diffusion models, determining the consequences, are not standardized. Five models are currently applied (DNV, Shell, SAVE, AVIV, TNO). In a benchmark study (Ale et al., 2001), it became clear that there are big differences in the output. The more probabilities and consequences were prescribed, the better the comparability of the results. But it cannot be said that one model is better/provides “safer” results than the other. The differences between the output of the five models occur due to (i) different available software, (ii) arguments of practicality and (iii) matters of principle.



Figure 6. Example of risk contour.

The uncertainties in the applied QRA models are:

- Human factors
- Diffusion models
- New technologies or safety measures are not incorporated in the Coloured Books, causing uncertainty.

By summarizing the output of the QRAs of each installation within the plant, the risk contour is determined. The criteria adapted for external safety is 10^{-6} /year of each plant.

4.4 Nuclear power industry

In 1972 the Reactor Safety Study (RSS), better known as Rasmussen Report (WASH-1400), was initiated, due to the increasing amount and size of nuclear power plants. This resulted in the first probabilistic safety assessment (PSA) for nuclear power plants.

There are two nuclear reactors in the Netherlands (Borssele and Dodewaard). The first PSA of the Borssele Nuclear Power Plant (NPP) was started in 1989 and finalized in 1991 (power operation). From 1991 to 1995 it has developed into a full scope 3 level PSA for all operating states (so including shut-down state).

The safety approach focuses on prevention and the system is redundant. In the nuclear industry there is actually only one hazard namely (the shut-down state and) potential transport (mechanisms) of radioactivity to the general population (due to nuclear fusion). The PSA is used to (EPZ):

- (i) Optimize component outage scheduling
- (ii) Support operational decisions
- (iii) Evaluate plant modifications.

In the NPP of Borssele (EPZ) the initiating events are selected according to NUREG/CR-3862. The total



Figure 7. Nuclear power plant (NPP).

number of initiating events selected for quantification is 96, (141 event trees because of the different plant operating states) resulting in 2080 core melt sequences. All these initiating events are worked out in QRA-models. Partly the Purple Book (CPR 1999) is used, but the PSA for nuclear power is more extensive than in chemical power industry (EPZ).

Scenarios smaller than 10^{-7} /year are not included in the total risk. Further, the following “cut-off frequency” is applied; if the probability occurrence of an event times the probability of failure of safety measure is smaller than 10^{-10} /year, it is not included in the total risk (NRG).

Human factors are part of the model. The pre and post accidental human interactions are explicitly incorporated in the model and the human interactions during the incident are implicitly taken into account.

Uncertainties in the QRA-modelling in the nuclear power industry are smaller than other engineering fields, because it is obliged to report failures. This to guarantee all NPPs (worldwide) are aware of possible failures and can take safety measures. Another result of obligatory reporting of failures is a worldwide database of probabilities of failures, decreasing the uncertainties of the applied values. On top of that, tests are executed to determine probabilities of failure (NRG) and limit uncertainty.

Nevertheless, in case of hardware and plant configuration modifications, uncertainties arise on the probabilities of failure.

Within the business area of the nuclear power plant, the risk contour must lie below 10^{-6} /year.

5 CONCLUSIONS

The conclusions regarding the effective application of QRA-modelling for assessing tunnel safety are split up into three parts. First, the general conclusions

regarding the safety approach in all engineering fields are described. Second, the conclusions regarding QRA-modelling in general are addressed. Finally the conclusions on the effectively improvement of QRA-modelling for tunnel safety are reported.

5.1 Conclusions regarding the use of QRA in other engineering fields

- 1) In the researched engineering fields scenario analysis is always used in combination with QRA-modelling, because this also serves as input of the QRA. Scenario analysis is used to determine all possible calamities (“what can go wrong?”) and to get insight in the development of the consequences (calamity plan).
- 2) A different safety approach can be distinguished; limiting consequences vs. preventing accident. Due to presence of users in the assessed tunnel system, the focus also lies on limiting the consequences (self rescue), besides the prevention of an accident. The remark must be made that the development of tunnel fires is an complex problem. For the self rescue process this is an important issue to assess.
- 3) The technical systems in other engineering fields (aviation, chemical process industry and nuclear power industry) than tunnel engineering, have a more redundant character.
- 4) Personal liability/accountability stimulates the determination (and maintaining) the safety levels. This “incentive” is much more present in the private sector than in the public sector.

5.2 Conclusions regarding QRA-modelling

- 1) Difference in open/closed systems; In nuclear power and chemical process industry, the personnel only, has influence on safety level (closed system). This is contrary to the safety level of tunnels and dikes. In tunnel safety and flood risk, not only the related personnel is involved, but also the users of the tunnel or the inhabitants of an endangered area (open system). In the open systems the safety level depends on “inexperienced” people when dealing with accidents.
- 2) The level of uncertainty is a major issue for the probabilities in tunnel safety. Especially for:
 - The human factors implemented in the QRA
 - Implicit or explicit human factors
 - Implementing users as well as the operator and maintainers
 - Self rescue process of users.
 - The values applied for technical systems. In aviation, nuclear power and chemical process industry, there are less problems. This is due to (i) obligatory reporting of failures, (ii) worldwide databases and (iii) more tests to determine the probability of failure.

- 3) The QRA for tunnel safety will always be less certain than the QRAs applied to some other engineering fields, due to the fact that the escape process of users has to be taken into account. For flood risk, the amount of people present in the endangered area (possible victims), depends on (i) location, (ii) available time to flee and (iii) available infrastructure.
- 4) For an innovative engineering field like tunnel engineering, not all probabilities should be fixated, in order to maintain flexibility (see chemical process industry).
- 5) The QRA should be applied sooner in the building process in order to use it as an actual design tool and not only as a verification tool of the final safety level.

5.3 Conclusions regarding the improvement of QRA for tunnel safety

Which issues should be addressed, to ensure an effective use of QRA? The focus in this research lies on the completeness of QRA-modelling and the uncertainties in QRA-modelling for tunnel safety. Therefore the following conclusions can be drawn, considering these aspects:

- A) QRA for tunnel safety is incomplete on the following aspects (which are missing in all researched engineering fields, applying QRAs):
 - No link between the impact of the safety plans/procedures and the QRA.
 - Lack of verification of the initial conditions and the actual conditions in practice. This is of importance because the conditions set lead to (i) a QRA, (ii) plans & procedures and (iii) Safety Case.
- B) In QRA-modelling the following issues can be considered uncertain:
 - Human factors (not clearly mapped, uncertain values)
 - Self rescue process and emergency response (implementation in the QRA-model is difficult)
 - Probabilities used for technical systems.

If these issues are resolved, QRA-modelling for tunnel safety can be considered an effective application tool for assessing tunnel safety. Then the questions/uncertainties regarding the risk criteria can be researched.

REFERENCES

- Ale, B. J. M. & Uijt de Haag, P. A. M. 1999. *Guidelines for Quantitative Risk Analysis (CPR 18)*, In National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands.
- Ale, B. J. M., Golbach, G. A. M., Goos, D., Ham, K., Janssen, L. A. M. & Shield, S. R. 2001. *Benchmark risk analysis model*. RIVM Report 610066015, National

Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Apostolakis, G. E. 2004. How useful is Quantitative Risk Assessment?. *Risk Analysis* (24) 3: 515–520.

CPR. 1999. *Guidelines for quantitative risk assessment CPR 18E (Purple Book)*. CPR Committee for the Prevention of Disasters, The Hague, the Netherlands.

EASA. CS-25 Certification Specifications for large airplanes.

Kaplan, S. & Garrick, B. J. 1981. On the quantitative definition of risk. *Risk Analysis* 1: 11–27.

Keller, W. & Modarres, M. 2005. A historical overview of probabilistic risk assessment development and its use in the nuclear power industry: a tribute to the late Professor Norman Carl Rasmussen. *Reliability Engineering and System Safety* (89): 271–285.

Lees, F. P. 1996. *Loss Prevention in the process industries – volume 2 Hazard identification, assessment and control*, London: Butterworth Heinemann.

Morgan, M. G. & Henrion, M. 1992. *Uncertainty – A guide to dealing with uncertainty in Quantitative Risk and Policy Analysis*, Cambridge: Cambridge University Press.

TAW. 2000. *Van overschrijdingskans naar overstromingskans*. TAW 00.65, The Hague.

Tunnelsafety. 2003. *Beleidsnota Tunnelveiligheid Deel A Procésseisen*. Project team for tunnel safety; Cooperation between (i) the Ministry of Transport, Public Works and Water management, (ii) Ministry of the Interior and Kingdom relations and (iii) the Ministry of Housing, Spatial planning and the Environment. The Hague, the Netherlands.

Tunnelsafety. 2005. *Beleidsnota Tunnelveiligheid – Deel B Veiligheidseisen*. Project team for tunnel safety; Cooperation between (i) the Ministry of Transport, Public Works and Water management, (ii) Ministry of the Interior and Kingdom relations and (iii) the Ministry of Housing, Spatial planning and the Environment, The Hague, the Netherlands.

VNK. 2005. *Veiligheid Nederland in Kaart – Hoofdrapport onderzoek overstromingsrisico's*. DWW-2005-081, Ministry of Transport, Public Works and Water management, the Netherlands.

Vrijling, J.K. 2001. Probabilistic design of water defense systems in The Netherlands. *Reliability Engineering and System Safety* (74): 337–344.

List of Persons interviewed

(Airbus) Bob Lipscombe d.d. 09-01-2006
 (SE) COWI, Søren Degn Eskesen, Malmö City Tunnel d.d. 28-11-2005

(DK) COWI, Jørgen Kampman, Copenhagen mini me tro d.d. 21-12-2005
 (EPZ) H. Schoonakker, QRA expert Borssele NPP d.d. 13-1-2006
 (UK) London Underground Limited, Clare Kench, Risk analyst d.d. 06-10-2005
 (NLR) A.L.C. Roelen, Senior Scientist Safety & Flight Operations Department d.d. 21-11-2005
 (NRG) H. Brinkman, expert nuclear power industries d.d. 13-12-2006

Abbreviations

BRZO Besluit Risico's Zware Ongevallen ("Directive Risks Severe Accidents")
 CBA Cost Benefit Analysis
 CPR Commissie ter Preventie van Rampen ("Committee or the Prevention of Disasters")
 CS Certification Specifications
 DK Denmark
 EASA European Aviation Safety Agency
 EPZ Elektriciteits-Productie maatschappij Zuid-Nederland (owner Borssele nuclear power plant in the Netherlands)
 HSL High Speed Line
 IAEA International Atomic Energy Agency
 LUL London Underground Limited
 NLR Nationaal Lucht- en Ruimtevaart Laboratorium ("National Aerospace Laboratory")
 NPP Nuclear Power Plant
 NRG Nuclear Research & consultancy Group
 PSA Probabilistic Safety Assessment
 QRA Quantitative Risk Assessment
 QRM Quantitative Risk Management
 RSS Reactor Safety Study
 SE Sweden
 SIL Safety Integrity Level
 TAW Technische Adviescommissie Waterkeringen ("Technical Advisory committee Hydraulic structures")
 UK United Kingdom
 VNK Veiligheid Nederland in Kaart ("Safety of the Netherlands mapped")
 WST Western Scheldt Tunnel.