Tunnel Losses: Causes, Impact, Trends and Risk Engineering Management

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ABSTRACT
Tunneling and Underground works are unequivocally subject to a diversity of inherent uncertainties associated with the geotechnical, hydro-geological and environmental regime that surrounds them. On many occasions, these uncertainties can provoke loss events of considerable consequences. The present contribution elaborates on losses that the insurance market has suffered in the recent years, following a construction failure event. These losses are being considered and analysed on a quantitative basis through evaluation of cost related data, with explicit discretization of the applied construction methodology and of the subsequent developed failure type since both of which are considered of major importance. Given the identified persistence and regularity of some loss-contributing factors, recommendations are provided on the basis of a proactive risk engineering management approach that are envisaged to reinforce the understanding of project risks and alleviate the incurred insurance cost.

1 INTRODUCTION
The underground construction sector has always been a very challenging area for all involved parties, including the insurance market. Main reason for that remains the uniqueness of the uncertainties sources and the subsequent inherent risks that the tunneling and underground projects are exposed to. In many instances, these risks materialize, leading to loss events with substantially high impact on reinstatement cost and incurred delays, which depending among others on the insurance coverage will have to be bared by the Insurance market.

In the recent decades and as the tunneling industry boomed and expanded with many major and significant projects undertaken around the world, the insurance market was faced with additional challenges. Increased competition during tender coupled with the scale and complexity of the projects and politically driven decision making exerted pressure on the project timelines, completion dates and budget. The pressure for on-time or even early project completion- to avoid liquidated damages or achieve bonus payments, respectively- along with cost reduction efforts and the incentive for innovative construction approaches, are some of the factors which contributed towards increased probability of
failure events. That, in turn, put additional pressure on the Insurance market which had experienced a significant amount of losses with substantial cost. One of the triggered mitigation actions was the introduction of the Code of Practice for Risk Management of Tunnel Works (ITIG, 2006 & 2012; MunichRe 2006, Wannick, 2007, Spencer, 2008, Adeyemo, 2011).

In the present contribution, an effort was made to demonstrate that there are certain factors that are persistently involved in tunnel losses. These losses are being considered and analyzed on a quantitative basis through evaluation of cost related data, with explicit discretization of the applied construction methodology and of the subsequent developed failure type. On the basis of the conclusions that can be drawn, recommendations are provided in the framework of a pro-active and targeted risk engineering and management approach and attitude that can highly improve the situation with significant gains for the insurance market and benefits for the involved project. The importance and benefits of proactive risk engineering management in the insurance industry have been qualitatively outlined by (Denney, Tillie and Konstantis, 2014).

2 TUNNEL LOSSES AND HAZARD SOURCES

As already highlighted above, the international insurance market has suffered major losses in the past years related to construction projects that involve tunnels and underground works. A very comprehensive list of major and noticeable tunnel failures in the past almost 50 years can be found in CEDD, 2005. Additional information including insurance losses cost data and the corresponding incurred delays can be found in Reiner, 2011, IMIA WGP48, 2006 and MunichRe Group, 2006. The above four references constitute the data sources of the present contribution. When a tunnel loss or damage occurs, reinstatement activities may exceed those implemented in the initial construction process. Consequently, the corresponding reinstatement cost may step well beyond the original construction cost. Experience has shown that cost of reinstatement could be several times the original cost. In the present contribution, a quantitative analysis of the foregoing documented and publicly available tunnel losses is carried out. In the following lines of this subsection, the main hazard sources of tunnel and underground work projects are outlined.

2.1 Geology – Geotechnical Conditions

The behavior of a tunnel and ultimately its execution success is massively depended on the overall properties (physical and mechanical) of its surrounding geo-materials and how these have been realistically identified and incorporated into the corresponding design and dealt with before, during and even after the construction process. The underground water regime can further influence the ground “properties” and potentially deteriorate the conditions under which the tunnel is going to be constructed. Unexpected and significant ground features, like faults, constitute a major risk during construction.

2.2 Tunnel Construction Method

Tunnel excavation method can vary depending on many factors, such as ground conditions, tunnel depth, contractors experience, machinery availability, etc. Indicatively, some of the most common methods used are: Tunnel Boring Machine (TBM); NATM; Drill & Blast (D&B); Roadheader; Hand Excavation and; Cut & Cover.
A combination of the above may be used in a single project, subject to alternations in ground, topological and other factors which could be related for instance to commercial and planning considerations. Each tunnel construction method carries a different risk profile.

2.3 Design Approach

The success of a tunneling project is inextricably related to the governing rationale of the design. Adequacy of design necessitates profound knowledge of the ground and surrounding conditions combined with awareness of the designer’s expertise and competence. Errors, omissions or misinterpretation of key elements, such as ground stresses, support measures requirements, deformational expectations, etc may put the tunnel safety and its whole scheme at risk.

2.4 Construction Execution and Workmanship

This is related to the flawless implementation of the selected construction and excavation method. A well-established construction management plan and workmanship specifications, encompassing meticulously the principals of sequential excavation and support steps in the example of conventional tunnelling, the timely and proper installation of support measures and comprehending the importance of targeted monitoring and pro-active advance ground probing, is of utmost importance in deterring major failure events.

3 TUNNEL LOSSES ANALYSIS

3.1 Objective

The main objective of the conducted analysis is to provide both a qualitative and quantitative evaluation of the available tunnel failures and insurance losses data, so that a clearer structured picture of the suffered losses can be deduced, aiming at the identification of the main factors behind a tunnel failure and the recommendation of mitigation measures.

The first part of the analysis covers tunnel failures in general, with emphasis on the various major contributing factors, whereas the second part deals with the actual losses that Insurance market has suffered, following a tunnel failure event. Tunnel failure can be defined as an unanticipated and unwanted event, inclusive of physical loss or damage, with potentially severe consequences that may adversely impact on the project’s budget, schedule and safety of humans and assets.

3.1.1 Ground Conditions

As shown from the analysis and presented in Figure 1, almost two thirds of the failures have occurred in soil type geomaterials surrounding the tunnel which can be vaguely attributed to their

![Tunnel Failures vs. Ground Conditions](image)

Figure 1. Tunnel failures and ground conditions (IMIA 2006, CEDD 2015, MunichRe 2006, Reiner 2011)
reduced strength and deformability characteristics as opposed to the rock type ground. It is noted that Figure 1 reflects only the mentioned impact of ground conditions neglecting, however, all other loss-triggering factors.

3.1.2 Construction Method

From Figure 2 below, it could be concluded that almost one third of the tunnel failures belong to the mechanized tunneling method, whereas NATM method follows marginally close. However, if the comparison is conducted on a “Mechanized” vs. “Non-Mechanized” method basis, then the “Non-Mechanized/Conventional” method takes the lead with almost two thirds of the cases. The interdependence and interaction between the geomaterial and the adopted construction method can decisively determine the potential failure type.

What is equivalently interesting is that the vast majority of both TBM & NATM tunnel failures are triggered more by the existence of soil-like conditions rather than rock-like as shown in Figure 3. This could be generally attributed to the reduced mechanical and deformational characteristics of the soil-like ground, which in turn could lead to a failure event via excessive deformations, loosening of their texture, excessive exerted stresses and structural instability.

This conclusion is further confirmed and validated when the failure types are examined.

3.1.3 Failure Type

Given the availability of information on tunnel failures, a structured and circumstantial approach was followed revealing the most prominent failure types.
From Figure 4 below, it can be concluded that face instability/failure constitutes by far the most prominent cause, counting almost half of the examined cases. Deformations of a tunnel section start developing in some distance ahead of the advancing face. If these are ignored, miscalculated or not properly mitigated (in a timely and structural manner), they become uncontrollable leading to instabilities and failures, subject to the strength and deformational characteristics of the ground. An initial assessment of face stability conditions can be essential in deterring upcoming failure events and is a key success factor for tunneling works, especially for shallow tunnels (like most of the urban metro tunnels) in challenging and difficult ground conditions (as soil-like proven to be). Support failure types – either as a result of overstress or insufficient support measures installation – equals to almost a quarter of the examined cases. It is of utmost importance to formulate a robust support scheme with a proper timely installation sequence in order to avoid potential failures.

A more detailed insight into the failure types explicitly highlights the contribution of ground conditions and the primary role of soil-like conditions, as shown on Figure 5. As it can be shown, the support failure in the rock conditions may be attributed to the load excess deriving from a sliding wedge and/or the insufficiency in the support capacity and resilience.

### 3.1.4 Loss Frequency

In Figure 6, the insurance losses frequency distribution is highlighted; however the shortfall of insurance related information on specific tunnel losses events is evident, primarily attributed to commercial sensitive information.
Insurance losses seem to span a wide range of values, even exceeding 150 USDm. However, they exhibit a rather normal distribution for values up to 50 USDm, with a mean value of approximately 10 to 15 USDm, but an elongated tail towards higher values and a peak in the range of 100+ USDm. The bell-shaped probability density function for this distribution appears to be in good agreement with most tunnel limits in the majority of placed Insurances Policies. However, we may also identify cases with high impact/low probability effects (also referred to as ‘black swan event’, widely described by Nassim Nicholas Taleb, 2010).

3.1.5 Project Delays

Based also on the limited data regarding the incurred delays imposed upon the project completion, it can be deduced that these span from relatively low (i.e. 1 month) to substantially high figure (i.e. 4 years) for very limited cases as shown on Figure 7 which outlines the frequency distribution of project delays, with a “reasonable” time interval of 3 months.

As it can be seen, there is almost a normal distribution for delays up to approximately 1 years’ time. These values could be considered in good agreement with common practice experience. Delays up to 3 years’ time seem to be quite often and regular, whereas more severe ones can be considered as limited and particular cases. In addition, effort was put in identifying any potential relationship between the insurance cost and the corresponding delays that the same project has suffered. Figure 8 illustrates this, with the potential of a linear trend being established, neglecting of course the extreme cases.

One interesting finding is that there are cases illustrating a very small economic loss but with significant time delays.
Figure 8. Relationship between insurance cost and corresponding delays

3.1.6 Quantitative Losses

Figure 9 illustrates the cost the insurance market sustained in relation to the various failure triggering causes. As it can be seen, half of the cost is due to fires in the tunnels, especially during their operation. Very characteristic examples of fire events include the Eurotunnel fires (both in 1996 and 2008), the fire in the Montblanc tunnel and also the Tauern tunnel fire event in 1999 in Austria.

Figure 9. Insurance cost per tunnel failure type

Failures caused by collapse of lateral support count for one fifth of the total incurred cost. Most prominent representative failures include the Singapore MRT/Nicoll Highway collapse in 2004 and the Cologne Metro collapse in 2009. Both collapses had direct and indirect third party impacts, such as fatalities, property damages and businesses interruption. With regards to tunnel collapses during construction, face instabilities stand out as the principal cause related to corresponding insurance cost. A different assessment correlating insurance cost with the actual tunneling construction method is presented in Figure 10. The higher percentage of the Cut & Cover method is attributed to the Cologne Metro collapse, which also includes an unknown amount related to third party liability. TBM losses seem to overrun the NATM related, perhaps due to the inclusion of higher values of the machinery (e.g. TBM and back-up system) used and the associated reinstatement costs. It has to be mentioned, however, that all major fire events have not been included in the figure as they relate to operational tunnels.
From the examination and evaluation of the existing information, three main categories of interest emerge as the most important and most influential related to a tunnel failure, i.e. Geology – Hydrogeology – Geotechnics; Design and Construction Management. Those categories sum up to approximately 80% of the overall causes of underground failures (see also Reiner, 2011).

4.1 Geology/Hydrogeology

The geological conditions and the hydrogeological regime can have a significant impact on the performance of the tunnel project construction and increase the probability of provoking a loss event. Prominent failure causes can emerge from the lack and knowledge shortage and can be directly attributed to the inadequate ground investigation schemes. Failure to identify any weak ground area or notable ground feature, like shear fault zones, can lead to disastrous results.

Low-bearing geological structures located at the tunnel’s crown can be catastrophic creating a knock-on effect initiated by a simple over excavation and resulting in excessive surface subsidence, subject to the tunnel’s depth. This can be particularly destructive in case of shallow urban tunnel projects with significant exposure to third party properties, as illustrated in Figure 11 where in the vast majority of the failures, the overburden ranges from 2m to 30m. Moreover, these depths are also prone to creating a “chimney like” failure mode, with enormous consequences for the overlying structures, both at grade and underground (e.g. utilities).

Last but certainly not least at all, is the importance of the underground water regime. The actual water level together with its fluctuation plays an important role in the stability and safety margins of the
underground/tunneling works. Combined with its exerted pressure (sometimes when having perched aquifers or artesian conditions) can create likely conditions to trigger a failure incident.

4.2 Design
Design and design errors occupy a substantial portion of the underground works failure causes and according to Reiner, 2011, they constitute around 40% of the overall plausible causes. An element of significant importance is related to tunnel face stability. As per the previous analysis, face instability is related to almost half of the failure cases. A thorough and specialized analysis of face stability conditions at the design stage is a key factor for deterring any potential failure incidents. The accuracy and validity of the face stability analysis should always be subject to sufficient field data obtained from a detailed and project-specific ground investigation scheme. However and due to the inherent variations, face stability assessment under uncertainty must be carried out on the basis of probabilistic analysis as presented by Konstantis 2011 and 2013. During construction, regular, consistent and systematic face mapping and instrumentation and monitoring is rendered crucial in obtaining real-time information allowing for realistic evaluation of the existing stability conditions, validation of the design’s assumptions and further improvements and value engineering. Realistic estimation and simulation of the stresses exerted by the surrounding ground to the tunnel is essential in the process of properly adjusting the desired and efficient tunnel profile. Ground-structure interaction is key in understanding the behavioural model which will then allow for improvements aiming at increasing the safety level and optimizing the design, as presented by Konstantis and Spyridis, 2013.

4.3 Construction Execution and Workmanship
All the above mentioned losses highlight the importance of a robust and applicable construction management plan, regardless of the chosen excavation method and the selected construction equipment. Of utmost importance is the adherence to the approved and substantiated construction sequence deriving from the design stage analysis, including the timely installation of the support measures. Deviations from that principle could lead to catastrophic results. Proper and targeted instrumentation & monitoring plans are extremely essential to validate the expected behavior, allowing for an economical and risk mitigated construction. The composition and qualifications of the construction personnel is one of the most decisive factors of the project’s overall performance. Lack of qualified/experienced personnel on site during construction (coupled with limited site investigation data) could be a source of forthcoming disasters.

4.4 Discussion
Despite the inherent uncertainties associated with the design and construction of tunnels and underground works and the various aspects and factors with significant and potentially destructive influence, there are things to be done and actions to be taken from the conceptual stage to operation, in order to mitigate, or even eliminate, construction failures and their consequences. These actions and the associated mitigation measures must be part of formalized risk registers, which can actually become contract documents (R. Goodfellow, J. O’Carroll, S. Konstantis, 2014).

During the early and tender stages, all the available and relative information must be conveyed to the tenderers to enable a proper risk assessment and evaluation which will in turn influence accordingly the design approach and construction methodology and equipment to be used, thus reducing the probability of failure events. Equally important is the ground investigation scheme. Its extent, suitability
and relevance to the individual project can be crucial in timely identifying the exact ground conditions and the existence of any major features capable of jeopardizing the safety of the works. The design stage has the dynamic to influence the risk profile of a project. A proper and well established design management plan and philosophy is always the first line of defence against future failures and corresponding losses. As mentioned by (Reiner, 2011), design errors contribute a significant percentage of the tunnel failures. In this regard, probabilistic assessments under uncertainty can provide a decision framework for design improvement and optimization (see for instance Konstantis and Spyridis, 2013).

Moving on to the construction stage, it is absolutely imperative that the design is implemented without deviations. Probe drilling ahead of the tunnel face can be extremely beneficial and avert any forthcoming disaster by providing critical information on the existing conditions to be encountered.

Risk Engineering Management must encompass the above (indicative and non-exhaustive) elements in a structured manner, adopting a pro-active approach that spans from the conceptual and insurance pre-placement stage until the completion and handover of the project. The first step is to undertake a benchmarking exercise against the Code of Practice for Risk Management of Tunnel Works in an effort to review the risk management frameworks of the project. In addition, Risk Engineering surveys must be carried out at regular intervals with the aim to identify the ongoing risk profile of the project and ensure continuous adherence to the Code of Practice principles. In view of providing a proper and adequate coverage of the tunneling works, the tunnel loss limits adopted in the Insurance Policy is a key driving element. Project hazards and associated risk scenarios and assessments must provide a realistic estimation of the Probable Maximum Loss.

5 CONCLUSIONS

Tunnels and Underground works face the risk of experiencing a failure event followed by a substantial loss and delay to be covered by the Insurance market. This contribution has elaborated on the (publicly available) tunnel failure incidents to date and subsequent insurance market losses. The loss events were examined, with the emphasis on the quantitative cost analysis and the related project delays. A potential linear relationship between cost and time delays seems to be established, excluding however the extreme cases. Insurance market losses tend to reduce in direct proportion to timely recognizing, comprehending and managing of the emerging risks, as also stipulated in the Code of Practice. A proactive risk engineering management attitude and probabilistic approaches (see also ITA, 2006) can efficiently contribute in reducing the size and frequency of major incidents, especially by integrating all important lessons learnt from past years in a continuous live updating process.

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