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A robust approach to major tunnelling fire safety during the construction phase

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ABSTRACT: Tunnelling projects are growing in popularity and complexity, increasing exposure to various hazards. Although Fire & Life Safety (FLS) considerations are crucial in design development phase, they can be overlooked in the construction phase.

Construction of underground structures represents the most dangerous phase of projects, with heightened complexity of hazards including fire due to multiple factors. Therefore, implementing strategies to control or manage fire related hazards during construction is essential for the safety of construction personnel and to facilitate effective incident response.

Multiple tunnelling projects in Australia, including road, rail, and hydro power, have adopted more robust construction phase FLS analyses to manage fire safety hazards.

The primary objective of these FLS analysis was to reduce fire risks So Far As Is Reasonably Practicable (SFAIRP), while secondary objectives include reduced construction costs, timelines and address stakeholder concerns.

Two critical factors inform risk-based analyses, frequency and likelihood, but, the lack of historical construction incident data can complicate the frequency side of these assessments. Nonetheless, a robust risk-based assessment can provide comprehensive evaluations of fire hazards, allowing clients to demonstrate that underground fire risks have been reduced SFAIRP. Additionally, Computational Fluid Dynamics allowed optimised ventilation arrangements and construction performance.

1 INTRODUCTION

Designers and constructors must consider fire safety during tunnelling construction, especially addressing Workplace Health and Safety legislative requirements for all types of work. Before 2013, Safe Work Australia partnered with state organisations (SafeWork SA, Workplace Standards Tasmania, WorkSafe WA, Workplace Health and Safety QLD, NT WorkSafe, Work Cover NSW, Comcare, and WorkSafe ACT) to create the *'Guide for Tunnelling Work'*. Each state's Workplace Health and Safety (WHS) legislation demands safety by design, requiring designers to minimise hazards So Far As Is Reasonably Practicable (SFAIRP). WHS legislative requirements typically define workplaces as somewhere tasks occur, relevant from concept phase to decommissioning of a project. Thus, these laws require designers and constructors to manage fire safety during construction, ensuring that hazards and risks are minimised SFAIRP.

Construction fire safety guidelines developed for the building industry are not necessarily applicable to a tunnelling construction environment. Tunnel construction is more aligned to underground mining, however, differ from mining in that mining can include different risks that may not be directly attributable to tunnelling.

Therefore, considerations of fire safety hazards in tunnelling could and should be better addressed via a first principles review of the intended tunnelling methodology and in line with the operational tunnel risk assessment process.

Past projects have considered construction fire safety to varying degrees and fortunately to date, our industry has been managed such that we have not had a significant construction phase underground fire incident in Australia or New Zealand. The fire safety risks that can occur during the construction phase vary depending on the type of construction, the tunnelling process, the method of construction and construction sequencing process. Factors influencing fire safety include but are not limited to; the presence of dead-end shafts, the provision of tunnel ventilation, the functional operation of tunnel ventilation systems, types of plant, the number of workers present, the ability to provide exits and access for emergency response crews.

The approach described in this paper has been adopted on multiple projects across Australia (road, rail and hydro). Outcomes of these studies resulted in construction phase fire risks being demonstrably reduced SFAIRP in compliance with WHS legislation.

The WorkCover NSW 2006 Guide for Tunnelling Work provides important baseline prescriptive fire safety measures for tunnelling projects under construction. However, these generic requirements are inherently limited by their one-size-fits-all prescriptive format and may not fully account for the diverse, complex, and evolving fire risks associated with modern tunnelling methods, materials, and equipment.

Therefore, a robust risk-based fire safety approach offers a more flexible and effective strategy that responds to the complex and changing nature of tunnel construction. It demonstrates that the construction phase fire risk is managed proactively and proportionately, supporting safer outcomes for workers, assets, and the public.

2 STEP ONE - SCOPING

2.1 *Considerations*

Numerous avenues need to be explored to build a comprehensive picture of the tunnelling construction approach and the environment where incidents could potentially occur.

With the primary objective being the reduction of fire safety risks to project personnel SFAIRP, considerations should include:

- Fire safety strategy for occupant egress
- The varying levels of tunnel construction completeness
- Emergency services response for varying stages of project completion
- Day-to-day fire safety measures

A comprehensive fire safety strategy can also serve to expedite construction or reduce whole of life costs if done strategically. Modern tunnel construction processes face elevated constraints, like increasing construction complexity, compressed delivery scheduling and environmental limitations. Tunnel construction methods may include Tunnel Boring Machines, Sequential Excavation, drilling and blasting, cut and cover, or trench methods for construction or combinations of these methods. Each tunnelling method carries specific hazards, often unique to the method, ground conditions, the location, and tunnel geometry at that time. Due to these factors, each project is distinct and warrants individual analysis; a copy-paste approach may prove less-than-ideal if an incident occurs.

Historical data is a valuable resource for framing scenarios and control strategies, but publicly available data for construction phase incidents is limited, necessitating alternative Risk-based Assessment (RA) approaches. Bowtie analysis has proven to be a useful tool that does not require quantitative frequency for each measure or hazard. Similarly, a Hazard Analysis and Preliminary Risk Assessment (HAPRA) has been developed to investigate hazards and control measures in more detail. Literature reviews facilitated a quantification of risks and reductions during the HAPRA process.

Assumptions made during the fire safety evaluation process require validation and consultation with the relevant parties to improve accuracy of the assessments. Existing construction policies serve as inputs to the fire safety strategy, generating awareness within the project and can highlight areas of special consideration.

2.1.1 *Fire Safety Risks During Construction*

The fire characteristics of an operational tunnel are different from those in a tunnel under construction. Similarly, evacuation, emergency response, and selecting safety equipment also differ from the completed tunnel solution. As a result, the hazards associated with fires occurring during tunnel construction can be higher than those associated with the completed operational tunnel.

Therefore, a fire safety strategy based on the final design may not be applicable until the completion of the construction phase.

The traditional understanding of fire dynamics in tunnels assumes that tunnels are complete and have two open portals, allowing airflow, access, and egress. However, this is only valid after the construction breakthrough has occurred. Each tunnel geometry and the resulting ease of egress can vary greatly by project, and the 'mainline' tunnel under construction may be the only means of access and egress.

During tunnel construction, unique measures such as special access shafts or entrance tunnels may be required to facilitate construction. These access tunnels may not be part of the final tunnel solution but can provide easier access during construction. The slope of an access shaft or tunnel typically varies with the project and depends on the geological and/or ground conditions. During certain types of tunnel construction, the access safety or tunnel provides the sole opening to the surface while both ends of the horizontal main tunnel remains closed until breakthrough. These access shafts or tunnels can be used to assist with personnel safety during an emergency

Several fires have occurred during the construction of tunnels, resulting in deaths or injuries to individuals, losses and damage to equipment, damage to tunnel structures, and delays in project delivery. Globally, fire has become a common construction accident; as there can be numerous potentially dangerous tasks being executed in parallel. The consequences of these fires depend not only on where fires occur in the tunnel, the fuel involved, the intensity and nature of the fire, the complexity of underground facilities, the response of the rescue service, and the availability of resources, including personnel and equipment. Although there is limited statistical data available, understanding the tunnel fire characteristics during construction is essential for effective fire control and evacuation management.

Previous studies showed that approximately 75%–85% of construction phase fire-related deaths arose from poisonous gas under fire conditions (Hu, Tang, Yang, Liu, & Huo, 2010). Compared to a tunnel during operation, the ventilation and smoke management systems available during tunnel construction may be considered a limiting factor, as the smoke may not be adequately discharged to provide smoke-free egress and access paths. The limited ventilation, coupled with the reduction or blocking of the tunnels' cross-sectional area or excavation faces by vehicles/equipment, can also influence the smoke spread through the construction shaft.

Fire accidents during construction of tunnels have been reported to cause smoke to quickly fill the tunnel, which can increase the difficulty for personnel to escape and for emergency responders to access. Therefore, a robust fire safety strategy developed specifically for the construction phase is paramount for personnel and responder safety in the case of an emergency.

2.1.2 *Physical Environment*

Generally, the tunnel environment during construction is rough. The tunnel construction environment is typically characterised by low illumination, wet surfaces, uneven and sometimes slippery ground, ongoing construction work with incomplete constructions, noise, and conditions that are constantly changing in appearance. These factors can impede and add complexity to the safety of personnel in the event of a fire.

Typically, tunnels are equipped with a forced ventilation system to manage air quality for the safety of workers in normal operating conditions. However, the system basis likely requires continual adjustment based on the tunnel geometry at the time or the construction method employed. Understanding the basis of the construction phase ventilation strategy and how modifications can be made to the ventilation system a key consideration of a robust fire safety strategy.

Perhaps the most crucial factor concerning evacuation is the extended travel distance from a working place (typically located in the most remote part of the tunnel) out to the tunnel entrance or a place of relative safety. This travel distance can, in some cases, be several kilometres, therefore, it's essential to have a pre-designed plan for managing an evacuation; including appropriate fire safety provisions, such as lighting, ventilation, and exits, to assist in making evacuation safe, given the conditions. A common problem for new tunnel construction projects is the lack of specific recommendations for fire safety provisions. Typically, fire safety provisions are included, but often with little understanding of the benefits of these provisions or whether they are sufficient for the specific tunnelling situation.

Whilst there are rules governing task lighting, it may not meet the egress lighting requirements away from the task location. The location and lighting levels within the tunnel's construction environment can vary depending on the proposed excavation plan. Depending on the evacuation strategy, the height of illumination points may be as crucial as regulating the distance spacing between illumination points. Equally, it's consideration should be given to the need for these emergency lighting points to be equipped with backup power supply, to cater for potential power outages and subsequent loss of illumination.

All the factors listed above can affect the possibility of evacuating safely. A number of factors can play a critical role in the safety of site personnel. An initial site induction may not provide a comprehensive knowledge of the site and emergency procedures in place. Therefore, it is paramount to have a comprehensive strategy in place to reduce the potential for fatal emergencies to occur.

2.1.3 *Evacuation*

Evacuation conditions for construction site workers differ significantly from those expected in operational buildings or tunnels. Tunnel environments can be quite complex and are continually changing, with cognitive and physical obstacles making evacuation challenging. In addition to construction site issues, modern tunneling methods can include the use of specialised Tunnel Boring Machines (TBMs) with complex internal layouts, the presence of flammable hydraulic fluids, complex electrical systems, and extensive conveyor belt systems; introduce specific hazards where rapid fire spread can impede egress and cause access challenges during emergencies. Evacuation and the notification of an alarm could be inhibited by factors such as; competing sounds, low-light conditions, isolated locations on the equipment impairing vision of incident or alarm, or other works which reduce focus on an incident.

Much of the preventive safety work relies on traditional construction safety procedures; limited work has been published focusing on the unique problems facing construction workers during evacuation from complex tunnel environments. A key factor for a successful evacuation from tunnelling construction sites is acknowledging the importance of procedural safety aspects. A typical tunnel construction site may include workers, subcontractors, and visitors, which can result in unclear or diminished levels of safety responsibility.

One of the problems that can occur in tunnel construction environments is recognising the fire threat; fire cues must be interpreted, and a worker's decision-making processes must be initiated. There may also be extended travel distances between the location of the workers and a place of safety, or an exit may be totally cut-off, limiting the potential for escape. Thereby necessitating careful consideration of the risks and developing appropriate controls to manage it, for the safety of both site personnel and responding emergency crews.

2.1.4 *Fuel loads*

Threats on construction sites can include flammable materials and dangerous construction activities, which can lead to fire accidents. Significant fire accidents on construction sites can lead to secondary accidents, such as collapse, burial, and explosion, all of which can result in more severe damage to life and property. Introduced hazards on construction sites can include the storage of flammable materials underground and hazardous construction activities like hot works, which can cause fires. Additionally, various gases may be stored or used for construction, and these stored gases can increase the risk of fire and explosion on the construction site.

A holistic review of storing combustible materials on construction sites was determined to be essential factors in preventing or limiting the severity of fire accidents. Underground fire risks can occur wherever potential ignition sources meet a flammable or combustible fuel sources. When quantifying fire scenarios within a tunnel under construction, several parameters can influence the characteristics of the scenario including the location of the fire, tunnel ventilation conditions, influence of the fire protection system (suppression systems, smoke extraction, fire alarm, etc.) during construction, and the distribution, density, and type of combustible materials.

Vehicle fires present distinct challenge regarding their frequency and locations, as vehicles are commonly found throughout tunnel construction zones, often in substantial quantities near a work or task location. A situation involving a vehicle fire that can rapidly spread to other vehicles near zones with a high concentration of personnel or close to a main evacuation route warrants attention when planning for egress safety.

Characteristics of the most frequent fires in underground mines across Australia identified the position of vehicle fires being predominantly from within the engine area with fire caused either by fuel/oils contacting hot surfaces or electrical fault.

2.1.5 *Ventilation*

Various ventilation systems can be employed in tunnel construction to manage air quality, with ventilation arrangements depending on the tunnels length and diameter, construction method, and specific construction hazards. Numerous arrangements of ventilation are possible within a project, with each potentially being more suited to the construction method employed and the tunnel geometry at that stage of construction. Past experience has shown the value of performing CFD analysis on the ventilation system to optimize the ventilation arrangements, and the smoke management outcomes for occupants and responders in the case of an emergency.

2.1.6 *Intervention*

Fire and rescue services have limited possibilities to perform fire and rescue operations in tunnels under construction due to long response routes, complex changing environments, and sometimes the need for more information. The inability for emergency response access in an incident can leave occupants trapped in the tunnel, needing self-sufficiency for hours until the incident is suitable resolved and it is safe for emergency services to enter. Whilst self-evacuation and self-rescue are always preferred; the emergency services' potential to perform a fire and rescue operation can influence the choice of egress provisions in the tunnel, with elements such as rescue chambers sometimes necessary.

Therefore, it is essential to define the emergency response tactics, methods, and available equipment to support a fire and rescue operation in the early phase of developing the Fire Safety Strategy. Conditions that primarily influence the rescue operation's process are the fire growth, heat release rate, location of the incident and if the fire occurs before or after the breakthrough (opening both ends of the tunnel). These parameters can influence or change the tactical approach of the whole fire and rescue operation.

Fire and rescue interventions in a tunnel under construction can involve either an offensive (direct firefighting) or defensive (waiting outside for safety) response strategy. Whilst these response strategies are typically not used simultaneously, they can be switched during an incident. Typically, there are five tactical approaches to handling a fire in a tunnel; including direct firefighting, rescuing individuals, controlling airflow, fighting from a safe distance, and caring for self-evacuated people. These tactical approaches can be used individually or in combination depending on the chosen strategy and available resources.

Emergency response to an underground construction site can be highly volatile. Therefore, comprehensive measures should be in place to minimise the chances of personnel being trapped underground or if evacuation is impossible, appropriate measures should be in place for personnel to safely shelter for the required time and alert the surface of their whereabouts allowing responders to perform a headcount.

2.1.7 *Summary*

High consequence environments such as underground construction sites can place multiple personnel at risk in the event of a fire. Historical data shows that these incidents can increase in severity in a short period of time. There are a multitude of factors to consider when performing a risk-based assessment for a construction site and due to a shortage of incident data, alternative methods of risk-based analysis may need to be employed to perform a comprehensive and holistic analysis. Risk-based assessment techniques, such as bowtie analysis and/or Hazard Analysis and Preliminary Risk Assessment (HAPRA) serve as tools to evaluate construction fire safety risks comprehensively without the specific need for historical data. This methodology provides a robust approach to the construction phase fire safety of underground projects.

3 STEP TWO - ANALYSIS

3.1 *Bowtie analysis*

3.1.1 *Overview*

The Bowtie analysis is a qualitative risk assessment methodology that effectively communicates complex risk scenarios in a clear and easy-to-understand graphic format, illustrating the relationships between the causes of unwanted events and the potential for loss and damage escalation.

Whilst other risk assessment methods focus on specific aspects, like Fault Tree Analysis (FTA) identifying possible causes of an incident, Event Tree Analysis (ETA) detailing possible outcomes of an incident, or Failure Mode and Effects Analysis (FMEA) on identifying and prioritizing failure modes and its effects; the Bowtie analysis integrates these perspectives to provide a balance representation of potential threats or causes without a dependency on likelihood statistics.

Each bowtie can display preventative control measures (for each specific threat) that limit the potential for the top event to happen and show the mitigative control measures that are implemented after the event has occurred, to limit possible consequences, specific for each credible scenario evaluated.

The main advantages of the using the Bowtie approach in risk-based analysis are:

- Provides a solid technique of identifying all risk events and promotes an understanding of their reciprocal relationships.
- Uses a format that is an easy-to-understand medium to communicate the cause-and-effect relationships underlying more complex risk scenarios for a wide range of stakeholders.
- It helps to demonstrate the controls implemented to manage risks and therefore provides a way of identifying weaknesses, gaps and opportunities for a continuous risk reduction.
- Enables verification and connection to relevant sections of the construction management system that support controls, including critical security elements and critical safety activities.
- The easily communicated process increases the workforce awareness of the risks associated with their facility and how these risks are managed; and
- Uses the workforce's knowledge and expertise, which best understands the actual state of operation of existing controls and threats as inputs to the risk management process.

3.1.2 *Application of bowtie analysis*

The development of the construction phase Fire Safety Strategy is limited to considering fire safety hazards that may occur during the tunnelling construction works and demonstrating that the fire safety risks associated with these hazards have been reduced SFAIRP. Risk-based assessments can become too granular and therein lose their value in influencing fire safety outcomes. Therefore, there is no point in evaluating every single vehicle and process present during the construction process, as the granular assessment process will lose its value to the construction safety team.

To address this potential issue, and where appropriate, the assessments examined systems or subsystems, rather than individual items or topics. An example of this approach could be that the mobile plant could be classified as a system. Similarly, the TBM conveyor could be considered another type of system. For more complex plant and equipment, such as the TBM, it is considered more appropriate to focus on the TBMs subsystems, rather than the TBM itself. As an example of the TBM considerations, it may be more appropriate to focus on the hydraulic systems of the TBM, rather than the TBM itself.

This system-based approach to assessing fire safety hazards enables the Fire Safety Strategy to add value and efficiency to the fire safety risk reduction process. Developing the Bowtie analysis based on systems used in the construction process, is a foundation step to inform the HAPRA analysis which provides a deeper level of analysis.

3.2 *HAPRA analysis*

3.2.1 *Overview*

The HAPRA can employ a qualitative, semi-quantitative or quantitative risk assessment methodology that effectively communicates complex hazards as scenarios, in a more detailed manner than shown in a Bowtie analysis. When considering hazard scenarios, the HAPRA provides a classification of preventative controls and their associated limitations. Thus, allowing a likelihood and consequence to be applied for a specific audience (for Tunnel Projects, this could be construction personnel or emergency services), resulting in a preliminary risk ranking being determined.

The HAPRA process then applies mitigative control measures, which aim to reduce either the likelihood or consequences of the event occurring, before reevaluating likelihood and consequence considering the implementation of all Risk Control Measures (RCMs). Considering the residual risk rating allows each audience to determine if the risk can be further reduced or if it is considered impractical to further reduce the risks, thereby, demonstrating that the risk has been reduced SFAIRP using the RCMs implemented. The main advantages of the approach to adopting HAPRA process are:

- Provides a solid technique for a more comprehensive identification of all fire safety hazards and events, promoting an understanding of these hazards and providing comments on their reciprocal relationships.
- It helps to demonstrate the level of control (preventative or mitigative) that has been applied to the hazards, thereby providing a way to identify weaknesses, gaps, and opportunities for reducing fire safety risks.
- Enables verification and connection to relevant sections of the construction management system that support controls, including critical security elements and critical safety activities.
- Highlights limitations of control measures that could hinder performance.
- Gives quantitative residual risk ratings once risk control measures are implemented.
- Increases the workforce awareness of the risks associated with their facility and how these risks are managed; and
- Uses the workforce's knowledge and expertise, which best understands the functional operation of the construction process, including existing controls and threats.

3.2.2 *Application of HAPRA analysis*

For a tunnel construction project fire safety strategy to be developed, the HAPRA analysis receives input from the Bowtie analysis undertaken and provides a platform for evaluating and classifying threats and controls. The risk ratings, coupled with the commentary and risk control measure classifications, can be used to substantiate decisions on which control measures are worth implementing to reduce the fire safety risks during construction.

3.3 *Worked Example – Bowtie and HAPRA analysis*

Figure 1 shows an example of Bowtie analysis for fire incident (top event) occurring in the TBM electrical system. The 'left' bow identifies the threats that can cause the event and the preventative control measures designed to stop each specific threat from leading to the TBM fire. The 'right' bow identifies the potential outcomes if a TBM fire occurs and mitigative control measures used to limit the severity of consequences of the event. Another critical aspect of Bowtie is the identification of escalation factors that can cause a barrier to fail or become less effective. The Bowtie analysis provides visual information to inform stakeholders and also to provide valuable tool for further discussion.

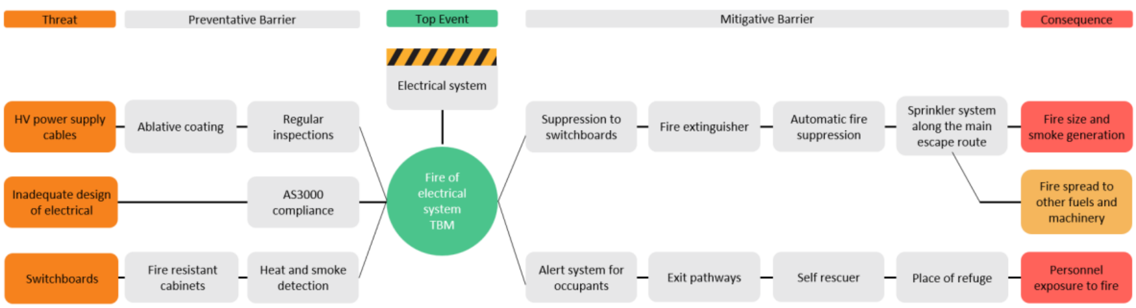

Figure 1. Sample Bowtie analysis for the electrical system in a TBM, wording has been simplified for the purposes of this paper.

Subsequently, the structured output of the Bowtie analysis directly informs and feeds into the HAPRA process, where risk ratings based on likelihood and consequences, can be calculated and actionable controls can be assigned to responsible parties.

4 STEP THREE - OUTCOMES

The documented risk-based approach to FLS in the construction phase of tunnelling projects has provided several key positive outcomes to Projects on which they have been employed. The primary positive outcome is improved levels of fire safety for the site, using controls that are reasonably practicable. The nominated risk-based assessment approach using Bowtie and HAPRA assessments, allows project hazards to be identified, understood and assessed in a systematic fashion. The HAPRA allows both a qualitative and quantitative approach to be adopted to validate the risk mitigation controls. The approach improves safety outcomes over other methods by;

- Improving stakeholders' understanding of project risks by providing simple visual explanations, e.g. Bowtie structure.
- Capturing project specific hazard details by engaging workforce/operators inputs to the HAPRA analysis process.
- Demonstrating that risks are reduced SFAIRP by assessing whether control measures that could be used to mitigate or prevent risks are reasonably practicable.

A further positive outcome of this process is projects can effectively demonstrate that their obligations to Workplace Health and Safety (WHS) legislation have been met.

5 SUMMARY

In summary, construction of tunnels are complex, unique, and can possess a relatively high fire safety risk profile due to their underground nature; which can inhibit egress and emergency response access during fire events. The underground constraints associated with tunnel construction meant that compliance-based risk assessments applicable to buildings are not suitable for these types of projects, and more suitable processes should be used instead. This paper presents a robust risk-based assessment method for assessing and addressing the fire safety risks for these projects using a combination of Bowtie and HAPRA analysis.

Using a risk-based assessment which utilises this combination of Bowtie and HAPRA analyses, allows the hazards and risks associated with construction phase works to be clearly communicated to all relevant parties. This robust process allows projects to determine which risk control measures are deemed *'reasonably practicable'* to implement. The use of the risk-based assessment methodology allows hazards and risks to be monitored during construction and satisfies the projects statutory obligations to reduce safety risks SFAIRP.

6 REFERENCES

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