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Comparison of the effects of new and existing building developments on large tunnels

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ABSTRACT: Assessing the interactions with nearby buildings is a key consideration during tunnel lining design, more so with the increase of tunnelling in developed urban areas where tunnelled infrastructure is intended as a catalyst for growth and densification. The interactions between tunnels and building developments will be varied, not only because of the buildings themselves, but also because the effects depend on the relative timing of the building and tunnel construction, even where the building is the same.

This paper compares the interactions between large tunnels such as metro tunnels and existing and future building construction. It presents an analysis of a hypothetical tunnel to demonstrate potential differences in the effects on the tunnel design due to building loading or unloading. It also discusses consideration of clearances between the building and the tunnel, and the potential impacts on tunnel constructability.

1 INTRODUCTION

In high-density urban environments, tunnelling serves as a strategic catalyst for sustainable growth and controlled densification, optimising land use while minimising disruption at ground surface. As urban development continues to intensify, large tunnels, such as those used for metro systems and roadways, will be increasingly constructed near or beneath existing or future buildings. This proximity will bring interactions between tunnel structures and adjacent buildings, making it essential to evaluate how these interactions influence tunnel design and construction.

These interactions between tunnels and buildings vary, not only influenced by the structures themselves, but also by the relative sequencing of construction activities. Even with identical structural configurations, variations in construction sequences can lead to different impacts on tunnels.

Therefore, this paper compares the interactions between a hypothetical tunnel (with an internal diameter of 6.4 m which is typical of rail and metro projects) and both existing and future buildings as they relate to three major aspects: effects on the tunnel design due to building loading or unloading, effects due to clearances between the building and the tunnel, and the potential impacts on tunnel constructability. It highlights how different construction sequences between tunnels and buildings influence requirements for tunnel lining design, proposes mitigation measures to minimise risks and associated adverse effects, and notes the importance of the project team understanding these differences, at least in principle, for assessments of acceptability of adjacent developments.

As there is a large number of permutations of tunnel, ground, and adjacent developments, this paper aims to provide an indicative comparison of such impacts due to different construction sequences. By adopting this illustrative perspective, the study seeks to identify and summarise impacts and potential risks that can inform planning and mitigation strategies and design works in future projects.

2 PURPOSE AND METHODOLOGY

The primary objective of this comparison is to demonstrate how the relative construction sequence of buildings and tunnels influence tunnel lining performance. To this end, a set of typical development allowances has been adopted. Reference has been made to tunnel design requirements for Future Development Loads (FDL) in published documents for recent major tunnel projects such as Melbourne Metro Project (Bennett 2018), West Gate Tunnel, North East Link, and Suburban Rail Loop (Suburban Rail Loop Authority 2025). Based on a combination of project experience, technical guidelines, and engineering judgement, three interactions of developments with tunnels were considered to evaluate their potential effects on the design of a tunnel and its construction. These were:

- Application of additional loadings to simulate buildings above tunnels
- Application of unloading effects to simulate bulk excavation above tunnels and deep excavation adjacent to tunnels
- Consideration of the implications of the clearances between tunnels and a development, particularly deep foundations, such as piling works.

In each scenario, different construction sequences have been considered to assess tunnel lining performance. Scenarios where tunnels are constructed before or after buildings have been compared separately against a baseline scenario without any buildings. This approach helps to separate and clearly demonstrate the impact of construction sequence on tunnel behaviour. Effects due to loading or unloading on tunnel lining, effects due to the clearances between the building and the tunnel, and the potential impacts on tunnel constructability are discussed in Section 3, Section 4, and Section 5 respectively and illustrate the significance of the loading sequence used to assess the risk to tunnels and tunnelling from adjacent buildings.

3 EFFECTS OF LOADING/UNLOADING ON TUNNEL LINING

The effects of loading and unloading on a tunnel lining are influenced not only by the quantum of the building loads, but also by the timing of the construction sequences of the tunnel and buildings. The timing of construction can lead to different load distributions applied on the tunnel lining, affecting its structural performance. Details of the analyses and comparison of the results are provided in Section 3.1 and Section 3.2 respectively.

3.1 *Analysis of tunnel lining*

For the purposes of the modelling, the following parameters were adopted for the hypothetical tunnel lining:

- Tunnel internal diameter: 6.4 m
- Lining thickness: 300 mm
- Concrete stiffness: 34,800 MPa for short term and 17,400 MPa for long term
- Ground parameters: Unit weight 21 kN/m3; effective cohesion 2 kPa; friction angle 36^{o}; drained modulus 80 MPa; unload/reload modulus 240 MPa; Poisson's ratio 0.3 and at rest earth pressure coefficient 0.7.

As a starting point, the hypothetical tunnel lining without any development was modelled in Plaxis 2D as a baseline. The impacts on the tunnel lining in this scenario, for comparison with the building load cases, are indicated in Figure 2.

To illustrate the influence of construction sequence on tunnel performance, the following loading and unloading cases were modelled using Plaxis 2D as shown in Figure 1.

- A 50 kPa vertical loading, representing effects from building developments near the surface above the tunnel
- A vertical unloading condition, modelled as a 7 m depth bulk excavation above the tunnel with 7 m of ground remaining between the excavation and the tunnel
- An adjacent deep excavation down to tunnel level, modelled as a limited lateral release of 20 mm at 5 m horizontally from the tunnel

Each of the building load cases was activated either before or after the tunnel lining construction in the Plaxis model with a ground relaxation factor of 20% applied, and the resulting impacts on tunnel lining can be compared with those from a baseline case involving a tunnel without any developments. The results illustrate the trends under the various scenarios and show, in Figure 2 and Figure 3, that, in some cases, the MN results shift closer to the capacity boundary of the MN interaction diagram when external development is conducted after tunnel construction.

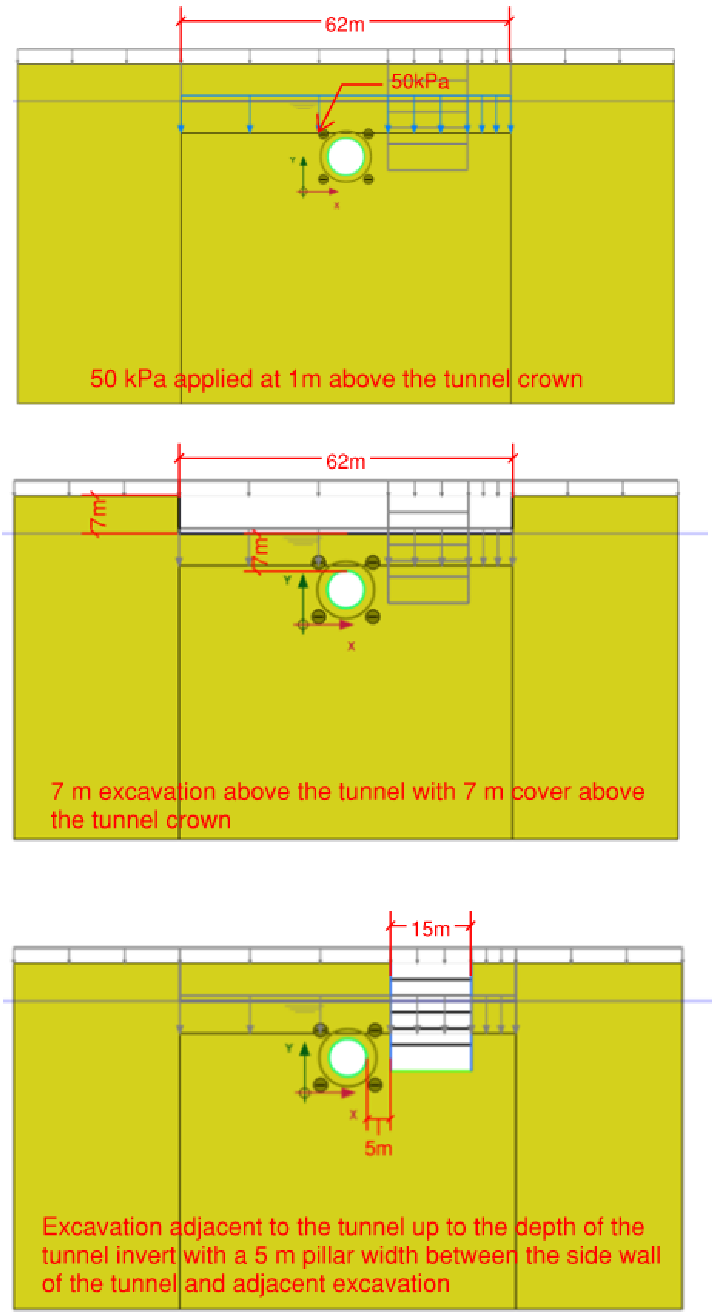

Figure 1. Plaxis model to simulate loading and unloading cases. For comparison purposes, soil parameters and material properties in each model are the same.

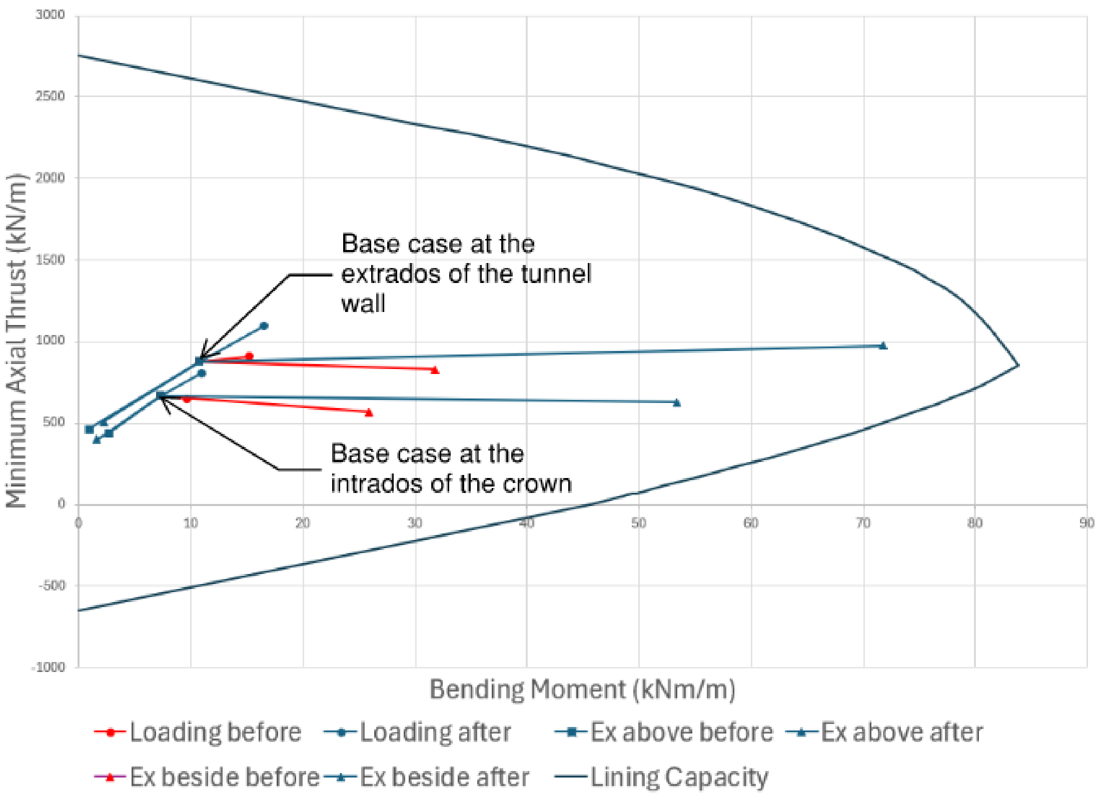

Figure 2. Comparison of the outputs of the Plaxis models.

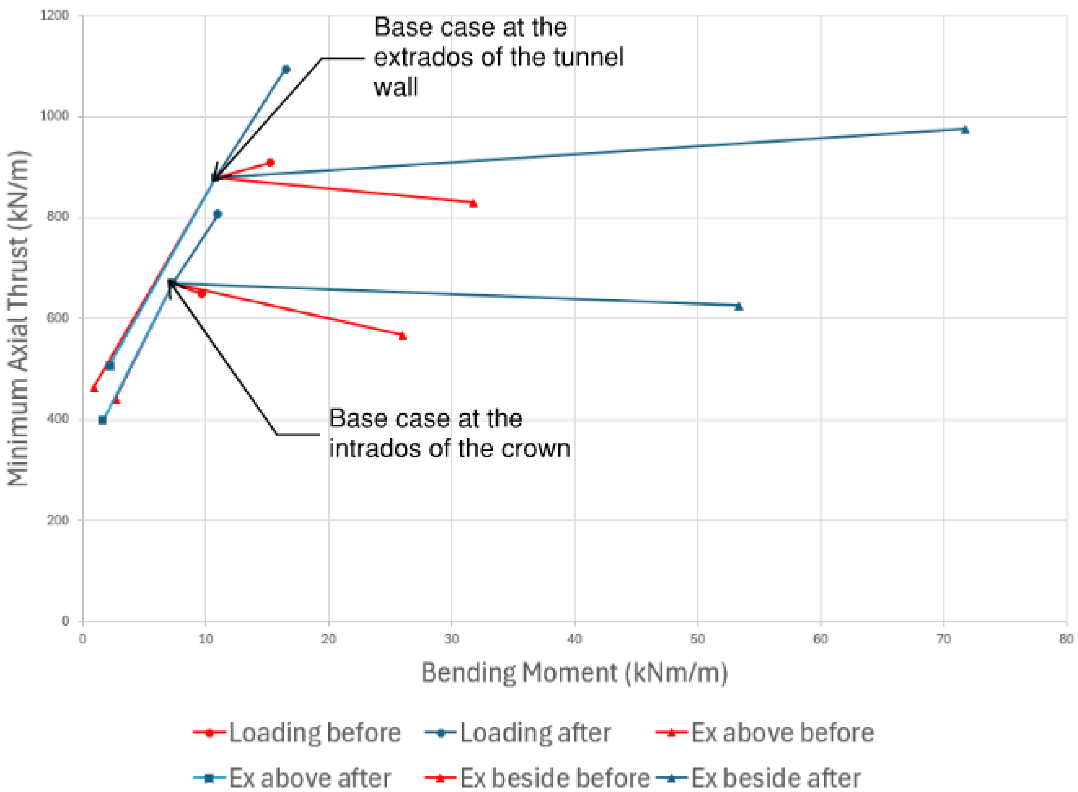

Figure 3. Detail of the outputs of the Plaxis models.

3.2 *Loading effects on tunnel lining*

The results plotted in Figure 2, indicate loading effects experienced by the tunnel lining with different construction timing in relation to a development for the following scenarios. For easy comparison, resulting stresses calculated on an uncracked section are shown in Table 1.

Table 1. Stress from Plaxis results calculated on a monolithic section.

	Minimum stress (difference from baseline)* (MPa)	Maximum stress (difference from baseline)* (MPa)	Comment
Base Case	1.7	3.7	
50 kPa before tunnel	1.5 (-0.2)	4.0 (+0.3)	Increased average stress across the lining section. Small difference on tensile side from responses to Ko and n effects. In-crease in peak compression.
50 kPa after tunnel	2.0 (+0.3)	4.7 (+1.0)	
7 m excavation before tunnel	1.3 (-0.4)	1.6 (-1.1)	Reduced average stress across section. Reduction in peak compressive stress
7 m excavation after tunnel	1.2 (-0.5)	1.7# (-1.1)	
Side excavation before tunnel	0.2 (-1.5)	1.8 (-1.9)	Tensile changes on tensile side and compressive changes on peak compresion due to moment increases.
Side excavation after tunnel	-1.5 (-3.2) -1.5# (-3.7)	4.9 (+1.2)	

*Calculated on a monolithic section.
#Peak value changed position and shown below

In the hypothetical case analysed, the positions of the critical stress cases remained in the same areas in most cases, with the most tensile cases at the intrados of the crown, and the most compressive stresses at the extrados of the tunnel wall. However, the two results marked with a hash tag show where the minimum or maximum stress changed position from the wall to the crown, or vice versa. However, in both cases, the stress values at the original positions were within 10% of the listed values.

– Loading scenario (50 kPa load applied above the tunnel)

Applying development loads after the tunnel has been constructed causes higher axial force and bending moments when compared with the same building loading in place before the tunnel was constructed. The structural configuration of the lining and the ratio of moments to axial forces would be used to determine whether this was critical for the design of the lining, but in any case, it would need to be assessed for the tunnel design in areas where this loading might arise.

– Unloading (7 m ground cover above tunnel)

When excavation is carried out above the tunnels, the modelling indicated only a relatively small difference in the tunnel axial forces and moments, but still requiring assessment during design as the changes bring the loadings slightly closer to the structural capacity of the tunnel lining. The modelling also indicated, as would be expected, that the ground heave associated with an excavation would affect the vertical alignment of an existing tunnel but would not be expected to affect a tunnel driven after the excavation in most circumstances. Reduced axial loading across joints in a segmental lining would also need to be checked for its effects on joint seals.

– Adjacent excavation (5 m distance to tunnel)

Compared with a deep development excavation before tunnelling, excavation after tunnelling clearly leads, in our example, to an obvious increase in bending moments for the tunnel design resulting from the lateral ground movement and stress release. In this case, this could be the critical design loading for design.

These results demonstrate that loading effects on tunnels are generally more larger when buildings are constructed after tunnels, which matches both the authors' experience over a number of projects and assessments, and experienced industry expectation. Therefore, considering that the timing of future developments can be uncertain, understanding the potential sequence of nearby developments and incorporating potential future development effects into the tunnel design are important factors both during the design of tunnels, and assessing the acceptability of proposed adjacent developments.

These findings are consistent with the anticipated interactions. When a building has been constructed, its loadings are already added to the stress field through which a tunnel is driven. Only a portion of the ground stress is applied to the tunnel lining. Conversely, when a tunnel lining is already in place, it experiences the full magnitude of the changes in the ground stress field. If the lining is stiffer than the surrounding ground, it can attract an even higher proportion of the general ground loading to itself.

4 EFFECTS OF CLEARANCE ON TUNNEL LINING

Effects of clearance on tunnels primarily concern the structural and geotechnical impacts arising from minimal distances between building foundations and tunnels. The clearance which may affect the tunnel design and construction include ground cover above a tunnel, the proximity of deep excavations, piles to tunnels, relative base levels of adjacent excavations, and pile toe levels surrounding tunnels. Whether the tunnel is constructed either before or after the surrounding buildings, the various consequences of these clearances must be considered in the tunnel design and construction and also the protection of tunnels after they are in place.

4.1 Clearance effects from existing building on future tunnels

When a building has been constructed before the tunnelling works, it might require management of ground movement effects during tunnel construction to protect the existing structures in their proximity. The ground movements caused by tunnelling not only include settlement and heave at ground surface but also vertical and lateral soil displacements on deep foundations or adjacent retention systems. These movements might have impacts on the existing building's stability and serviceability, such as potentially inducing differential settlement on the ground surface, increased bending moments in piles, or additional loading on retaining structures.

When deep piles are installed prior to tunnel construction, their presence may change the initial stress in the ground, thus, altering ground conditions that need to be considered in the tunnel boring process. Potential pile-induced ground stiffening or the transfer of concentrated stresses near the pile shafts also need to be accommodated in the tunnel lining design. These interactions can result in complex stress redistributions around the tunnel and may require enhanced lining sections or, in cases where practically feasible, modified alignment to avoid conflict with foundation clearance zones.

4.2 Clearance effects from future developments on existing tunnels

When the tunnel is already in place before a building is constructed, the future construction of deep foundations and excavation activities can pose potential risks to the tunnel. Close proximity might lead to not only stress concentrations but also mechanical interference on the lining. To avoid potential risks to the existing tunnel lining, building construction in the vicinity of an existing tunnel with minimal clearances needs to be reviewed from the following perspectives.

– "Out of Tolerance" intrusions into the ground

When a building is constructed close to an existing tunnel, there is a risk that excavation, ground retention, or foundation work may unintentionally extend into the protected zone around the tunnel. This can happen during piling, deep excavation, or even utilities installation. If these intrusions go beyond the limits of no-go buffer zones (i.e., "out of tolerance"), they may physically damage the tunnel lining. Also, loads transferred from piling works may alter the surrounding soil support conditions, increasing the tunnel's stress or displacement.

– Impact on redundant ground support systems of the tunnel

During mined tunnel construction, ground support systems (such as rock bolts, dowels or cables) might be installed as temporary works and could be redundant depending on the tunnel design and site condition. However, the proposed building works nearby, especially involving deep foundation installation, could potentially interfere with these support elements and cause damage to the tunnel lining itself or of the waterproofing system.

– Local disturbance of the ground around the tunnel lining

Even without direct physical contact, nearby construction can disturb the ground surrounding the tunnel. This can happen due to the interruption of ground arching actions, vibration from piling works, or changes in groundwater levels. Such disturbances may lead to ground settlement or heave, which can impose forces on the tunnel lining beyond those that were designed for. As time passes by, this can lead to cracking, joint displacement, leakage at seals, or misalignment of the tunnel.

– Local loading and unloading from piles

The presence of deep foundations, particularly large-diameter piles, can induce significant local loading changes on tunnel linings and these effects from future piles are generally larger than those from existing piles. When piles, especially larger diameter piles, are installed in close proximity to tunnels, the concentrated loads imposed on the surrounding ground, both by skin friction and end bearing, can lead to localised increases in pressures on the tunnel lining. These effects arise from the additional stresses transmitted through the ground to the tunnel structure during both installation and service stages of pile foundations. Conversely, excavation of these piles, particularly for large piles, can cause temporary unloading of the ground above or adjacent to the existing tunnel. This unloading may lead to stress redistribution, ground relaxation, and even movements of the tunnel lining. Risks for piling adjacent to a tunnel lining need to be identified and managed.

5 IMPACT ON TUNNEL CONSTRUCTABILITY

An existing building might influence the construction methodology of a new tunnel. To maintain the minimum required clearance between existing buildings and tunnels, very precise tunnel direction control is essential.

In addition, strict vibration and settlement limits on the building development may require adjustments in tunnelling methods, such as altering advance rates and face pressures.

This constraint might also limit the availability of suitable construction sites and access routes for tunnel works if the development is in the vicinity of a tunnel launch site or its main access routes. Limited surface access due to known and approved developments may constrain construction programs, spoil removal routes, or site setups.

Moreover, the need to protect the tunnel against known future ground disturbance may lead to the early implementation of enhanced waterproofing systems, more conservative ground support systems and ground improvement works during tunnel construction. Early and continuing coordination among all interested parties is essential to anticipate and resolve these construction challenges.

Further complexities arise when tunnelling and building construction occurs concurrently. Close coordination becomes critical to mitigate risks where surface and underground space works influence each other, to prevent construction delays, and to ensure overall safety. Tunnel construction must be carefully planned and executed to account for nearby building works and avoid adverse effects from simultaneous excavation or piling. For instance, deep excavation adjacent to a tunnel might cause unexpected ground movements that destabilise partially completed linings, while vibrations from piling could affect tunnel works. Additionally, real-time monitoring systems and adaptable construction planning may be needed to ensure that both tunnel and building works proceed smoothly without any disruption. It should also be recognised that concurrent works would make understanding the sources of observed measurements more difficult.

6 MITIGATION MEASURES

While existing or future buildings near tunnels present challenges, potential adverse effects on tunnels can be effectively mitigated by integrating appropriate design and construction measures, and also maintaining close collaboration among all interested parties throughout planning, design and construction stages. Some practical measures have already been briefly discussed in other sections, and more measures applied on tunnels and buildings can be implemented collectively to ensure the safe coexistence of buildings and tunnels.

6.1 Measures applied on buildings

If the magnitude of loading/unloading and the limits of ground movement are of concern, they can be mitigated by optimising foundation design, adjusting construction stages, or using light-weight structures directly above the tunnel. These are some examples of measures that could be considered during a building's design and construction stages.

- One of the key contributors to tunnel deformation is the unloading of ground leading to reduced pressure on a tunnel lining during basement excavations. To mitigate this, if an issue, excavation works can be staged to control the magnitude of unloading. Temporary support systems such as struts or ground anchors can also help to maintain stability and minimise ground movement near the tunnel alignment.
- Where developments are proposed directly above tunnels and additional loading on the tunnel lining is an issue, structural bridging systems can be incorporated into the building design. These systems transfer loads across the tunnel clearance zone without applying unacceptable additional stresses onto the tunnel itself. Common solutions include transfer beams, deep slabs, or portal frames designed to span over the tunnel.
- For deeper foundations, building loads can be transferred to below the tunnel stratum using sleeved piles, which are designed to prevent load transferring into the ground until the pile sockets into deeper, more competent ground. This approach helps avoid stress concentrations or ground movements around the tunnel, particularly in soft soils, thereby reducing potential impacts on the tunnel structure.
- The clearance between buildings and tunnels could also be controlled by relocating pile positions, using shallow foundations, or adjusting excavation depths at the early design stage. If proposed clearances are less than the allowances included in the design, it must be demonstrated that the risk to the tunnel can be maintained at acceptable levels with proper engineering control and design refinement.

6.2 Measures applied on tunnels

Tunnel design and alignment should proactively accommodate the loadings and locations of existing and known and approved future developments or could be adjusted as necessary to avoid potential detrimental effects and conflicts with building foundations.

- To accommodate additional loading beyond the initial design requirements, design changes could be proposed for tunnel lining such as thicker linings, higher-strength materials, or reinforced segments in zones with additional loadings. While these changes increase initial costs, they significantly reduce constraints on future developments and lower the potential risk on the tunnel structure.
- To mitigate adverse effects on buildings and tunnels, the ground movement impact could be controlled through refined tunnel construction methods (e.g., earth pressure balance (EPB) or slurry TBMs), controlling face pressure and advance rates, or implementing ground improvement techniques such as jet grouting or freezing to stabilize ground conditions.
- Additionally, continuous monitoring of ground and tunnel conditions during construction is essential. Instrumentation systems (e.g., strain gauges, settlement markers, piezometers) could provide real-time feedback, allowing for rapid intervention if site conditions exceed predetermined thresholds.

For future unknown developments, current tunnelling projects in Victoria incorporate additional design loading allowances to provide some capacity for future works in the vicinity of the tunnels. While not accommodating all possible developments, these allowances allow some flexibility for feasible and safe construction of future works.

Besides the mitigation measures discussed above, allowances of clearances and loadings from both existing and future buildings should be clearly identified in the tunnel design requirements. Moreover, clear allocation of responsibilities between stakeholders, such as who is involved in determining acceptability of a development, and detailed risk assessments also plays a key role to mitigate potential risks on tunnels. A successful application of these measures relies on early planning, thoughtful design, good communication and efficient coordination at both design and construction stages.

7 SPECIAL CONSIDERATIONS ARISING FROM AUTHORS' EXPERIENCE

The period between the commitment to tunnelling and the construction of the tunnels' permanent lining is a phase in the timing of the interactions that requires careful consideration. This is because both the designers and the assessors of developments need to understand that there are a number of possible sequences which could change both the types and magnitudes of the interaction effects.

It has been typical practice that when a proposed development has been approved by the appropriate authorities, it is treated by the tunnel project as a given loading, with the allowance for future development loadings (FDL) also applied as an additional loading. Given the lead time for tunnelling between commitment and construction, the expectation is that the approved development will be in place by the time that tunnels are driven past. However, this is not a certainty, and the possibility that the development's changes could occur after tunnelling should be a design case.

A similar situation arises during the early periods of a tunnelling project when new developments are proposed after the commitment is made for a tunnel project. In these cases, the effects of a development must be accommodated within the FDL allowances to avoid varying the projects specified loading requirements. It would normally be expected that the critical load cases for the tunnel would be when the development occurs after tunnelling. However, recognising the different time scales usually involved, the implications of all relative timings should be considered. It is also vital that the details of any developments approved during this phase are provided to the project's construction team.

The reviews and assessments of proposed developments for recent tunnel projects are conducted within the framework of applications for planning permits, where the application is referred to the project authority in response to a planning overlay. As the overlays are established for the protection of the tunnels over their lifespan, the referral triggers are related to the more critical cases, usually the tunnels being in place. The assessment of a proposed development is usually conducted by a multidisciplinary team that integrates the planning framework with geotechnical, structural, and construction expertise. Within this setting, it is critical for tunnelling engineers to be able to clearly articulate design assumptions, potential risks, and their implications to other disciplines and stakeholders. Effective communication and collaboration across the project team are essential to ensure alignment on design methodologies and to support informed decision-making throughout both the design, construction, and assessment phases.

8 CONCLUSION

The different effects on tunnels from existing and future buildings have been compared from loading, clearance and construction aspects and summarised below.

- Loading: Tunnels are generally more sensitive to loading/unloading effects from future developments compared with those due to existing buildings. When buildings are constructed before tunnels, the tunnel design should comprise the ground conditions and loadings altered by the existing building foundations. When buildings are constructed after tunnels, significant loading/unloading effects due to future excavations and deep foundations need to be considered in the tunnel design. Local stress redistributions and disturbance of existing ground condition also need to be incorporated in the tunnel design.
- Clearances: When buildings precede tunnel construction, management of ground movement effects caused by a nearby tunnel construction is required to protect existing buildings. Depending on the clearance between foundations and tunnels, additional loading and changed ground conditions induced by existing buildings may need to be considered in the tunnel design. In contrast, when tunnels are in place first, subsequent building works, especially deep excavation and piling, will pose potential threats to tunnel integrity due to stress concentration,

interference with ground support systems, or disturbance to surrounding ground. Effective clearance management and construction tolerances are vital to ensure safety of tunnels.

- Constructability: Existing buildings may constrain available surface access and underground space for tunnel construction, demand strict control of tunnel alignments, or require adjustments in tunnelling methods to manage vibration and settlement limits. Future developments, even when considered in tunnel design, may still bring uncertainties because of unknown foundation details and construction activities. When tunnels and buildings are constructed concurrently, careful coordination of excavation, foundation, and tunnelling activities must be carried out to avoid potential disruptive interference between the two projects. Real-time monitoring, flexible construction planning, and early engagement with stakeholders are also critical so that these constructability challenges could be managed effectively.

By integrating the mitigation measures discussed in Section 6 and maintaining close collaboration among all interested parties, the safe coexistence of tunnels and buildings can be achieved and provide strong support for sustainable developments of urban areas and transportation systems.

9 REFERENCES

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