Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Statistical interpretation of tunnel project characteristics and their influence on technical risks – current and future challenges

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ABSTRACT: Tunnels are an increasingly significant part of our built infrastructure. Simultaneously, they are subject to a diversity of inherent uncertainties associated with the geotechnical, hydro-geological, and physical environment surrounding them. The associated risks can materialize on many occasions, leading to disasters with substantially high reinstatement costs, incurred delays, and damage to adjacent third-party assets and the environment. Such disasters can occur due to extreme natural events and unforeseen and unforeseeable ground conditions or accidents. but also, human-driven issues, such as substandard design, poor project management, aggressive project timelines leading to safety shortcuts, compressed budgets and application of innovative techniques not yet fully tested and validated, are some factors contributing to an increased probability of risk materialization and disastrous events. This paper aims to provide a statistical interpretation of tunnel project characteristics and their influence on technical risks based on a database with approximately 400 tunnel failure cases. A further goal of the study is to support decision-makers in the risk management process, such as owners, engineers, and insurers by improving their understanding of project sensitivities. The results indicate the significance of technical characteristics (such as tunnel dimensions, construction type, and ground formations). Still, they also reveal some dependence between lower project risks and the application of current project and risk management practices.

1 INTRODUCTION

During the last century, the world population increase has contributed to underground space development. Underground space is considered to be a major asset in today's infrastructure (Paraskevopoulou et al. 2019). Just in the last decade, an annual increase of 5-7% in the tunnelling and underground industry has been observed with Asia and more specifically, China leading this increase. However, uncertainty is a significant concern in tunnelling. The variability and complexity of the geological medium and in-situ conditions can exacerbate the design leading to construction failures and const overruns (Benardos et al. 2013; Paraskevopoulou & Benardos, 2012; 2013; Paraskevopoulou and Boutsis, 2020). Consequently, the optimisation design of underground structures is desired to primarily secure the working personnel's safety and avoid cost overruns and project delivery delays while ultimately targeting sustainability and resilience. This work discusses tunnel failures analysing the leading factors by presenting statistical interpretation indicating the driving parameters. The ultimate goal of this presented work is to assist the decision maker and shareholders

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(owners, engineers and insurers) in the risk management process in tunnelling to improve the potential losses, better estimate the length of project delays and cost overruns.

2 BACKGROUND

2.1 *Uncertainty in tunnelling*

In tunnelling, common practice to assess risks is developing case-specific Geotechnical Baseline Reports (GBRs). There, however, fail to give information about the geological problem and instead provide information on allocating risks between the parties involved, commonly between the owner and the contractor). More specifically, the anticipated geological model in the report falls into the contractor's financial responsibility. Anything else that automatically exceeds or is not mentioned in the baseline statements is the owner's responsibility (Yau et al. 2019; Yau et al. 2020), leaving many grey areas hanging. The latter implies the need for a sound Geological Investigation (GI) at the preliminary stages of the design to develop an understanding of the most probable geological scenario. Carter (1992) showed that the risk of unforeseen problem(s) can be reduced with an expenditure increase in the geological investigation. Venturini et al. (2019) developed this further by showing the various optimum scenarios based on the geological complexity and the GI campaign. Paraskevopoulou and Boutsis (2020) investigated the GI expenditure increase and its contribution to the total cost of tunnelling projects. They highlight that uncertainty cannot be eliminated by reduction, showing which of the three levels of uncertainty can be improved in a tunnelling scenario shown in Figure 1. Finally, Paraskevopoulou et al. 2021 showed how geological and geotechnical uncertainty could be captured and reduced from the initial design stage using a tunnel case study of a twin tunnel excavated in the heterogeneous molassic environment in Northern Greece.

It is implied from the above then that the biggest hurdle to overcome is to reduce the level of uncertainty you need to have a) a comprehensive understanding of the geological model (geological/depositional history, tectonics, geodynamics etc) and; b) a thorough understanding of the geotechnical model (quality of direct investigation, quality of geophysics etc).

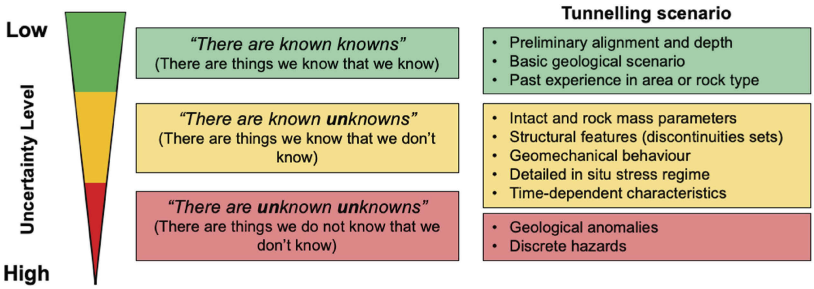

Figure 1. Design uncertainty levels associated with a tunnelling scenario (presented in Paraskevopoulou and Boutsis, 2020; modified from Langford 2013). Original quotes are from former US Secretary of Defence Donald H. Rumsfeld.

2.2 *Failures and collapses in tunnelling*

It is evident these days that 40% of tunnel collapses are attributed to design and construction errors (Reiner, 2011) whereas 20% of all failures result in accidents (Proske et al. 2019). Spyridis and Proske (2021) concluded that the collapse frequency in real tunnel construction projects can be explained based on specific boundary parameters with reasonable scatter. They continue that failure probabilities for tunnels under construction and operation appear to be governed by many non-structural parameters. As such, tailored target values can apply to different structures and life-cycle phases. Furthermore, the differences between individual probabilistic computations and the deviation between observation and computation may indicate either the requirement or the application of hidden safety in the current computations. Heller (2002) suggests tunnel failures have different severity impacts, which depends mainly on the geological medium, excavation and support methods adopted. Sousa (2010) analyses 234 cases of major tunnel incidents concluding that 48% of the reported failures were recorded in NATM (observational construction method), 30% in Mechanised tunneling and 15% in Drill and Blast. Spyridis and Prsoke (2021) enriched the dataset of Proske et al. (2019) that was initially based on Konstantis et al. (2016) analysing 321 cases and concluded that 58% of the reported tunnel failures are attributed to NATM construction methods, 25% to TBM, 12% to Drill & Blast and the 5% to Cut & Cover and other construction methods. Sousa and Einstein (2021) showed that 56% of the analysed accidents using Sousa's (2010) database occurred near the tunnel face and less behind the face in the excavated tunnel. Recently Paraskevopoulou et al. 2022 also showed that the 48% of the failures are attributed to the observational method (NATM), 34% to mechanized tunnelling ang 14% to Drill and Blast only 4% to Cut & Cover based on the analysed dataset. It can be easily concluded that all these studies agree that most tunnel failures occur when tunnelling with NATM.

2.3 *Risk assessment in tunnelling and cost overruns*

The tipping point for introducing and applying risk management in the UK tunnelling steamed from the Heathrow Express Tunnel Collapse back in 1994 when the Health & Safety Executive (HSE) reported "the worst civil engineering disaster in the UK in the last quarter century". The collapse's recovery took nearly two years and cost around £150M, accounting for nearly three times the cost of the original contract. It was not until 2003, though, that the Code of practice was established. The final version was published in 2006 by the International Tunnelling Insurance Group (ITIG) and revised years later in 2012. The Code of Practice aims to provide guidelines on best practices to minimise risks in tunnelling by first assessing it, recording it and ultimately proposing mitigation measures. These activities take place in the risk register a live document/platform that required constant updating during the project's progress.

Poor design practices can lead to failures when risk assessment in tunnelling is not adopted. Dunn (2012) suggested that these failures can have a range of severity levels from accidents that can harm personnel and/or equipment, consequently triggering project delivery delays and, thus cost overruns. Paraskevopoulou and Boutsis (2020) showed that cost overruns can seldom be avoided. Paraskevopoulou and Benardos (2013) proposed a tool that assists in cost estimation of road tunnels based on the quality of the geological medium and can be used by practitioners to preliminary the tunnel cost. Konstantis et al. 2016 proposed a linear relationship that relates the insurance cost and the corresponding delay of the project, analysing the frequency distribution of 27 cases due to the limitation of data available; one can imagine why.

3 THE DATABASE

The initial database in the presented work was provided by Spyridis and Proske (2021), and it was further developed by Paraskevopoulou et al. (2022). The database includes a list of the tunnel incidents (failures) during both construction and operation. The main factors analysed are: failure type, report causes, length of the tunnel, the diameter of the tunnel, overburden, *excavation (tunnelling) method*, excavated medium: rock, soil or both, fatalities, losses and the source of information (Figure 2).

The initial database was enriched by adding seven more factors: tunnel type, geological information, stress conditions, water conditions, portal failure, third-party impact and delays shown in Figure 2.

A	B	C	D	E	F
Year	Country	Project Name	Tunnel Use	Failure Type	Construction /Operation
G	H	I	J	K	L
Cutting Technique	Incident, Report and Cause	Length (m)	Diameter (m)	Overburden (m)	Rock/Soil
M	N	O	P	Q	R
Geological Information	Stress Conditions	Water Conditions	Portal Failure	Third Party Impact	Fatalities
S	T	U			
Losses (mil. $)	Delay	Source of Information			

Figure 2. Main parameters selected during the development and generation of the database.

4 STATISTICAL INTERPRETATION & SELECTIVE RESULTS

Based on the dataset, statistical interpretation is performed in order to identify key relationships and trends to assist in developing a further understanding about the tunnel failures examined. The dataset is examined in terms of tunnel types, tunnel dimensions, construction type, and ground formations, the impact of code practice, failures during operation etc.

4.1 *Failures during construction*

From the analysis it is shown that the tunnel type does not have a significant impact on the failure type as shown in Figure 3a. However, the tunnelling/construction method does have an impact. As previously mentioned, NATM and TBM tunnels govern the failure types. This implies that the geological medium can impact primarily the likelihood of failure (Figure 3b). Drill & Blast tunnels usually preferred in good quality geological medium (hard rocks) have reported less failures than the other two.

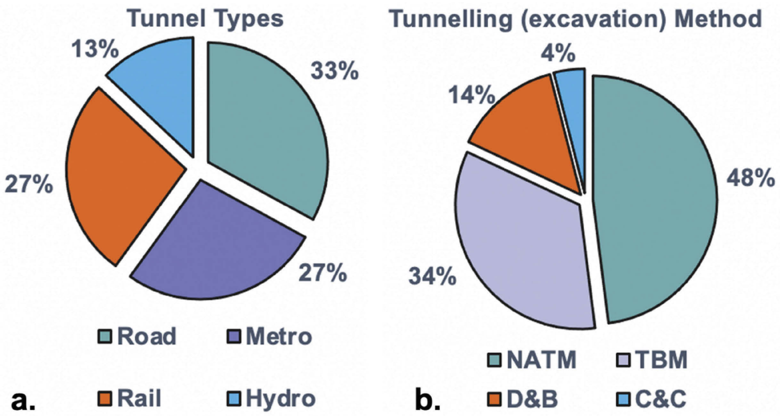

Figure 3. Distribution of a. tunnel types; and, b. distribution of tunnelling (excavation) methods, examined in this database; all tunnels examined have reported failures during construction (presented in Paraskevopoulou et al. 2022).

The geological medium a tunnel excavated can be simply described as rock or soil. It is expected that excavation and support can hinder challenges in soil-like materials, and the common practice is more standardised. This grouping showed that 64% of the failures are observed during rock construction compared to 36% in soil. However, this separation between soil and rocks does not assist in further understanding the failure likelihood. For this reason, further categorisation is performed.

Figure 4 highlights the wide range of ground materials that failed during construction. It is shown that 56% of the observed failures are in sedimentary rocks (i.e. sandstone, shale, marlstone, limestone, chalk), whereas the remaining varies from granite to coal and other volcanic. It should also be added that in this categorisation NATM's failures occurred 44% more in rock than in soil, while TBM's failures occurred 8% more in soil than in rock.

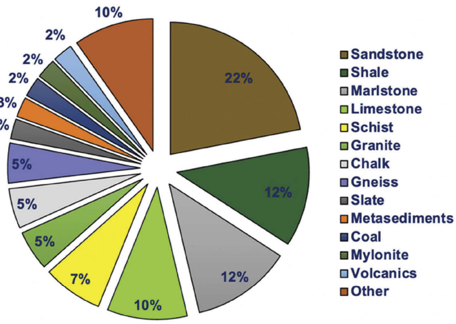

Figure 4. Rock materials in which failures have been reported during tunnel construction (presented in Paraskevopoulou et al. 2022).

From the analysis it was shown the tunnel length does not impact significantly during construction. It is worth mentioning that 45% of NATM failures took place in tunnels less than 3 km. The tunnel diameter however does affect the likelihood of failure as it is rational to be inferred given the increase of the tunnel face exposure and around 30% of the reported failures have occurred in diameters between 10-13 m corresponding to NATM practices. (Figure 5a) while in TBM tunnel failures are reported in tunnel diameter less than 10 m. The overburden (Figure 5b) shows that in 15-30 m overburden failures are reported more in tunnel excavated in soils whereas in more then 30 m the failures are related to tunnel excavated within rock, which can be easily justified as usually with depth the transition between soil and rock takes place.

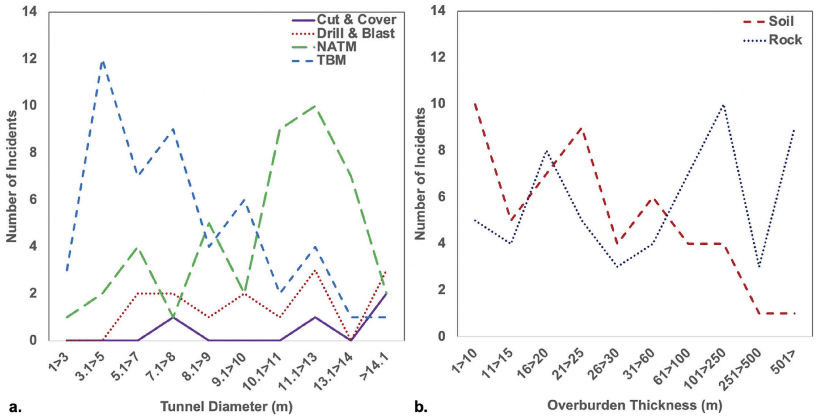

Figure 5. Number of reported tunnel failures per: a. excavation (tunnelling) method; and b. overburden thickness grouped based on for soil and rock medium (presented in Paraskevopoulou et al. 2022).

4.2 *Failures during operation*

Tunnel failures, however, do not occur only during construction. From the database analysed it is shown that various external factors and discrete hazards have a significant impact on the number of incidents. Fires and earthquakes account for the 82% of the failures during operation as shown in Figure 6a whereas the failures due to design errors are only 18%. The severity of these failures is also a major parameter to consider as some of them can lead to fatalities. Figure 6b show that the 90% of failures due to fire causes lead to fatalities.

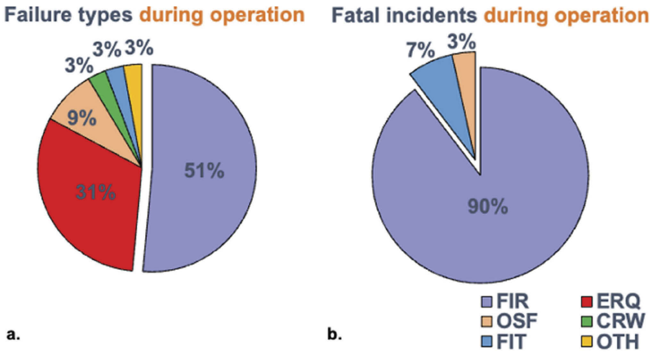

Figure 6. During tunnel operation: a. failure types; and, b. fatal incidents, where: FIR (fire), OSF (support overstressing), FIT (Fit-Out Works), ERQ (earthquake), CRW (crown) and OTH (other type) (presented in Paraskevopoulou et al. 2022).

4.3 *Code of practice*

The dataset was categorised into two groups before and after 2006, the year when the Code of Practice was published. Figure 7a illustrates the impact of the code's establishment and implementation.

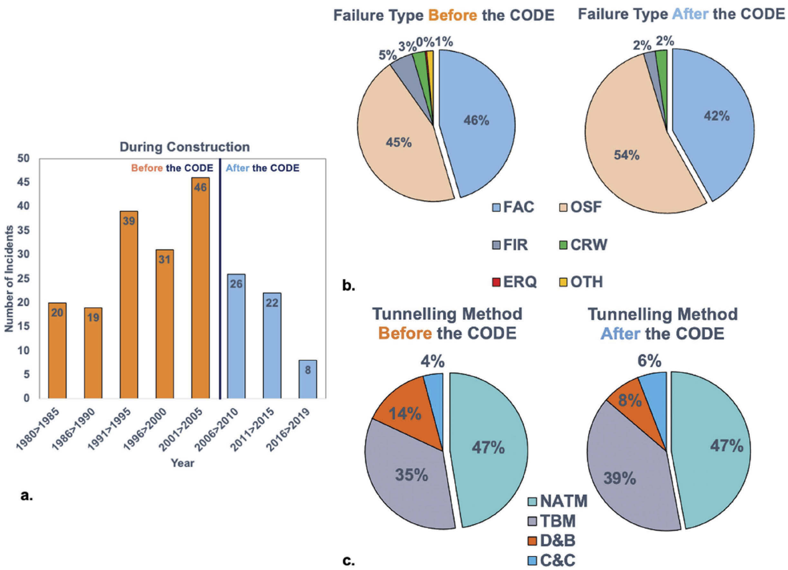

Figure 7. a. Number of reported tunnel failures per five-year period showing the impact of code of practice; b. Failure types before and after the code; and, c. Tunneling method before and after the code, where: FAC (face instability), OSF (support overstressing), FIR (fire), ERQ (earthquake), CRW (crown), OTH (other type) (presented in Paraskevopoulou et al. 2022).

It is evident that there is a decrease of reported failures; however, what is important to state is that the main failure types of the reported incidences remain the same and are attributed to face instabilities and support overstressing covering up to 91% and 96% before and after the code, respectively shown in Figure 7b. There is not a direct impact about the failures based on the tunnelling/construction method as shown in Figure 7c.

5 A LOOK-AHEAD: YESTERDAY'S UNKNOWNS - TODAY'S RISKS

The global situation at the inception of this paper can nothing but confirm that risk management is and needs to be a live process, whilst several unforeseen or unforeseeable situations (unknown – if not neglected – unknowns per Figure 1) materialise to a tremendous extend. It is evident that a risk identification procedure must closely observe international incidents, absorb experiences from the tunnelling community, and remain constantly resilient to manage unexpected events.

Characteristic examples in the last few years include the significant disruptions in the supply chain, steep increases in steel and energy prices, the lack of skilled personnel, the rapid shift of most industry sectors to digitalisation. These are certainly intensified by the outbreak of the Covid19 pandemic (Ayat & Kang, 2021) and the war in Ukraine, but also from events of less importance, such as e.g. the "Ever Given" container ship 2021 accident (Lee & Wong, 2021). These call for immediate adjustments in the organisation and management of projects at various life-cycle stages, from planning to delivery; technical changes and associated risks are then to be considered, related to e.g. material specifications and consistent material quality, latent structural defects, occupational safety, switch to new technologies such as electrical equipment and automatized construction methods.

It is also important to register and understand the risks that are potentially related to climate change. This mainly refers to technical risks from extreme weather, surface and groundwater fluctuations, and unidentified geological degradation due to water/ice cycles and permafrost melting. These can impact on both the surface (site/portals) and the underground space conditions (Mishra & Sadhu, 2022; Palin et al. 2021; Epting et al. 2021). Geotechnical designs, toolbox excavation support, and risk mitigation measures must account for more onerous geotechnical parameters, water tables and extreme natural events to ensure an equivalent risk profile compared to previous years.

Finally, rapid technological advancements are de facto developed to improve construction conditions and reduce project risks, but their innovative character may also induce implementation and integration risks. The global industries' effort to reduce the climate impacts of construction (e.g .reduction of greenhouse gas emissions) must also be accounted for here. Examples include digital planning (e.g. BIM) and integrated sensors, robotic applications, and new types of energisation of equipment such as batteries and hydrogen. These also induce new types of risks and require a devoted mitigation design.

6 CONCLUDING REMARKS

Uncertainty is an integral part in tunnel design. Even in the favourable cases of sound geological models, there is always going to be a level of uncertainty which cannot be eliminated, the residual uncertainty which will impact the tunnel performance during construction – excavation period. Having more insights on the likelihood of failure modes and types based on the historical event undoubtedly has value in tunnelling industry. Developing such databases can contribute to developing a further understanding of tunnelling incidents. During operation, the main factors of such incidents are earthquakes and fires. However, during construction NATM tunnels reported more failures than TBM tunnels, whereas, in Drill & Blast tunnels, less failures take place. Finally, the Code of Practice for Risk Management in Tunnel Works has had a clear positive impact on the annual tunnel incidents and failures during construction. This has been achieved by improving the transparency on risk transfer throughout the project with a live risk register. However, recent years have disclosed new types of risks that previously belonged to the sphere of the unforeseen or the unknown. Expansion of state-of-the-art risk management concepts can certainly form the basis for dealing with such risks at the structural level of a project or an organisation. Still, at the same time, an awakening monitoring of global situations and open communication amongst the international technology and engineering community is necessary to identify such risks and plan mitigation methods accordingly.

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