Revised Comparison of Tunnel Collapse Frequencies and Tunnel Failure Probabilities

Panagiotis Spyridis, Dr.Eng., CEng[1]; and Dirk Proske[2]

Abstract: Comparison of calculated failure probabilities of technical systems with observed failure frequencies is an important part of the assessment of probabilistic calculations and can point to significant factors that are neglected in the calculations. Recent comparisons of failure probabilities and failure frequencies of nuclear power plants, bridges, and dams have shown that the calculated and observed values correspond surprisingly well. In addition, although various factors could be identified which have both positive and negative influences on the observed values, they almost cancel each other out. This study focuses on the comparison as it relates to tunnels. Extensive statistics indicate that most tunnel collapses occur during construction. Although this is also seen to a certain extent in bridges, it is not to the extent seen in tunnels. Events such as earthquakes and floods, which are the major causes of collapse of other structures, account for only about 10% to 20% of all tunnel collapses. Increasingly, tunnels are also being proven probabilistically. Based on these calculations, the available failure statistics can be compared with representative probabilistic tunnel proofs. The comparison shows large deviations between individual computations as well as between the mean value of all computations and the observed collapse frequencies. **DOI: 10.1061/AJRUA6.0001107.**

Introduction

Probabilistic methods have been established for several decades in various engineering disciplines. They are used, for example, in the design of aircrafts, spacecrafts, ships, and civil engineering structures (Spaethe 1992). The results of probabilistic calculations are, on the one hand, the weighting of the input variables and, on the other hand, the probability of failure or substitute measures (Spaethe 1992). The probability of failure can be, for example, the probability of exceeding the ultimate limit state in a structural analysis, the probability of occurrence of a core meltdown, or the probability of failure of an engine (Proske 2009).

Today, probabilistic or semiprobabilistic safety concepts form the basis for the safety analysis of structures in practically all industrialized countries. In addition, because many developing countries use standards from industrialized countries, the proportion of structures designed this way is growing steadily. In nuclear technology, probabilistic safety analyses (PSA) are currently available for practically all nuclear power plants (Proske 2019). In the literature, probabilistic safety analysis of nuclear power plants is intensively evaluated. Some publications (Kauermann and Küchenhoff 2011; Raju 2016) assume that the results of the probabilistic safety analysis in terms of core damage frequencies are systematically too low and do not fit with observed frequencies. This discrepancy may be due to unidentified load or resistance effects and properties, but there presently is no firm evidence for any of these causes.

Despite this discussion in the nuclear power sector, in other areas it is still assumed that the calculated failure probabilities and the considered collapse frequencies should not be compared (Bolotin 1969; Spaethe 1992; Ellingwood 2001; Imhof 2004; Oberguggenberger and Fellin 2005; Vogel et al. 2009; CEN 2002). In these exemplary references it is assumed that for various reasons there is a systematic bias between the collapse frequencies of structures and the calculated failure probabilities. This can be attributed, on one hand, to inherent safety from conservative engineering design concepts, assumptions, and simplifications, or robust detailing and, on the other hand, to hidden defects and gross errors.

However, the suggestion that actual and design failure probabilities are not comparable remains debatable because the determination of partial safety factors for building materials can be based on experience as well as on probabilistic calculations. In such a case, both the observation and the results of the calculation are equated. Further arguments can be found in Proske (2019).

Regardless of whether the observed frequencies and the calculated probabilities are comparable in principle, the authors have compared:

- The observed core damage frequency in nuclear power plants with the result of PSA (Proske 2016);
- The observed bridge collapse frequency with the result of probabilistic calculations (Proske 2017, 2018a); and
- The observed failure frequency of dams with the results of PSA calculations (Proske 2018b).

An initial comparison for tunnels was conducted by Proske et al. (2019). The validity was limited by a small sample size of tunnel collapse data and probabilistic calculations. Therefore, this study is a revision and improvement considering the larger sample size for both the collapse data and the probabilistic computations. Table 1 compares the two data sets.

The data sets do not encompass all tunnel failure cases because (1) contractors and owners of tunnels rarely report failures or defects to the public, and (2) there is an indistinct border zone

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[1] Professor, Faculty of Architecture and Civil Engineering, TU Dortmund Univ., August-Schmidt-Str. 8, 44227 Dortmund, Germany (corresponding author). ORCID: https://orcid.org/0000-0001-8378-2500. Email: panagiotis.spyridis@tu-dortmund.de

[2] Professor, Div. of Civil Engineering, Bern Univ. of Applied Sciences, Pestalozzistrasse 20, 3401 Burgdorf, Switzerland. Email: dirk.proske@bfh.ch

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Table 1. Data sets used for investigations in the preliminary and current studies

Data sets used in previous and current/revised studies	Previous study, Proske et al. (2019)	Current study
Number of tunnel collapses	114	321
Ratio of collapse during execution to overall collapse	80%	92%
Number of probabilistic computations of tunnels	3	31

between failure and acceptable performance during tunnel excavation as well as operation of tunnels. At the same time, probabilistic calculations in the references used rely on varying methodologies and modeling approaches to calculate predictions. Although the main tunnel types and characteristics are presented subsequently for better comprehension and completeness of the database, distinguishing the analysis approach for different tunnel types is beyond the scope of this study. Besides these limitations and respective challenges, the assembled database is the largest of its kind in current international literature, and it is considered largely representative of the state of the industry with respect to the objectives of this study.

This study aims to investigate the extent to which failure probabilities of tunnels of desktop calculations and real-life cases converge. An extensive review of published project information and scientific studies is performed, a comprehensive database is assembled, and finally the failure probabilities and their trends against significant tunnel parameters are statistically analyzed. The conclusions allow for a rational evaluation of the effectiveness of today's civil engineering risk- and reliability-based designs. This type of comparison of statistics of failures and probabilistic calculations toward the rationalization of failure probabilities for tunnels is so far a singular attempt in international literature. The outcome of this research is important in the performance assessment of construction projects and built underground assets and can also prove necessary in order to calibrate target failure probabilities in practice.

Statistics of Tunnel Collapse

Tunnel Stock

According to ITA (2016), a tunnel is an artificial subterranean passage open at both ends. It has been estimated that there are approximately 40,000 tunnels worldwide (ITA 2016). Although detailed numbers are given for some countries such as Switzerland (STS 2020; SBB 2018; ASTRA 2016), for most countries only limited information is available (DOT 2019; CIA 2020; Statista 2020). The missing numbers of road and railway tunnels for several countries were calculated using a factor from countries with known data. The ratio of road to railway tunnels was assumed to be 1.5 for this calculation. The data used is given in Table 2. Based on these numbers, there are considerably more than 50,000 tunnels worldwide (Table 2). Considering all uncertainties, the authors estimate the worldwide number of tunnels to be in the range of 125,000 ± 10%. However, for the estimation of the collapse frequencies we have used the estimate of 50,000 tunnels.

Tunnel Length

Based on tunnel length data from Austria, Belgium, Chile, Croatia, Czech Republic, Germany, Great Britain, Japan, Mexico, Netherlands, New Zealand, Norway, Portugal, Slovakia, Slovenia, South Korea, Sweden, Switzerland, Taiwan, Turkey, and the United States, (ASTRA 2016; CIA 2020; SBB 2018; Statista 2020) the mean road tunnel length is 1,120 m with a coefficient of variation of 52%. Based on data from Germany and Greece, the mean rail tunnel length is 1,060 ± 340 m. However, the median value of the tunnel length is much shorter due to the skewness of the tunnel length distribution. Therefore, the conversion of tunnel lengths into the number of tunnels and vice versa is not straightforward.

Table 2. Current tunnel stock based on the authors' estimations by linearly extrapolating data for the last decade from references in the "Tunnel Stock" section

Country	Tunnel stock
China	27,000
Japan	16,000
Norway	2,350
Korea	1,500
Germany	1,500
Switzerland	1,300
United States	850
United Kingdom	600
Spain	420
Netherlands	60
Hong Kong	30
Sweden	35
Overall	51,645

Tunnel Stock Development

Tunnels have been used for transportation for centuries. Excavations have found tunnels several thousand years old, with the earliest dating back 4,000 years. Early tunnels were built not only in Egypt, but also in India and China. The first tunnel whose engineer is recorded is the 1,036-m water tunnel of Eupalinos of Megara in Samos, Greece, built in approximately 530 BC (ITA 2016; Sandström 1963).

The number of tunnels and tunnel construction projects has been growing rapidly worldwide. In 2016, the annual growth amounted to approximately 7% in financial terms (ITA 2016). PR Newswire (2020) estimates an annual growth rate of the tunnel and metro market of approximately 5%.

Since 2013, approximately 5,200 km of tunnels have been built every year (ITA 2016). However, in 2016, the tunnel construction market was already approximately 23% larger than in 2013 (ITA 2017). Using a conservative estimate of 5,200 km per year, it is estimated there will be more than 30,000 km of tunnels in 2019.

The figures for worldwide market shares differ depending on the publications selected. According to ITA (2016), China accounts for approximately 50% of the current worldwide tunnel construction market. Since the beginning of the 2000s, China has had the most tunnels as well as the most tunnel construction projects. However other countries such as Indonesia and India also show a growing tunnel market (ITA 2016). In comparison, tunnel construction data for Germany can be found in Schäfer (2019) and Statista (2020). Whereas the number of German railway tunnels increased only slightly in recent years (about 1% per year), the number of road tunnels in China, for example, increased by approximately 12% per year.

ITA (2017) predicts the global output in tunnel construction projects from 2018 to 2026 to be in the range of EUR 680 billion. In contrast, according to GlobalData (2019) the sum of global tunnel construction projects is USD 1.75 trillion. Major contributions come from Europe with an approximate 40% share, the Asia-Pacific region with a comparable share, the United States with 15%, and the Middle East and Africa with approximately 10% (GlobalData 2019). However, the amount includes not only tunnel costs but also the cost of overall infrastructure projects that include tunnels. Overall, the tunnel market represents about 6% to 7% of the global infrastructure construction market which is growing strongly. Based on all the figures given, the tunnel market and thus the number of tunnels are highly dynamic. The validity of the results determined in this study must be reviewed in the coming years.

Tunnel Collapses and Relevant Databases

Evaluation of the collapse data of tunnels must take into account two special considerations that do not occur in other structures:

- Most tunnel collapses occur during construction. In Proske et al. (2019), collapse during construction was greater than 80% of the overall collapse data. This contribution has increased to more than 92% of all collapses considering the larger sample size according to Table 1.
- Much of the damage to tunnels is related to transportation accidents within a tunnel that are followed by a fire. Such fires pose a serious threat to tunnels due to the heat and the change in material properties (Ingason et al. 2015).

Databases and catalogs of tunnel collapses and damage can be found in Seidenfuss (2006), Zhao (2009), Sousa (2010), Reiner (2011), CEDD (2015), and Zhang et al. (2016), to mention a few.

Statistical investigations of tunnel collapse data can be found in Seidenfuss (2006) and Špačková et al. (2013). The latter considers a correction for possible nonreported collapses (underreporting). This effect was also noticeable in the statistics of bridge collapses (Proske 2018a). The values in Špačková et al. (2013) are given in collapses per tunnel length (Table 3). Converting the numbers from Špačková et al. (2013) into annual failure rates per tunnel by assuming an average tunnel length, values in the range of 10^{-2} to 10^{-3} per year are obtained (Fig. 1). However, this conversion from tunnel length to number of tunnels is connected with uncertainties. Fig. 1 shows the data from the collapse databases as well as the previous statistical investigations, and also the development of tunnel collapses over time. The figure includes the annual collapse frequency computed from the collapse data (triangles), trend analyses for both the overall data and the data only related to collapse during operation, and the results from the two other statistical analyses (rectangles). Accordingly, it provides the basis for comparison with probabilistic calculations, which are also included in the graph as circles, and discussed in more detail in the next section.

Table 3. Failure rate of tunnels according to Špačková et al. (2013)

Type of tunnel	Estimated lower bound of collapses between 1999 and 2004	Estimated lower bound of collapse rate, per km
Road	17	0.013
Rail	33	0.012
Water, sewage, or both	12	0.009
Other	1	0.003
Total	63	0.011

Compared with Proske et al. (2019), a significant difference in the trend analysis is observed. This trend of the previous study was based on 114 collapse cases whereas the current study uses data from 321 collapse cases. Although the previous analysis showed an overall decreasing trend, the new analysis would show a slightly increasing collapse trend over time (not included in Fig. 1). However, the new data discloses a sharp change around the year 2000. Therefore, two trend lines have been used for the new data (up to the year 2003 and afterward).

A question consequently arises as to whether the peak around the year 2000 is a statistical anomaly or a real phenomenon. Between 1994 and 2003 several major tunnel collapses occurred, such as at the Munich Metro, the Great Belt Link, Heathrow Airport, and the Los Angeles metro tunnel (1994–1995). In 2003, partly as a reaction to these collapses, the Joint Code of Practice for Risk Management of Tunnel Works was introduced by the British Tunneling Society and the Construction Risk Insurers (BTS 2003). The International Tunnel Association endorsed it a decade later (arguably due to further tunnel catastrophes worldwide, for example the Nicholson Highway collapse in 2004), but it was already widely applied internationally. Although without a concrete scientific reference, the authors are aware of a consensus in the market that the establishment of this Code improved safety in tunneling, which is also apparently supported by the statistical data.

Furthermore, trend lines for the overall collapse data and the collapses only during operation have been added by using an offset. In contrast to other structures, collapse statistics of tunnels are dominated by the construction period. Based on the current data set, only 8% of all collapses are related to collapses during operation. This is also visible to a certain extent in bridges (Proske 2018a), but not to the extent of tunnels. Accidental effects such as earthquakes and floods, which dominate the collapse of other structures, account for only about 10% to 20% of all tunnel collapses.

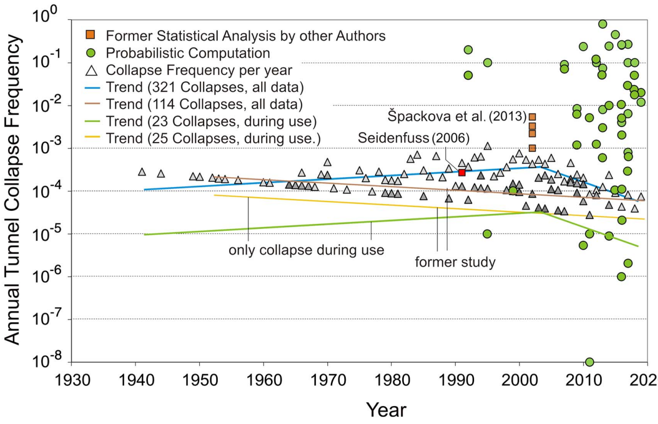


Fig. 1. Distribution of tunnel collapses frequency over time. Multiple collapse frequencies correspond to the same year in some instances because they are derived from different publications. The trend lines are based on linear regression. The data split for 2003 marks the establishment of the Joint Code of Practice for Risk Management of Tunnel Works in the UK (BTS 2003). Sources of data from other than the current study are derived from Seidenfuss (2006), Zhao (2009), Sousa (2010), Beard (2010), Reiner (2011), Špačková et al. (2013), Ingason et al. (2015), CEDD (2015), Zhang et al. (2016), Konstantis et al. (2016), and Proske et al. (2019) (the latter is referred to in the figure as former study).

Tunnel Collapse Causes

At the inception of this study, and for the foreseeable future, there is no unified design standard specifically applicable for the geotechnical and structural design of tunnels. Although some nationally acknowledged guidance and best-practice documents are available, the need for standardization is evident, as noted by Athanasopoulou et al. (2019). In practice, the design standards or guidelines implemented for each project are selected and applied by the tunnel owner or related authority. Hence, it is possible that tunnels in the same region, of similar age, or even in the same infrastructure network, are designed and constructed with different engineering methods. Project-specific rock or soil conditions and the type of tunnel by use contribute to a great diversity of tunnel characteristics. This diversity may also become visible in the statistical evaluation. For example, in Proske et al. (2019) the ratio of tunnels in rock to soil was 1:2 but is 2:1 for the new data.

Another significant element is that failures during construction may mobilize a large part of the underground space, and consequently cause an influx of large ground volumes or flooding of the excavated tunnel, excessive settlements or collapses of assets in the vicinity and on the surface, and significant delays in delivery. Such consequences may be associated not only with many injuries and fatalities (Fig. 2), but also exorbitant losses, of similar order, or even a multiple of, the original project budget. Simultaneously, failures in tunnels occur at a small area of the tunnel compared to its length, and although they may affect the project as whole, the structural stability of the undamaged structure remains (unlike e.g., in bridges). The fact that collapses can occur early in the structure's life cycle (construction phase) in relation to the magnitude of the consequence, can justify special risk and safety concepts from an engineering viewpoint. However, the number and frequency of tunnel collapses with many fatalities is rather low, in relation to collapses of other types of structures, such as buildings or dams (Proske 2020).

Tunnel failures and failure causes can be associated with various tunnel types using different classifications. Tunnels can be classified by use as transportation, energy supply and cable, sewage and water treatment, and pressurized flow tunnels, and as auxiliary structures (Thewes and Maidl 2013). Transportation tunnels are probably the largest classification of tunnels and can be further classified as road, railway, or pedestrian tunnels. Railway tunnels can also be divided into heavy, rural, and freight rail tunnels, and urban, light rail, or metros. Auxiliary tunnels may include vertical access and escalator shafts, temporary construction works, ventilation tunnels, or cross passages. Water-carrying tunnels are used for water supply, irrigation, and sewage treatment, but they also form a significant part of large nuclear and hydropower plants. Tunnel structures are also used for other industrial sectors such as the access to and withdrawal of material from mines and in the oil and gas industry. In some cases, complex combined systems are devised (such as combined rail and highway tunnels, or road and flood relief tunnels). The diversity of types of tunnels and the related operators is one of the challenges in obtaining an overall worldwide number of collapses.

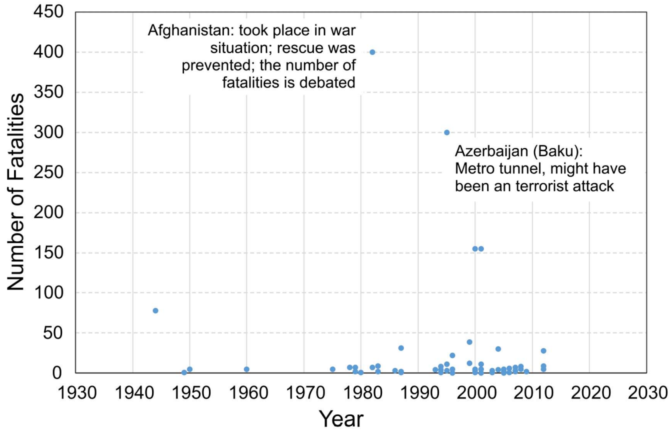


Fig. 2. Number of fatalities per tunnel collapse over time. Sources of data from other than the current study are derived from Seidenfuss (2006), Zhao (2009), Sousa (2010), Beard (2010), Rainer (2011), Špačková et al. (2013), Ingason et al. (2015), CEDD (2015), Zhang et al. (2016), and Konstantis et al. (2016).

For most of the types of tunnels mentioned so far, the load development is essentially stable in the long term. In contrast, pressurized tunnels are typically parts of hydropower plants during construction (diversion tunnels) or operation (head-race, penstock, or both types of tunnels), and they pose a significant structural distinction from other types of tunnels because the inner applied load may exceed the ground loads, and it is moreover a significant cyclic action. Rock swelling may also affect a tunnel's stability over time. Therefore, tunnels might not only be categorized by use, e.g., means of transport, but also by the stability of the loading. This study has not investigated the collapse data regarding this classification of tunnels, however it may indirectly influence the outcome of the comparison.

Another classification of tunnels is related to the load-bearing system. The majority of mined tunnels, and occasionally mechanically excavated ones, are constructed with a primary support to create a safe and suitable underground space, which accommodates the installation of a final lining of the tunnel and the required infrastructure. In some cases, the primary support also acts partly or entirely as the final, long-term support of the tunnel. The support system can consist of a rock or soil anchoring pattern in unlined tunnels in healthy rock environments, or of a lining that is constructed with bricks (perennial structures); cast-in place; sprayed concrete; or concrete, cast-iron, or steel prefabricated segments. In tunnels with a concrete final lining, unreinforced or fiber reinforced material is often used rather than rebar. This can strongly influence the failure or degradation modes, in correlation with the environmental and loading conditions (Maidl et al. 2014). The different types of linings correlate to various possible tunnel shapes. For example, segmentally lined tunnels are circular, whereas brick and sprayed lined tunnels are mostly arch shaped. Again, this study has not investigated the collapse data regarding this classification of tunnels, however it may indirectly influence the outcome of the comparison.

The load bearing system type is also strongly associated with the selected construction method. Tunnels can be excavated by various methods including drill and blast (hard rock), road-header (soft and hard rock), and conventional or mechanized excavation via a tunnel boring machine (TBM) (rocks and soft soil). Cut and cover tunnels are usually constructed at shallow depths, which are usually related to soft and weathered rock or soft soil. Manual excavation has been implemented to a great extent for historical and generally older tunnels, as well as for minor excavations in confined underground areas. TBM excavation is associated with concrete segmental lining (rarely with metallic segments, unlined, or with sprayed concrete linings in rock). Brick, iron, or steel segments have more widely been used in the lining of manually mined tunnels. Drill and blast, road-header, and conventional excavation are associated with anchoring systems and sprayed concrete support systems. Fig. 3 compares the contribution of the construction method to the collapse data of this study with the results of Konstantis et al. (2016).

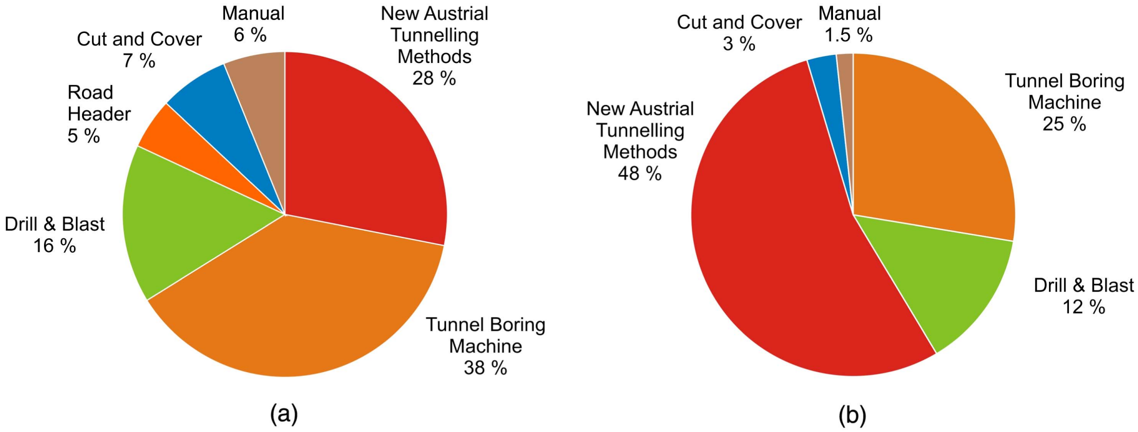


Fig. 3. Tunnel collapse, failure, or both, and construction methods: (a) Konstantis et al. (2016); and (b) current study using 321 samples.

As mentioned previously, the types of failures in a tunnel can be separated into failures during construction or operation. During operation, structural failures can be related to failure of the lining system, support system, or both, or to failure of the installed secondary structures. In both cases, failures can result from loss of load bearing capacity due to excessive loading situations (internal or external pressures), degradation of materials, and accidents and defects. Fire accidents have gained attention in the industry and consequently in safety standards, after historical catastrophic events in well-known and frequently used tunnels. During construction, failures are mostly related to ground instabilities in supported segments or at the excavation face, and also to failure of the temporary support measures. Fig. 4 shows the contribution of various failure causes and compares it with the results of the previous work (Konstantis et al. 2016).

The tunnel collapse frequency may also be related to some geometrical conditions. For example, Figs. 5 and 6 show the collapse tunnel frequency in relation to tunnel depth and length, respectively. Again, a previous study by Konstantis et al. (2016) is used for comparison in Fig. 5.

Numerous studies and publications have been carried out to identify the causes of tunnel collapses. Some of these investigations only cover external influences, whereas others also consider human error. Further publications also cite the rock conditions or rain as the main reasons for collapse (Zhang et al. 2016). As mentioned previously, fires caused by transportation accidents inside tunnels also play a significant role in tunnel damage and failures (Ingason et al. 2015). Further discussion can be found in Beard (2010).

The publications and the considerations presented in this section show that a simple determination of the cause of failure is not straightforward. This requires a substantial volume of detailed data about each tunnel, which is on the one hand difficult to accumulate and on the other hand difficult to prepare for a uniformly comparable representation.

Probability of Tunnel Failure

Several researchers have attempted to predict the failure probabilities of tunnel structures based on reliability assessments and probabilistic calculations. The literature used focuses on structural assessments, geotechnical assessments, or both, in both operation and construction [Bergmeister (2010), Johansson et al. (2016), Lü et al. (2011), Meschke et al. (2018), Bergmeister (2016),

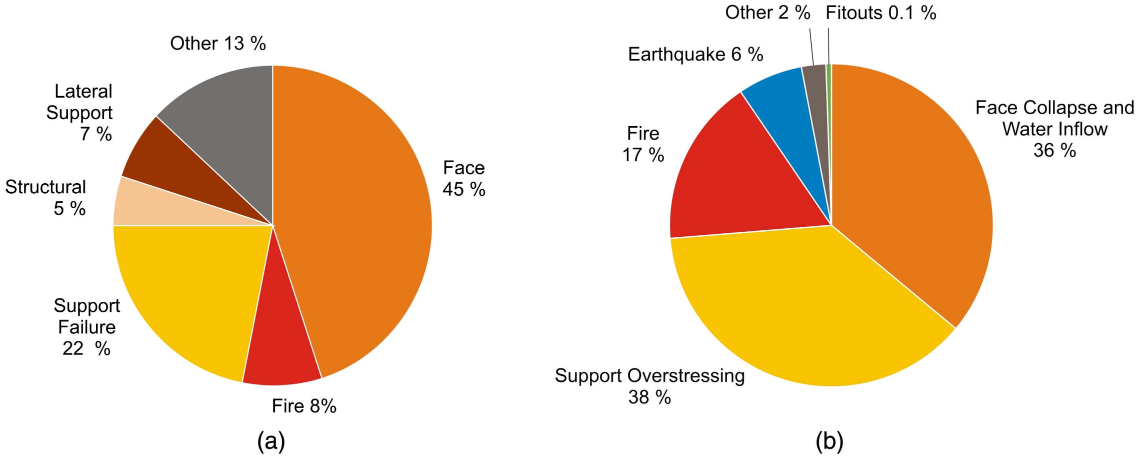
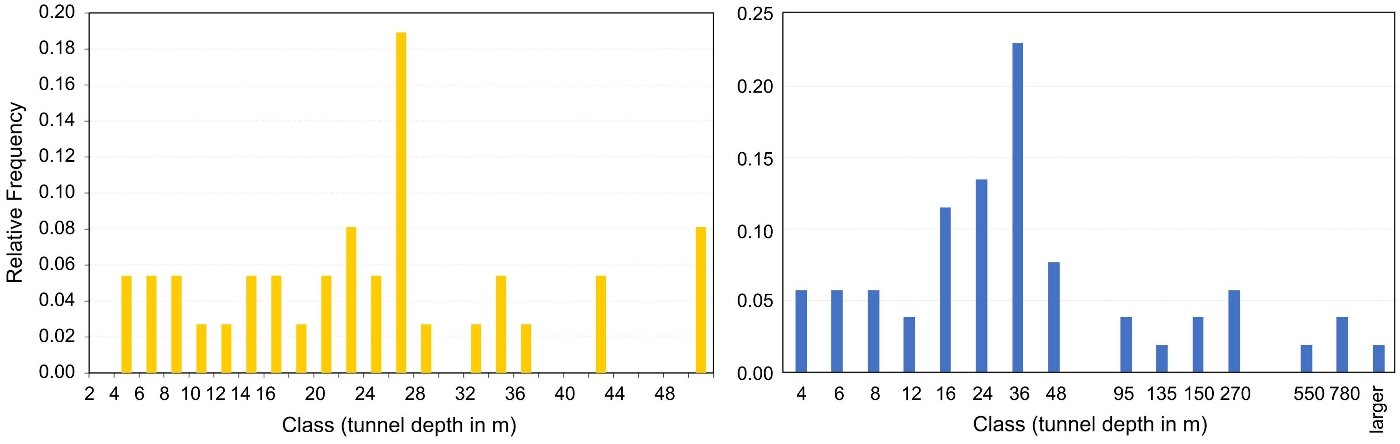


Fig. 4. Distribution of tunnel failure types: (a) Konstantis et al. (2016); and (b) current study using 321 samples. Lateral support: sidewall failure; Structural: excess of the lining flexural capacity, shear capacity, or both; Support failure, overstressing, or both: compressive damage and crushing of lining; Face: face stability loss, including daylight vertical failures close to the face; Earthquake: seismic event leading to extensive damage and closure; and Fire: fire event leading to prolonged closure.



(a)

(b)

Fig. 5. Distribution of tunnel collapses over the tunnel depth: (a) Konstantis et al. (2016); and (b) current study using 321 samples.

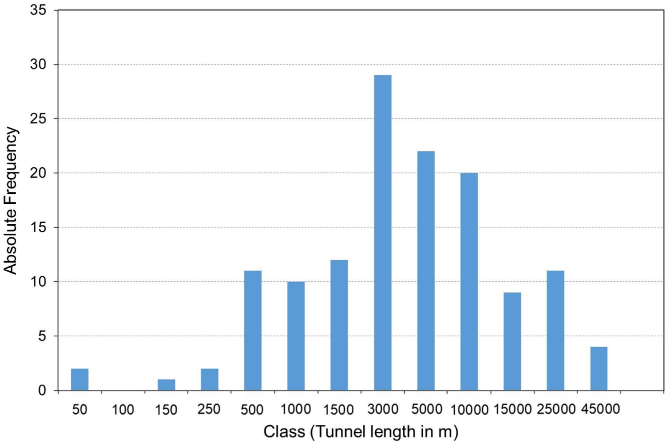


Fig. 6. Distribution of tunnel length.

Bjureland et al. (2017), Breitenbücher et al. (1999), Fortsakis et al. (2011), Fuyong et al. (2019), Gharouni-Nik et al. (2014), Goh and Hefney (2010), Goh and Zhang (2012), Hamrouni et al. (2017), Kohno et al. (1992), Kroetz et al. (2018), Langford and Diederichs (2013), Laso et al. (1995, Li and Low (2010), Li et al. (2016), Liu and Low (2017), Low and Einstein (2013), Lü et al. (2012, 2013, 2017), Miro et al. (2015), Mollon et al. (2009), Papaioannou et al. (2009), Spyridis (2014), Spyridis et al. (2016), Su et al. (2007), Wang et al. (2016), Yang et al. (2018a, b), Zeng et al. (2016), Zhao et al. (2014)]. The models rely either on empirical, analytical, or numerical geotechnical models. The assumptions regarding tunnel stability and structure assessments varied in published literature, as did the geometrical and material properties used as input. Consequently, different levels of accuracy and sophistication are met, but overall detailed information on the investigated tunnels is taken into account in the desktop analyses.

The predicted and calculated values of the failure probability in each study and for every tunnel has been derived either directly from Monte Carlo simulations or inverse derivations from the reliability index, β, as per the classical definitions presented in the theoretical background of the study by Spyridis (2014). Results of failure probabilities of tunnels are indicated in Fig. 1 by circles. Target values for the probability of failure are given in various codes, for example in Eurocode 0 or in documents related to tunnels e.g., Johansson et al. (2016) and are not shown explicitly in Fig. 1.

Fig. 1 shows that the results of the probabilistic safety assessments of the tunnels have significantly higher values of probability of failure compared to the collapse values observed. This means that the calculation results are conservative. However, the mean values of all probabilistic computations differ by two orders of magnitude from the observations. Additionally, the probabilistic computations show a large variation, not only between different publications but also within individual publications.

The result of the mean values of the probabilistic computations is especially in contrast to previous publications (Proske et al. 2019) and also in contrast to the comparison of structural collapses and probabilistic computations for other types of structures (Proske 2019). For other types of structures, such as bridges and dams, observed collapse frequencies and computed probabilities of failure comply surprisingly well and further investigations of this are required.

One possible reason for the large individual span of the computational results and the deviation of the mean values between computation and observation can be the large uncertainties during design and construction of tunnels and the large variation of technologies and building conditions as explained in the previous section, as compared to other types of civil structures.

Summary and Conclusion

The main objective of this study is to compare the observed collapse frequencies of tunnels and the calculated failure probabilities. Toward this objective, the following steps were taken:

- Available data sets and publications for both parameters have been sourced and integrated in a comprehensive database.
- Data per tunnel and per tunnel length corresponding to the observed collapse frequencies have been distinguished.
- Considerations for the categorization of tunnels and their particularities regarding the study have been highlighted.
- Uncertainties in the estimation of the overall tunnel stock have been identified.

Although the existing data have some limitations as described in the Introduction, the database is considered to be as representative as possible. Based on this database, the observed tunnel collapse frequencies and the computed probabilities of failure show a significant deviation from each other. In general, the probabilistic computations show larger median and mean values. However, the available probabilistic studies also show a considerable variability, sometimes by up to six orders of magnitude. This variability can be interpreted as a very large uncertainty in the probabilistic calculations. This uncertainty may be a direct result of the large influence of input variables (e.g., soil, rock, and earth) with a large uncertainty. In contrast, the observed collapse frequencies show limited scatter. The results from Špačková et al. (2013), given as failure rate per tunnel, show only slightly higher failure values than the authors' values. The values from Seidenfuss (2006) comply with the authors' results. However, as discussed in Johansson et al. (2016), Meschke et al. (2018), Diamantidis et al. (2000), Stille (2017), and Zulauf (2012), the application of usual target values for structures in tunnel construction may require further discussion or the introduction of new parameters as shown in Shin et al. (2009). With regards to the preceding finding, the following conclusions can be drawn:

- The observed collapse frequency in real tunnel construction projects can be explained based on certain boundary parameters with reasonable scatter.
- Due to the large variance in results by probabilistic investigations, and the deviations of their results from actual statistical numbers, a systematic approach considering the real data presented herein would be beneficial.
- Failure probabilities for tunnels under construction and in operation appear to be governed by a multitude of nonstructural parameters and as such tailored target values can apply for different structures and life-cycle phases.
- 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.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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