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Importance of risk mitigation for a live tunnel refurbishment project

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ABSTRACT: Working in a live tunnel presents numerous challenges, particularly when performing asset maintenance within limited shutdown periods. This paper highlights how Burnley Tunnel Low Voltage Cable Refurbishment Project succeeded through exploring the critical strategies for risk mitigation during the stages of design development, focusing on the complexities associated with live tunnel environments. With the privilege of collaborating with pre-selected contractors in the project, a proactive approach was adopted by conducting early stakeholder engagement through comprehensive workshops. These strategies facilitate effective coordination, allowing for the identification and management of potential risks before they can escalate. The collaborative efforts of the clients, contractors, and designers in early engagements ensure that maintenance activities can be executed efficiently, reducing project disruptions and enhancing overall project success.

1 INTRODUCTION

Underground structures typically comprise multiple systems and pieces of equipment, each with a designated design life. During operational construction activities, routine maintenance and repairs are often necessary to ensure the assets' longevity. However, for live tunnels, maintenance shutdowns must be limited in both frequency and duration due to the significant impact of downtime.

Given the involvement of multiple stakeholders in large construction projects, it is crucial to establish alignment with the client from the outset. This includes understanding design limitations, determining acceptable risks, and agreeing on processes such as program, design coordination, and communication methods to ensure the project's success. Poorly planned projects can lead to issues such as stakeholder misalignment, increased project risks, schedule delays, and budget overruns [1].

In Australia, several live tunnel systems are approaching the end of their design life and require critical updates and refurbishment of mechanical, electrical and ITS equipment. The Burnley Tunnel is one such example, where major Low Voltage (LV) cables, which are directly buried along the tunnel's length, are approaching the end of their operational lifespan and require replacement to ensure continued system integrity and reliability.

Burnley Tunnel is an integral component of the CityLink Tollway managed by Transurban. The tollway tunnel facilitates eastbound traffic movement from the West Gate Freeway to the Monash Freeway. Beneath the Yarra River and traversing the inner suburbs of Richmond and Burnley, the tunnel serves as a strategic bypass, offering an alternative route that circumvents the central business district. The 3.4 km three-lane Burnley Tunnel comprises different sections, including 460m of cut and cover at the west portal, 2.84km of driven tunnel, and 180m of cut and cover at the east portal. Additionally, a 1.4km Emergency Egress Tunnel (EET) runs parallel to the eastern part of the main tunnel. The infrastructure includes eight Cross Passages (CP) linking the Burnley Tunnel to the EET, four CPs providing an emergency exit to the Domain Tunnel and three emergency refuges located in the central section of the Burnley tunnel. The Burnley Tunnel map is shown in Figure 1.

Figure 1. Burnley Tunnel Map [2].

Burnley Tunnel LV Cable Refurbishment Project implements five essential design stages: concept design, preliminary design, detailed design, final design, and issued for construction. Risk mitigation is a critical component of construction project management. Figure 2 illustrates the correlation between risk severity and associated costs throughout the project life cycle. In the initial stages of design development, risk management is strategic, concentrating on identifying potential risks and opportunities linked to design. Although the severity of risks is higher at the initial stages of a project, the associated mitigation costs are low. However, as the project advances towards completion, the costs associated with these risks increase substantially [3]. Therefore, it is critical to implement risk mitigation strategies at the earliest possible stage to prevent cost escalation.

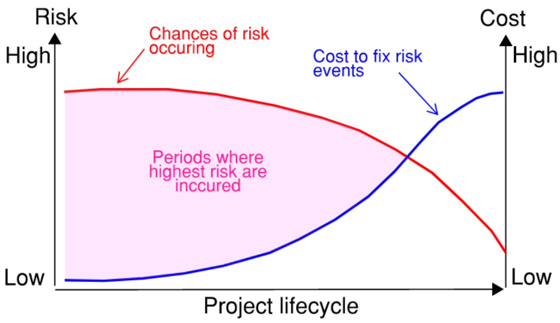

Figure 2. Project life cycle associated with risk management and project cost [3].

The main challenge of this work is the reliance on the electrical power of all the tunnel systems to sustain operations, and the maintenance planning for repair work should LV cables fail. This represents a high-risk maintenance item as replacement of the cable requires significant work that results in a major tunnel downtime. To resolve this issue, an alternative permanent and more sustainable solution is explored requiring access to the roadway tunnel areas.

With pre-established stakeholders such as clients, designers, contractors, and suppliers, the project risk is managed from the concept design by considering the whole-of-life of the asset. Given the high-risk nature of construction projects, significant emphasis has been placed on risk identification and mitigation during each design phase. This paper will explore the advantages of early risk mitigation in Burnley Tunnel LV Cable Refurbishment Project, outlining specific processes and methodologies that can be effectively implemented to achieve successful risk management outcomes.

2 PROJECT RISKS AND CHALLENGES

Modification of existing tunnel components induces various challenges. For Burnley Tunnel, the existing cables are situated behind the concrete New Jersey Barriers (NJBs) and are encased in hardened, stabilised sand (shown in Figure 3). In addition, the cables that are the primary focus of this project are obstructed by vertically stacked conduits. Removing and replacing these conduits would require prohibitively long tunnel shutdowns. Additionally, removing existing cables can damage other services, in particular some critical control cables are also buried. Therefore, the relocation of cables is investigated.

Figure 3. Burnley Tunnel existing cable routes' location.

Due to spatial constraints and the need to accommodate existing tunnel components, the range of viable options to move a large number of cables from buried locations to open locations is limited. The confined space within the tunnel introduces feasibility and constructability challenges for the proposed new cable positioning. As the tunnel remains in operation, certain assets must be accessible during shutdowns to ensure emergency readiness, which further narrows the range of potential solutions.

Since Burnley Tunnel has been operating for many years, there are inherent risks related to discrepancies between as-built documentation and existing tunnel conditions. Such inconsistencies can affect the precision of design, and incorrect assumptions being made. Therefore, the lack of precise information may result in redundant work, threatening the project schedule and overall program integrity.

Given that the Burnley Tunnel is an operational tunnel, a contractor has been pre-selected by Transurban (the client) to facilitate early engagement, ensuring that constructability is integrated during the design phase. This proactive approach enhances coordination and minimises potential issues during construction/ installation.

Involving multiple stakeholders in a project can enhance design quality by incorporating diverse perspectives. However, collaborating with numerous stakeholders can also introduce risks such as communication challenges, decision-making delays, and conflicting interests. Therefore, effective stakeholder engagement, clear communication, and well-defined roles and responsibilities are crucial to mitigating these risks and ensuring project success.

3 RISK MITIGATION

Based on the aforementioned challenges, the following stakeholder engagement strategies are implemented in sequence throughout the design development phases to identify, assess, and agree on risk mitigation measures. These strategies ensure proactive identification, communication, and timely escalation to the client, providing opportunities to optimise the schedule, budget, and quality of the design. The key outcome of these engagements is the selection of the cable ladder alignment and the finalisation of the overall system layout.

3.1 *Site visit*

To enhance the precision of the design, at the start of the project, the design team conducts a comprehensive site inspection and manual measurements to validate as-built structures and existing services clearance geometry. A point cloud survey is performed to refine the tunnel geometry and generate a precise Three-Dimensional (3D) model. This survey allows for the cross-verification of the 3D model's accuracy by overlaying the point cloud data, ensuring alignment and precision in the geometric representation (as shown in Figure 4). 3D models serve as a critical design reference, particularly when a plan view drawing involves multiple interfaces. The model significantly reduces the need for additional site closures for inspection or information validation.

Figure 4. Point cloud survey overlaying the 3D model.

Additionally, since Burnley Tunnel has been operating for years and cable route installation requires drilling into the tunnel lining, an Ultrasonic Pulse Echo (UPE) test is conducted during the site visit. The UPE test assures the tunnel lining thickness and concrete quality are adequate for drilling and further verifies the design's structural integrity. This approach enables accurate analysis of the existing tunnel conditions and ensures the precision of cable route design.

3.2 *Risk and Opportunity (R&O) workshop*

During the concept design phase, cable arrangement optioneering is conducted to explore potential risks and opportunities associated with identified cable routes early in the process, allowing the team to focus on the agreed-upon option moving forward. The workshop aims to rigorously assess the maintainability, constructability, and operational aspects of each design option through a collaborative exercise involving multidisciplinary stakeholders, including clients, contractors, and designers.

The workshop adopts a collaborative approach through using a common workspace for ease of collaboration, to ensure that diverse perspectives are considered, and facilitating a comprehensive risk and opportunity analysis. To support structured outcomes, a dedicated facilitator is engaged to lead the workshop objectively, promote effective team collaboration, and prevent critical aspects being missed. Additionally, to accommodate people who attend online, a secretary is in charge of transferring the physical sticky note to the Miro board to ensure everyone's voice is heard (as shown in Figure 5). Furthermore, a "parking lot" is assigned for capturing additional discussions which are to be considered outside of this workshop. This ensures all agenda items are covered, and the discussion is not being sidetracked.

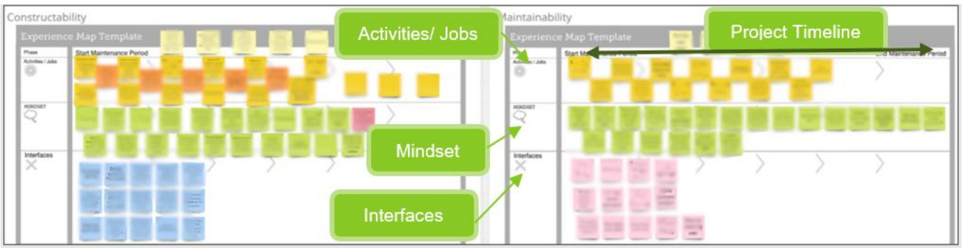

Figure 5. R&O workshop Miro board activities.

The R&O workshop ensures that all stakeholders' perspectives are heard and incorporated into design decisions, while also allows for the rapid pivoting of ideas when necessary. After the ideations and brainstorming, towards the end of the workshop, each participant has the opportunity to give scores to their preferred options. Based on the scoring and feedback that is collected during the workshop for each cable route option, a ranking table is developed to evaluate the options across key criteria: Fire Safety, Electrical Performance, Structural Integrity, Material Suitability, Constructability, Maintainability, and Business Impact. This comprehensive assessment provides a clearer direction for selecting the optimal cable route options to advance to the preliminary design phase (as indicated in Figure 6). At this stage, the focus has shifted from broad, generic design approaches applicable to all projects to project-specific criteria, including detailed consideration of cable route options.

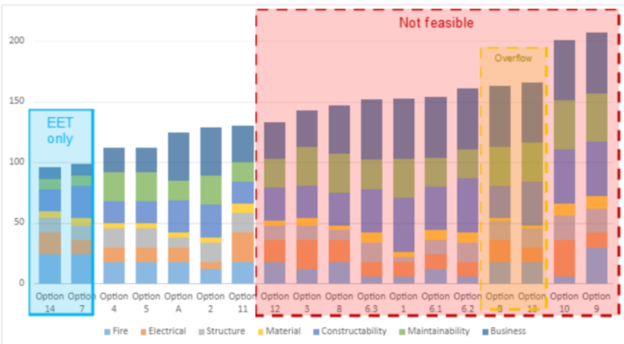

Figure 6. Ranking of options.

3.3 *Safety in Design (SiD) & Early Contractor Involvement (ECI) workshop*

A SiD workshop is an effective tool to identify potential design risks, plan mitigation strategies, and enhance stakeholder collaboration. During a SiD workshop, all relevant regulations and fire life safety aspects are considered. It focuses on risks to Health and Safety and the Environment throughout the entire lifecycle of the assets, including construction, commissioning, operations, maintenance, demolition, and disposal. Incorporating SiD workshops early in the project ensures that all risks are proactively addressed.

For the Burnley Tunnel LV Cable Refurbishment Project, it is particularly crucial to hold these SiD and ECI workshops since there are some other upgrade works happening at the same time. There are numerous interfaces that the cables traverse within the tunnel, so it is necessary to examine the associated safety risks and identify potential constructability issues. Hence, it is important to ensure the new LV cable routes do not adversely affect other concurrent work. To achieve this, the workshop involves the client and the pre-established contractors to gain a better understanding of the existing tunnel environment and minimise the number of assumptions made.

The SiD workshop encourages participants to adopt the viewpoints of various involved parties. For the Burnley Tunnel LV Cable Refurbishment Project, multiple stakeholders interface with the tunnel, such as Transurban, Fire Rescue Victoria (FRV), Department of Transport and Planning (DTP) and Tunnel users. This practice of "placing oneself in others' shoes" ensures that all potential risks are considered and addressed, for example, FRV typically focus on emergency mitigation, which means designers must ensure that the cable route design shall not obstruct the evacuation route. DTP holds a responsibility for ensuring the safety of motorists using the tunnel and for protecting the integrity and value of this asset that they will own from the date of concession termination. This is mostly achieved by ensuring optimum application of standards, concession deeds and industry best practice, meaning that designers must achieve compliance with these requirements. The value of understanding the roles and responsibilities of each stakeholder cannot be overstated, as it fosters a holistic approach to risk management.

For information management, a risk register is used during the workshop to track information and facilitate continuous updates throughout the project. This tool not only maintains up to date records but also enables automatic risk ranking based on the likelihood and consequences of identified risks [4].

In addition, the ECI workshop focuses on assessing the constructability of design with input from all stakeholders. Contractors possess an intimate understanding of the tunnel environment, and their insights are crucial for ensuring the design can be implemented within the limited timeframe available. For instance, a deemed feasible cable arrangement is proposed during the workshop and one of the key takeaways from the contractor is that the allocated space is too tight to work effectively and can result in longer installation times. The outcomes of the workshop validate all design aspects and feasibility, allowing further refinement of the cable arrangements in the subsequent design phases to prevent impractical design.

3.4 *Failure Modes, Effects, and Criticality Analysis (FMECA) workshop*

Following the refinement of the cable arrangements and cable support systems, a FMECA workshop is conducted with the client's maintenance personnel and relevant discipline-specific owner’s engineers. The workshop is led by a FMECA facilitator/ Subject Matter Expert (SME) who identifies and prioritises potential failure modes based on their likelihood and consequences in advance, allowing for effective stakeholder discussion and a more thorough assessment.

FMECA is similar to the Hazard and Operability (HAZOP) analysis which is more widely adopted in the water industry. The key difference is that FMECA focuses on assessing individual component failures and their impact on system reliability, whereas the HAZOP process evaluates process deviations, risks and their associated hazards [5].

The FMECA template is developed based on principles from the Reliability Analysis Center [6]. FMECA workshop is a systematic approach used to analyse and assess potential failure modes within a system, subsystem, or component. The following categories can be adopted in the FMECA:

- Component Identification - The analysis begins by breaking down the system or asset into its various components, identifying the lowest maintainable item within the system.
- Failure Mode Identification - Each component is evaluated to identify potential failure modes, which are events or conditions that can lead to a functional failure or loss of performance. Failure modes are described in the format of "the event" due to "a failure mechanism".
- Failure Effect Analysis - The consequences and effects of each failure mode are assessed, considering either local or higher-level impacts
- Criticality Assessment - The consequences and likelihood of each failure mode are classified. The consequences refers to the seriousness of the consequences resulting from failure, and likelihood is an estimation of how likely the failure is to happen. The Risk Priority Number (RPN) is calculated by multiplying the consequence and likelihood values.
- Prioritisation and Risk Mitigation - Based on the RPN, failure modes are prioritised, focusing on those with the highest risk levels. This allows for the identification of critical failure modes that require immediate attention and mitigation, from a reliability perspective.

By following the FMECA process, critical failure modes are identified, allowing for the development of effective maintenance strategies and allocating resources efficiently to minimise risks and increase system reliability. Additionally, it is imperative to continuously review the risk register to ensure that any newly identified risks are recorded and addressed accordingly.

4 CABLE ARRANGEMENTS PROGRESSION

Through the early stakeholder engagements outlined in Section 3, the key insights from those discussions are as follows:

- The ability to have a full tunnel closure could facilitate higher production rates by reducing operational disruptions and improving worker efficiency
- The removal of existing assets may present significant complexity, potentially leading to longer shutdown periods
- The trapeze cable ladder design has been identified as the preferred option due to its superior efficiency in terms of installation time
- The cantilever cable ladder design offers ease of anchor drilling, and simple install resulting from anchor drill holes specified perpendicular to the tunnel wall

Two cable route options were developed during preliminary design: a fully in-tunnel route and a partial in-tunnel and EET route. For the in-tunnel option, all essential and non-essential cables are installed on one side above the traffic envelope on the Equipment Room East (ERE)/escape passages side of the tunnel. Following the SiD and ECI workshop outcomes, the EET route was excluded in the post-preliminary phase. The EET route emerged as the most economically viable option, given that cable and cable ladder installation can proceed at any time, thereby avoiding the scheduling constraints and additional costs associated with night-time tunnel closures. Despite its benefits, the EET option was limited by cable volume, restricted access to overhead areas, and additional space requirements, impacting installation efficiency.

Reflecting stakeholder considerations, the in-tunnel cable route has been developed as a trapeze-supported cable ladder extending through the tunnel and to each ERE, as illustrated below.

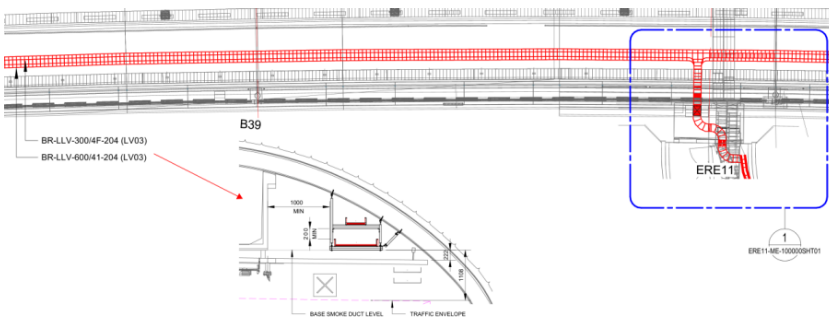

Figure 7. Final in-tunnel cable route design at a specific location for illustration.

Furthermore, at jet fan locations, there are two cable support arrangements designed to accommodate the existing tunnel geography. One of them comprises a wall mounted arrangement for essential cables and a cantilevered beam for non-essential cables (shown in Figure 8) and there is also wall mounted cable ladder arrangement for both essential and non-essential cables (shown in Figure 9).

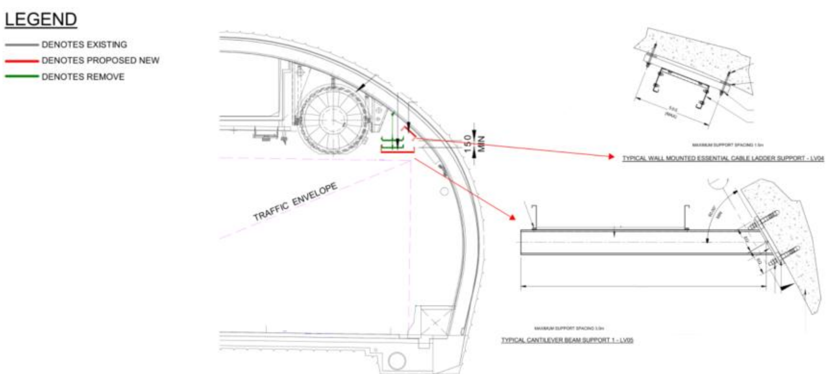

Figure 8. Cable route design near jet fans – Cantilevered & Wall mounted arrangement.

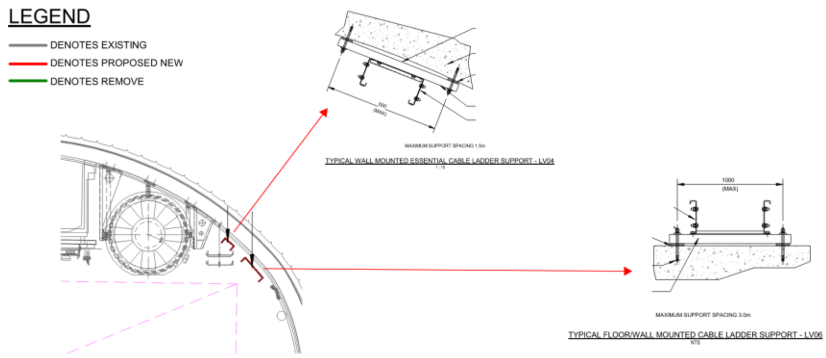

Figure 9. Cable route design near jet fans – Wall mounted arrangement.

5 CONCLUSION

The benefits of early stakeholder engagement are evident from the Burnley Tunnel LV Cable Refurbishment Project. The client recognises the process's efficiency, as it enables early identification and mitigation of risks before they escalate, which would otherwise have led to increased costs and project delays.

The engagement workshops enable the rapid iteration of ideas, ensuring that the constructability and maintainability of the cable system are shaped by the critical input and perspectives of all stakeholders, thereby embedding their concerns at the core of the design. The cables are now relocated from an area that is difficult to access to the top side of the tunnel, which can be easily accessed when needed without full tunnel closures. Additionally, there is no obstruction for future maintenance work, which is an improvement from the NJB option, where the cables are encased in hardened, stabilised sand. Moreover, through the workshops, the severity of the risks associated with the new cable arrangement is reduced, alongside the contractors' confirmation that the cable routes are simple to construct and install.

A comprehensive project plan is developed at the start of a project, incorporating a systematic risk identification and mitigation framework that is aligned and agreed upon with the client. The strategies are thoroughly reviewed and agreed upon with the client to ensure alignment with their expectations.

By leveraging workshops that prioritise and integrate stakeholder perspectives, the team achieves a deeper understanding of project requirements, resulting in more effective collaboration and improved design outcomes. Implementing the workshops demonstrates that a thorough engineering process has been adopted through the design phase and demonstrates a proactive approach to maintaining strong stakeholder relationships. Moreover, having the same designers with clear task delegation throughout the project is also an important factor in the project's success.

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