Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)
Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-5183-4_S06-03-030-cd

Measures for Tunnel Safety Management

Dana Prochazkova

VUT, Purkynova 464, 61200 Brno, Czech Republic, prochdana7@seznam.cz

Jan Prochazka

VUT, Purkynova 464, 61200 Brno, Czech Republic, japro2am@seznam.cz

Jana Viktorie Martincova

VUT, Purkynova 464, 61200 Brno, Czech Republic, 23907@usi.vutbr.cz

Tomas Kertis

VUT, Purkynova 464, 61200 Brno, Czech Republic, kertis@sport-sky.cz

The present article summarizes the requirements and demands for tunnels on surface routes from the safety viewpoint. Based on real data on tunnel failures, database of sources of risks, which were the causes of the tunnels´ failures, is established. The list of agents of failures was compared and supplemented by findings from research accessible in the scientific literature. The analysis of tunnel failures shows that in most cases, failure cause was combination of several sources, and therefore, the procedure for integral risk determination was proposed and tested in practice. Based on present knowledge, generic model for tunnel safety management is created. By critical analysis of failure impact data and response procedures and considering the risk management principles, they are proposed measures to improve tunnel safety.

Keywords: Transport infrastructure, tunnel, risk, safety, risk sources, tool for integral risk judgement, lessons learned, measures to improve safety.

1. Introduction

Tunnels on surface routes belong to critical elements of traffic infrastructure, which is important part of critical infrastructure of each country. Therefore, their problems are regularly solved on the ESREL conferences and regulated by the World Association PIARC. Each tunnel is represented as socio-cyber-physical system, the structure of which is system of systems (Procházková, Procházka 2020).

Present knowledge summarized in guidelines of PIARC (2021), legislation (EU 2004, 2008) and works (Procházková 2017, 2018, Procházková, Procházka 2020) require so each tunnel would be constructed in such a way as to be safe, i.e. stable, which means that it reliably performs its function (safe transport service) over its lifetime and does not harm itself and public assets in the vicinity, namely even under its critical conditions. Therefore, it also has specific equipment (PIARC 2021, Procházková, Procházka 2020), e.g.: smoke detectors and hazardous substances detectors; fire alarm; and illuminated fire emergency exits at fixed distances from each other, which are designed in such a way that smoke does not pass through them, etc. Most road tunnels and all railway tunnels have a ventilation system for extracting the smoke and hazardous substances. In tunnel, there are emergency stations located at fixed distances from each other, which are equipped with a telephone, alarm button and often fire extinguisher device. Many tunnels have cameras that are connected to the control panel in the tunnel manager's room. The tunnel manager can call emergency services if necessary. In addition, large tunnels have their own control systems that modify the transport mode inside the tunnel. According to the legal requirements of most developed countries, safety of road and rail tunnels is checked every four years, or after each of the breaches of tunnel security.

It is clear that tunnel accidents are much more dangerous than off-tunnel accidents, especially when hazardous substances are present. The presence of hazardous substances may result in fire, explosion and air contamination; accidents with BLEVE and VCE phenomena are particularly dangerous. Therefore, emergency services (police, firefighters and paramedics – integrated rescue system) regularly carry out drill to cope with accidents in tunnels. The article submitted summarizes on knowledge and management of the risks towards safety of tunnels in their construction and operation.

2. Summary Knowledge on Tunnels and Their Safety

Tunnels are technical facilities that are excavated in various geological subsoils, from soil to hard rock. Therefore, from the point of view of current knowledge (PIARC 2021, Procházková, Procházka 2020), safety of tunnels begins with the location and it is determined by: quality of specifications (terms of references), which must consider both, the geotechnical conditions in the subsoil and the sources of other risks at the site, and the requirements of the expected operation, i.e. in particular the limits and conditions given by the material used and the structure used; quality of construction; and way of operation in accordance with the stipulated limits and conditions set, and also maintenance quality during the life cycle.

As for any technical facility, the tunnel safety is determined primarily by the measures inserted into the project rather than by those taken during the operation (Procházková, Procházka 2020). According to the findings in (Haukur 2012, Kroon, Kampmann 2004, NFPA 2010, PIARC 2021, Powers 2007, Procházková, Procházka 2020, Sutcliffe, 2004) in the tunnel design, many aspects must be considered in order to correctly select safety measures and procedures. Normative guidelines and the results of risk assessments are used to select measures. It is easy to identify tunnel safety measures and procedures through normative directives and checklists. Normative guidelines provide a standard set of solutions and have the advantage of setting the consistent benchmarking and are easy to apply in similar projects. According to valid ISO 9000 standard, except to normative requirements , the risk analysis results need to be applied from safety reasons.

Engineers at tunnel construction have to deal with both, the static and the dynamics when building the tunnels. The static describes how the physical forces interact and what is needed to create balance on the tunnel structure. According to specific conditions, materials – masonry, steel, reinforced concrete and methods of their inter-connection - are then chosen. From the point of view of dynamics, specific measures are implemented against changes in material and object over time, against vibrations associated with vehicle traffic and in seismic areas, also caused by earthquakes. Since the environment, in which the tunnel oven is stored, is still working and the movement of vehicles contributes to changes in the environment, geotechnical monitoring, which is based on the measurement of deformations of the tunnel excavation, is of great importance during the tunnel construction and the operation. From safety reasons tunnel complex needs to include a lot of systems, e.g. systems: mechanical; drainage; electric (lighting); ventilation; communication; traffic monitoring; information; early warning; for the detection of fire, smoke and other hazardous substances; and fire extinguishers.

3. Risk Management towards Tunnel Safety

The risk management technique itself formally reviews the management and settlement of risks in the context of benefits and costs of outputs before each stage of risk management. The Coase theorem (Coase 1960) is used to determine the economic optimum in the cost of risk settlement; Figure 1.

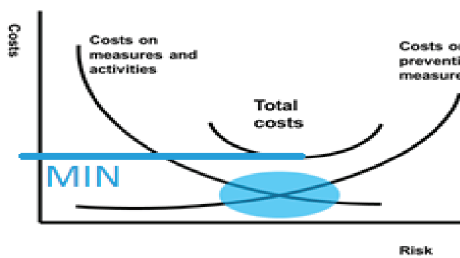

Fig. 1. The total cost interval in which safety is ensured; the area of optimal costs for safety margins is marked in blue.

This figure shows that it is necessary to compare the cost of risk reduction and the cost of necessary measures, i.e. the application of the CBA method (Procházková 2018) with compliance with safety requirements. It is clear from the figure that in practice it is about ensuring an acceptable level of safety. This means that some risks are not sufficiently eliminated and may cause damage in the future, and therefore, in the context of risk settlement, it is also important to prepare and ensure the response including the appropriate technical equipment and qualified response personnel and by that ensure the ability to carry out response and recovery (Procházková, Procházka 2020).

The purpose of the construction of tunnel safety management system is to find economically efficient processes that ensure certain level of safety and security of the objects in question, and this is monitored at all stages, i.e. from design, through analysis and development, construction, operation, modernization to disposal (Procházková 2017, Procházková et al. 2019).

4. Data and Methods Used at Research

By collecting and processing the real particulars on tunnel failures and accidents, database of the sources of the risks, which were the causes of the tunnels´ failures, was created. The list of causes of failures was compared and supplemented by findings from research accessible in the scientific literature. The database (CVUT (2022) contains data on 965 road and railway tunnel failures and 53 case studies since the beginning of the 19th century; for reader information for example the terrorist attacks in the underground railway have been recorded since 1883. The data were critically analyzed, tunnel failures were sorted and represented by the Ishikawa diagram. In cases of sufficient number of qualified data sets, the case studies were processes and evaluated. For decision-making on integral risk, the decision support system (Procházková, Procházka 2020) is used.

5. Results of Tunnels´ Failures Research

A critical analysis of the data in the EU project materials (EU 2006) and our database (ČVUT 2022) shows that, as a rule, a combination of several factors is the cause of each transport tunnel failure. A Fishbone diagram showing the basic categories of causes of tunnel failure is shown in Figure 2.

Results of critical analysis of both, the tunnel failures and the case studies (Procházková, Procházka 2020), confirmed the conclusions for complex technical facilities (Procházková et al. 2019). They confirmthat the human factor plays a major role in the occurrence of accidents, both as the cause of accidents, where its manifestations have already been demonstrated by work (Reason 1993), as well as the architect of an effective response.

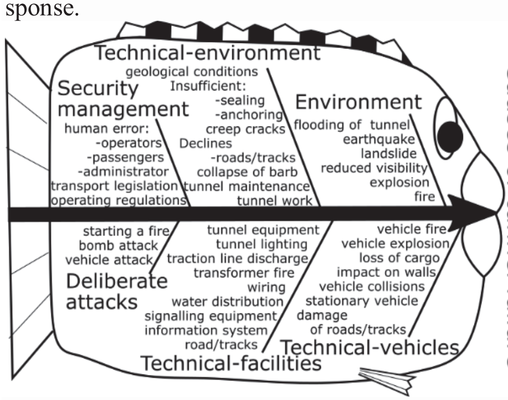

Fig. 2. Sources of risk of tunnel failure on the routes.

The analysis of tunnel failures performed (Procházková, Procházka 2020) confirmed the participation of the human factor in more than 80% of tunnel failures. In doing so, three main causes have emerged. The first cause is human error, which originates in poor communication and cooperation. The second cause is a failure or insufficient response of operators and managers to situations that have the potential to cause tunnel failure. The third cause is that both managers and operators take a high risk without being sufficiently aware of its impact.

The tunnel failures analyzed were either caused by the occurrence of a harmful phenomenon (disaster) not envisaged in the project or underestimated in size, or by the accumulation of many small harmful causes, which in themselves do not have significant harmful potential, in a short period of time. Their accumulation is the cause of latent conditions, which can have a long incubation period, which results from the fact that large numbers of sources of failure can be based on systems and will manifest themselves when a trigger appears in the form of human error. Therefore, to prevent tunnel failures, it is necessary to avoid: major risk prevention errors, and also the occurrence of minor errors, the accumulation of which in a short period of time is dangerous (Procházková, Procházka 2020), which is also confirmed, for example, by (Geysen, 2002, Procházková et al. 2019).

Detail investigations and results of discussions with experts given in (Procházková, Procházka 2020) show that tunnel failures occur because: so far, outdated risk assessment methods are used for tunnels (e.g. tree models) that do not consider the concurrency of several phenomena; the operator or owner is mainly focused on performance (i.e. profit) and the public administration allows it to do so; personnel in contact with the causes and impacts of risks do not have sufficient competences to implement proactive measures and operating regulations adapted to current conditions (normal, abnormal, critical); and technical decisions are subject to various specific, political or economic pressures and do not take into account the specific risks that arise during operation.

According to research results (Procházková, Procházka 2020), the basic reasons why tunnel operators are unwilling to influence risks are also: lack of awareness of the risks and their impacts on the tunnel and its surroundings; subjective feelings of the responsible body who does not consider the risk to be up-to-date; the idea that the risks relate to the distant future; the steps leading to risk identification and reduction are generally contrary to the immediate (mostly economic or political) interests of the operator or owner; and in most case, a particular competent worker (who identifies risks symptoms) is not the one who can directly decide on risk reduction steps.

Improper risk management in tunnels (Procházková, Procházka 2020) is caused by shortages that are observed in practice:

- Due to tunnel complexity, tunnel decision-making processes shall to be multilevel (Zairi 1991), but in practice in organization management structure responsibilities for activities and decisions are not often clearly determined.
- The management considers work with risks as compliance with standards and regulations, which covers only 68.4 % of possible conditions (Procházková 2017), which means that 31.6% of possible conditions they neglect.
- In-service engineers and its management have a close understanding of safety; the technical safety orientation of the equipment is so prevalent that the technical equipment does not present a danger during its life cycle.
- There is a lack of cooperation between professions – builders, machinists, economists, chemists, computer science, human resources, etc. – each profession works separately, which does not allow to solve interdisciplinary and multidisciplinary problems.
- Many managers believe that everything is eternal, i.e. they do not consider changes in technical equipment over time and with a change in conditions, and thus underestimate the maintenance, repair, skill and observance of work regimes that respect physical, chemical and biological laws.

A critical analysis of tunnels´ failures listed in the database (CVUT 2022) has shown that some causes of failure are often repeated, such as traffic accidents, inadequate maintenance, poor quality of repair and modernization. Their common root cause is the lack of a culture of safety of tunnel participants, their lack of training and motivation to target safe work and safe behavior.

6. Measures for Tunnel Safety Management

Based on knowledge and experiences with management of complex systems with socio-cyber-physical nature (Procházková 2017, Procházková et al. 2019), the tunnel safety management generic model was establish using the principles of risk-based design and risk-based operation (Procházková et al. 2019).

Generic model for tunnel safety management contains activities to ensure the safety; roles of all items which are involved in safety; tasks specified in the safety management system; and items of risk management process directed to safety and their order. Its main features are shown in Figures 3 and 4.

For tunnel safety, the operator needs to ensure three public interest objectives:

- The first objective is to ensure the dependability of the tunnel and its equipment, since the item being monitored ensures the services for which it is created.
- The second objective is to ensure the integral (systemic) safety of the tunnel, i.e. to protect the tunnel from disasters of all kinds (both internal and external, including the human factor).
- The third objective is to ensure that even under its critical conditions the tunnel does not endanger itself and its surroundings, i.e. other public assets, i.e. the systemic nature

changing over time in different ways must be considered.

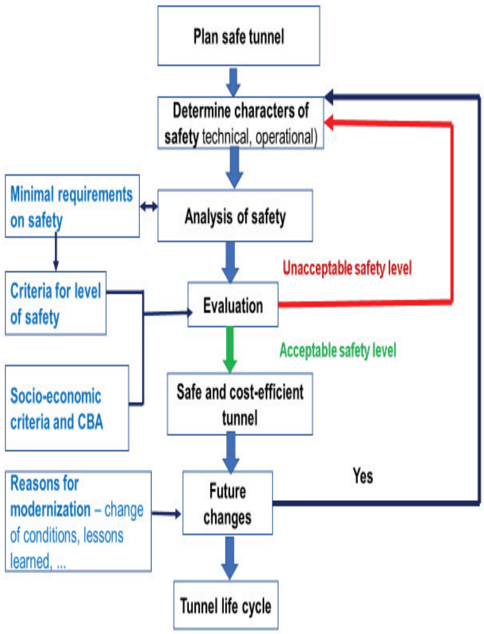

Fig. 3. Procedure for ensuring the safety of tunnels on the road; processed according to (EU 2006).

At the owner / operator level, safety management requirements are often at odds with their primary objectives in the short and medium term, as operators focus primarily on profits. Therefore, state surveillance must exercise effective and correct supervision, as it concerns human lives and health, but also economic prosperity, because transport infrastructure is the backbone of critical infrastructure that is necessary for national security.

In view of long-term development, i.e. maintaining the competitiveness over time, a risk management system aimed at preventing the loss of profit due to neglecting low frequent high risks (Procházková, Procházka 2020) needs to be put in place in the tunnel management today. With regard to the importance of tunnels, it is, therefore, the State needs to enforce risk management to focus on preventing the losses in public assets (the lives and health of people, property, the environment, the public good, infrastructure and others), and therefore, the State needs to put into practice legislation that imposes consideration of certain risks and the appropriate settlement of certain risks.

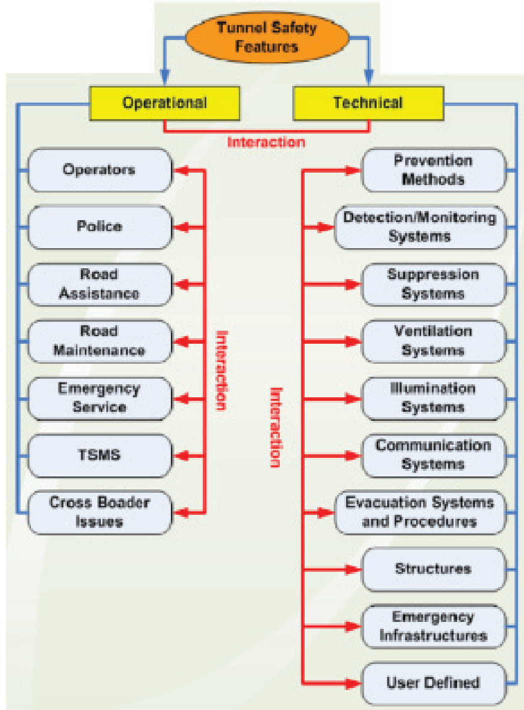

Fig. 4. Aspects relevant for the safety of tunnels on the road; processed according to (EU 2006).

Because the sooner the response to a traffic accident or tunnel failure or breakdown for another reason is initiated, the lower the losses, and therefore, it is already necessary to create conditions for response when designing tunnels with high traffic. For practical use, the tool for integral risk management towards integral safety in the form of decision support system is constructed for tunnels (Procházková, Procházka 2020). By this tool it is possible to monitor tunnel conditions and in time to apply countermeasures.

The concept of tool deems tunnel as a socio-cyber-technical system. It is considered that the competences and responsibilities that free up the necessary resources for risk management and settlement measures and activities for the benefit of safety depend on the level of the organizational structure. The highest competences are at the highest levels, as shown in the work (Procházková 2017). Therefore, also at this level there are the greatest responsibilities for managing the risks of tunnels in favor of safety in the State; and the principle of liability, which is common in Europe (Delongu 2016), is considered, which in the present case means that responsibility for tunnel safety, i.e. for the level of work with risks associated with a technical facility, lies with both, the owner and the public administration, which has a duty of supervision in the public interest. The tool for integral risk determination in the form of decision support system (DSS) was constructed by using the principles of decision with multiple objectives (Keeney, Raiffa 1993). The complete tool is in (Procházková, Procházka 2020); example is in Table 1.

Table 1. Selected parts of checklist for integral risk assessment for the tunnel during the operation. DRM - Directorate of Roads and Motorways; RA - Railway Administration.

Criterion	Assessment	Note.
The extent to which the Ministry of Transport understands and implements responsibility for the integral safety of the tunnel.		
The extent to which the Ministry of Transport and the control documents for the operation of the tunnel consider the impact of disasters that are possible in the territory by using the All-Hazard-Approach and remedy the deficiencies.		
……		
The extent to which DRM/RA and the control documents for the operation of the tunnel consider the impact of DRM/RA errors in the enforcement of the principles of safety culture and remedy the deficiencies.		
……..		
The extent to which the tunnel manager understands and implements responsibility for tunnel safety.		
The extent to which the tunnel manager and the tunnel management documents consider the impact of tunnel manager errors in the tunnel safety management section and remedy the deficiencies.		
The extent to which the tunnel manager and the tunnel management documents consider the impact of the tunnel manager's errors in the safety and risk awareness section and implement the correction of deficiencies.		
……		
The extent to which the technical management (i.e. management of specific technical equipment) of the tunnel understands and implements responsibility for the safety of specific technical equipment of the tunnel.		
…….		

The assessment of individual criterions in Table 1 often assumes that all criteria have the same weight. Practical examples in (Procházková, Procházka 2020) show that in many cases some criteria are more important than others, and therefore, in practice it is often necessary to assign them higher weight. The rate of integral risk is determined according to Table 2 (Procházková 2017).

Table 2. Value scale for determining the risk rate; N = five times the number of criteria in Table 1; N = 1305.

The level of risk	Values in % N
Extremely high – 5	More than 95 %
Very high – 4	70 - 95 %
High – 3	45 - 70 %
Medium – 2	25 – 45 %
Negligible – 0	Low than 5 %

The evaluation of real cases according to Table 1 needs to be performed by team of specialists from different fields independently; in practice (Procházková, Procházka 2020), it comes useful team consisting of: worker of public administration responsible for territory safety; worker of public administration responsible for the development of the territory; representative of tunnel management; representative of the professional institution for the tunnel safety assessment, for example from the technical inspection; and representative of the Integrated rescue system. The resulting value is the median for each criterion, and in cases of great variance of the values in one criterion it is necessary, so that the worker of public administration responsible for territory safety may ensure further investigation, on which each assessor shall communicate the grounds for his / her review in the present case, and on the basis of panel discussions or brainstorming session, the final risk rate value is determined.

Considering: the ALARP principle as in works (Ale 2005, Boulder, Slavin, Ragnar 2007, Delongu 2016, EU 2006); the integrated approach as in works (Bruce 2003, Levitt, Logcher, Quaddumi, 1984); and the assumption that all risk sources have the same occurrence probability, we obtain the requirement for tolerable risk measured by the tunnel maximum annual losses ***RZTD***

$$\boldsymbol{RZTD < 0.1 \sum_{i=1}^{n} \frac{k_i \, HTD}{5\, T}},$$

where ***HTD*** is the tunnel utility value, $\boldsymbol{k_i}$ are result evaluations of risk sources in Table 1, n is the number of risk sources (in Procházková, Procházka 2020, it is 261) and $\boldsymbol{T}$ is the tunnel lifetime in years. When this condition is not fulfilled, it needs not the tunnel operation be permitted because the safety is not sufficient. It means that other risk reduction measures should be requested, followed by a further assessment of the tunnel safety.

According to results (Procházková, Procházka 2020), the DSS should be contained in the tunnel safety management system (TSMS), so the TSMS obtain the capability to prevent tunnel failures caused by risk sources combinations. The other research results for tunnel safety ensuring show that tunnel operator must:

- Monitor the situation and traffic operation in and around the tunnel using the cameras and sensors and communication equipment to ensure normal operation.
- Have a response ready in the event of tunnel failure.
- Have an effective warning system and the ability to quickly and correctly detect any phenomenon that may lead to the failure of the tunnel and its function.
- Have facilities for closing the tunnel.
- Have equipment for contact with emergency services.
- Have equipment for contact with tunnel users.
- Have trained personnel to control the tunnel in possible situations – normal, emergency and critical.
- Have maintenance plan.
- Have inspection plan – regular inspection of emergency exits, tunnel anchoring, geotechnical monitoring required are necessary.
- A risk management plan.

A risk management plan is particularly important for the tunnels operated, the model solution for complex technical facility of which is presented in the work (Procházková et al. 2019); it must be adapted to real tunnel architecture and conditions.

7. Conclusion

The article deals with the risks and safety of tunnels on roads and railways. It summarizes the requirements and demands on traffic tunnels from the point of view of safety, especially on its management. For purposes of the research, a database of tunnel failures on roads was compiled. Its critical analysis determines the causes of the risks that were the cause of the failure (Figure 2). The database and case studies (ČVUT 2022) as well as the project results (EU 2006) show that when a tunnel fails, the following occurs: loss of humans´ lives (history shows cases where hundreds of people died due to air contamination mostly caused by CO); damage to the health of humans in the tunnel and its surroundings; damage to the tunnel object (walls, ceiling, lining, roadway, rails, tunnel equipment); environmental damages around the tunnel; reduction of transport services; economic damage caused by delays in transport and delivery; and costs the response to traffic accidents and the cost of restoring the tunnel's operability.

From above given reasons, risks from all possible causes need to be considered according to the All-Hazard-Approach (FEMA 1996) developed for Europe in the FOCUS project (EU 2013). Particular attention should be paid to the transport of hazardous substances, i.e. to respect not only the ADR (UN 2019) and COTIF directives (OTIF 2020), but also the local specificities resulting from the analysis of local conditions (Procházková, Procházka 2020). Due to changes in conditions and technical objects over time, it is necessary to have the right plans for risk management, which are based on real conditions and possibilities of administrators, supervisors and other state administration (Procházková, Procházka 2020).

Because analysis of tunnel failures showed that in most cases, failure was caused by combination of several sources, the procedure for integral risk determination is proposed and tested in practice. For creating the tunnel safety, it is compiled the generic model for tunnel safety management. Its comparison with (PIARC 2021) shows consensus. This model is included into prepared national legislation codifying the safety documentation for tunnels. By critical analysis of failure impact data and response procedures and considering the risk management principles, they are proposed measures to improve tunnel safety.

Acknowledgement

Authors thank for support to TAČR project CK1000095.

References

Ale, B. (2005). Tolerable or Acceptable. A Comparison of Risk Regulation in the United Kingdom and in the Netherlands. *Risk Analysis*, 25 (2005),2, pp. 231-242.

Boulder, F., Slavin, D., Ragnar, E. (2007). *The Tolerability of Risk: A New Framework for Risk Management.* London: Taylor & Francis 2007, 160 p.

Bruce, J. F. (2003). *Investment Performance Measurement.* New York: Wiley 2003, 748 p.

Coase, R. H. (1960). The Problem of Social Cost. *Journal of Law and Economics,* 3 (1960), pp. 1-44.

CVUT (2022). Database of Tunnels Accidents and Failure. *Archives.* Praha: ČVUT 2022.

Delongu, B. (2016). *Risk Analysis and Governance in EU Policy Making and Regulation.* Springer 2016, 288 p.

EU (2004). Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on Minimum Safety Requirements for Tunnels in the Trans-European Road Network, *Official Journal* L 167 of 30.04.2004.

EU (2006). *Project Safe-T. Safety in Tunnels Thematic Network.* Brussels: EU 2006. www.safetunnel.net

EU (2006). *Land Use Planning Guidelines in the Context of Article 12 of the SEVESO II DIRECTIVE 96/82/EC as Amended by DIRECTIVE 105/2003 /EC.* Brussels: Joint Research Centre.

EU (2008). [5] EU. Council Directive No. 2008/114/ EC. *Official Journal* L 345, 23.12.2008.

EU (2013). *FOCUS Project.* Brussels: EU 2012, http:// www.focusproject.eu/documents/14976/-5d76337 8-1198-4dc9-86ff-c46959712f8a

FEMA (1996). *Guide for All-Hazard Emergency Operations Planning.* State and Local Guide (SLG) 101. Washinton: FEMA.

Haukur, I. (2012). *Proceedings from International Conference on Safety in Road and Rail Tunnels.* New York: Science Partner , 745 p.

Keeney, R. L, Raiffa, H. (1993). *Decision with Multiple Objectives*. Cambridge: Cambridge University Press 569 p.

Khouri, G. A., Molag, M. (2006). *Safe T Project Outline.* Brussels: EU 2006.

Kroon, I. B., Kampmann, J. (2004). Decision Support Model for Tunnel Design and Operation. *Tunnel Management International.* ISSN 1463 (2004), pp. 111-120.

Levitt, R. E., Logcher, R. D., Quaddumi, N. H. (1984). Impact of Owner-Engineer Risk Sharing on Design Conservatism. *ASCE Journal of Professional Issue in Engineering.* 110, pp. 157-167.

NFPA (2010). *Standard for Safeguarding Construction, Alteration, and Demolition Operations.* http://www.unece.org/trans/danger/publi/adr/adr2019.

OTIF (2020). *The Convention Concerning International Carriage by Rail.* www.otif.crg

PIARC (2021). *Tunnels Safety Manual.* https://tunnelmanual.piarc.org

Powers, P. J. (2007). *Construction Dewatering and Groundwater Control*. New York: John Wiley & Sons Inc.

Procházková, D. (2017). *Principles of Management of Risks of Complex Technological Facilities*. Doi: 10.14311/BK.9788001061824.

Procházková, D. (2018). *Analysis, management and Settlement of Risks of Technical Facilities.* Doi: 10.14311/BK.9788001064801

Procházková, D., Procházka, J. (2020). *Risks and Safety of Tunnels on Routes*. In: *Řízení rizik procesů a bezpečnost složitých technických děl*. Praha: ČVUT, pp. 268-318. http://hdl.handle.net /10467/ 91988

Procházková, D., Procházka, J., Lukavský, J., Dostál, V., Procházka, Z., Ouhrabka, L. (2019). *Management of Risks connected with Technical Facility Operation.* Doi:10.14311/BK.9788001066751

Reason, J. (1993). *Human Error*. Cambridge: Cambridge University Press.

Sutcliffe, H. (2004). Tunnel Boring Machines. *In: Bickel, J. O., Kuesel, T. R., King, E. H. (eds.). Tunnel Engineering Handbook. Dordrecht: Kluwer Academic Publishers,* p. 210.

UN (2019). *European Agreement concerning the International Carriage of Dangerous Goods by Road* (ADR). http://www.unece.org/trans/danger/publi/adr2019

Zairi, M. (1991). *Total Quality Management for Engineers.* Cambridge: Woodhead Publishing Ltd.