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The Blue Mountains Route Clearance Project – tunnel lining modifications for the Ten Tunnels Deviation

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ABSTRACT: Transport for New South Wales (TfNSW) has introduced a New Intercity Fleet (NIF) to enhance passenger comfort and accessibility, replacing aging rolling stock on the Blue Mountains and Main West railway lines. The NIF's larger kinematic envelope (KE) resulted in tunnel lining infringements at the heritage listed Ten Tunnels Deviation near Lithgow, NSW, built in 1910. To achieve the required NIF clearances, TfNSW initiated the Blue Mountains Route Clearance (BMRC) project. Within the Ten Tunnels Deviation, the scope of work involved modifications to the existing linings in eight of the ten tunnels.

This paper outlines the challenges, key learnings, and methods adopted to trim the tunnel lining within the Ten Tunnels Deviation. It presents investigations into existing lining thicknesses and the development of proposed treatment types. Key findings emphasise the importance of capturing accurate historical information and developing strategies to supplement missing data while embedding a risk-based approach to design and construction.

The knowledge gained is shared with the broader industry to benefit those rehabilitating historical tunnels in the future.

1 INTRODUCTION

The heritage listed Ten Tunnels Deviation had previously been modified in 1978 to accommodate new rolling stock. These modifications included replacing the ballasted track with a concrete track slab, lowering the track within the tunnels, and cutting chases into the tunnel walls to achieve the necessary clearances.

The ten tunnels are horseshoe-shaped and brick-lined in the crown and haunches, with the brick arch typically resting on a concrete wall below the spring line. Near the tunnel portals, the brickwork arch thickens and extends to the toe of the wall. At the portal, the brick arch is confined by brick buttresses. Tunnel 9 is unique as it is entirely brick-lined but the reasons for this are not known. The tunnels were excavated using drill and blast techniques, primarily into Banks Wall Sandstone. The lining's brick crown arch and concrete walls were constructed with timber formwork. The excavation method at the time locally resulted in significant overbreak, which was either bricked out or backfilled with tunnel spoil.

Modifying a 110-year-old heritage-listed tunnel presents significant design and construction challenges. Numerous uncertainties and constraints needed to be carefully evaluated to assess critical risks and develop safe lining treatments that allow a further reduction of the existing tunnel lining thickness. The old lining could not be expected to meet current standards because these standards did not exist at the time of construction, and its condition therefore had to be thoroughly examined. During an initial condition survey, it was found that the lime mortar had suffered substantial leaching and softening in isolated locations exposed to prolonged seepage inflow.

1.1 *The project*

The BMRC project was initiated by TfNSW to accommodate the modernised NIF along the Main Western Line through the Blue Mountains. In February 2019, construction started between Springwood and Lithgow. The Rail Corridor Modifications were to enable NIF train services all the way to Lithgow. The BMRC scope of works included providing adequate clearance for the NIF within the existing Ten Tunnels Deviation.

The BMRC project was delivered collaboratively by the Continuum Alliance which was formed between TfNSW and a joint venture between CPB and Lendlease Engineering (now Acciona). Aurecon was appointed by the Continuum Alliance to undertake the detailed design for the BMRC project. The works were undertaken in a series of allocated track possessions commencing in February 2019 through to May 2020. Site activities during track possessions ran to tight schedules and had to accommodate parallel maintenance activities scheduled by Sydney Trains within the same possessions. In addition, limited passenger and freight rail movements had to be maintained during possession windows. The Ten Tunnels Deviation is a heritage-listed 9.2 km section of the Main Western Railway Line between Newnes Junction and Zig Zag stations near the township of Clarence, New South Wales. Figure 1 shows a location map of the ten tunnels on the Main West Line in the Blue Mountains.

Figure 1. Ten Tunnel Deviation location map.


Figure 2. Tunnel 5: Country portal.

1.2 *History*

The Ten Tunnels Deviation, also known as the Zig Zag Tunnels, were commissioned to provide an alternative twin track route to the historic single track Zig Zag Railway. According to Heritage NSW (2023) the Ten Tunnels Deviation reduced journey times to Lithgow by 20 to 30 minutes. Construction of the Ten Tunnels Deviation commenced in 1908 and was completed by 1910. Fortunately, historical photographs (Figs. 3-6) were available to the project team, highlighting the tunnelling methods and technology of the time.

Tunnel excavation was undertaken using drill and blast methods. This involved the excavation of a short pilot heading followed by a heading enlargement and finally benching (Fig. 5). The photographs indicate that no temporary support was installed during these excavations. As the tunnel advanced, the rough drill and blast profiles in the heading and bench were manually scaled and smoothened to achieve the required horseshoe profile (Fig. 6). Overbreak above the springline was backfilled with tunnel spoil or bricked out during construction of the tunnel lining (Fig. 2). The treatment of overbreak was an important consideration when developing design loadings for the tunnels.

The horseshoe shaped tunnels were lined with concrete to the springline and masonry to the crown. The invert floor in each tunnel remained unlined. Each portal face was fully bricked and included an inclined buttress on both sides of the portal face (Fig. 3). The thickened brick arch lining extends approximately 7 m from the portal into the tunnel and this area was termed the "portal zone" (Fig. 4). Beyond the "portal zone" a mass concrete sidewall was placed with timber forms up to springline level (Fig. 4). Once the walls were cast, clay bricks were laid in the crown arch whilst temporarily supported by timber form and falsework. The bricks were laid in running bond and were set in lime mortar (Fig. 4). This arrangement applied to all tunnels except for Tunnel No. 9, which was entirely brick lined.

Figure 3. Tunnel 9: Construction of brick buttress at tunnel portal.

Figure 4. Tunnel 5: Brick arch lining and concrete to brick wall interface near the portal.

Figure 5. Pilot, heading and bench excavations. Note rough tunnel profile with large over-break. Source: Lithgow History Avenue c. 2010.

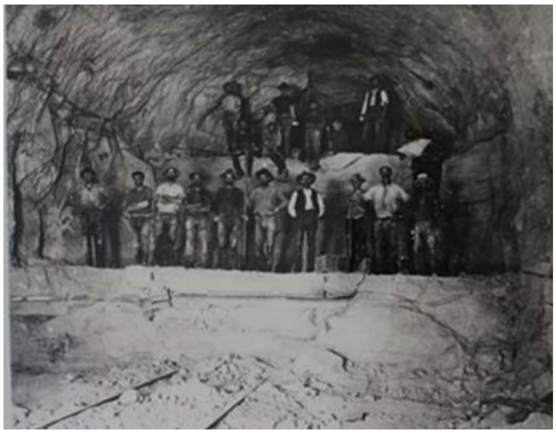

Figure 6. Heading and bench excavations. Note manual scaling of heading excavation profile.

2 THE CHALLENGE

The project objective was to provide sufficient clearance within the ten tunnels to accommodate NIF Rolling Stock (Fig. 7). To achieve this, the infringement zones for a sub-medium KE +100 mm structure clearance needed to be identified. Geometric checks confirmed two principal infringement locations within the tunnel cross section one in the tunnel haunch and at the other at the toe of the tunnel lining as depicted in Figure 8.

Figure 7. New Intercity Fleet (NIF) Rolling Stock.

Figure 8. Infringement zones for sub-medium KE +100 mm.

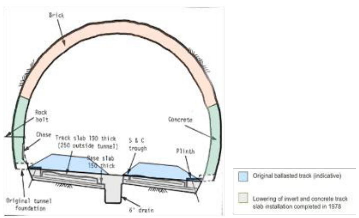

Figure 9. Typical cross section showing replacement of ballasted track in tunnels (Duncan 1980).

The initial challenge for the project team was to establish where the NIF infringements occurred within the tunnels, what trimming depths were required to remove the infringements and what remedial measures were necessary to ensure the integrity and stability of the tunnel lining. This initial investigation was further complicated because the lining was previously modified in 1978 to provide clearances for the significantly taller V-set rolling stock. This resulted in a suite of modifications including a reduced lining thickness of approximately 30% of the original lining thickness as reported by Duncan (1980).

The design objective was to develop a selection of lining treatment types for implementation during construction, whilst navigating various interrelated uncertainties such as the condition and the already locally reduced lining thickness of the existing tunnels.

3 PREVIOUS MODIFICATIONS

In the 1970s the V-set rolling stock was introduced across the Sydney Trains network. To accommodate the larger KE and increased loading, the ballasted track in all tunnels was replaced with a concrete track slab in 1978. The track slab was to also remediate drainage issues resulting in ballast fouling and formation degradation (Lord 1988). The work required major modifications to the existing tunnels including:

- Lowering of track and invert by approximately 650 mm and 400 mm respectively.
- Constructing concrete plinths with shear dowels to support the tunnel sidewall foundations.
- Cutting lining chases with a maximum design target depth of 150 mm resulting in a thickness reduction from approximately 450 mm to 300 mm (Duncan 1980).
- Installing rock bolts to horizontally confine the tunnel wall at the proposed chases.

A typical cross section of previous modifications are shown in Figure 9.

4 DESIGN APPROACH

To address the challenges and project objectives, the design team set out to investigate and identify potential remedial measures for the existing tunnel lining. A series of questions arose and had to be answered including:

- Where are the NIF infringements and what are the magnitudes?
- What is the existing lining thickness at the infringement locations?
- What is an acceptable minimum lining thickness after trimming?
- Where is underpinning of the existing lining required?
- What are suitable lining treatment types?

4.1 *NIF infringements*

The NIF infringements were located using the Amberg rail trolley (Fig. 10) which is a highly accurate laser scanning device guided by a total station. A digital version of the required KE was used by the Amberg trolley to identify and measure the NIF infringements. The infringements were recorded and could also be viewed in real time which was particularly useful during construction.

Drawings showing “heatmaps” were developed from laser scan surveys available for all ten tunnels. These drawings displayed colour contours representing the extent and depth of infringements projected onto tunnel sidewall elevations. The heatmap shown in Figure 11 presents a rather irregular infringement surface. This is attributed to the rough surface conditions resulting from the 1970s cutting campaign using jack hammers.

Infringement cross sections (Fig. 12) were developed at one metre intervals. Figure 12 shows the lining thickness reduction at the toe originating from the previous modifications referred to in §3.

Figure 10. Amberg survey trolley.

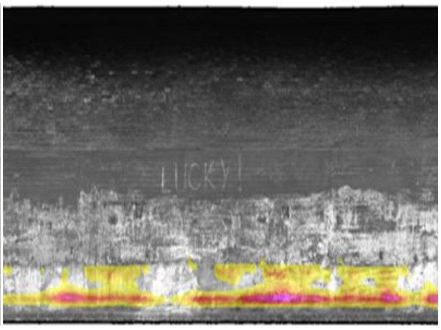

Figure 11. Infringement heat map on wall elevation.

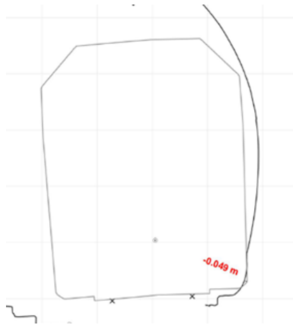

Figure 12. Example of survey infringement in cross section.

4.2 *Existing tunnel lining thickness*

Before any significant modifications could be considered, it was necessary to investigate the extent of previous lining trimming discussed in §3. Due to the lack of available construction records for the BMRC project, it was unclear how much cutting had occurred and whether the intended 300 mm residual wall thickness was consistently maintained. Therefore, early investigations for this project focused on establishing the existing wall lining thickness at the existing cut chases. Details of these investigations are set out in the following sections.

4.2.1 *Ground Penetrating Radar (GPR)*

GPR was employed by the project team to estimate the lining thickness of the tunnel concrete walls. The wall needed to be scanned approximately 1.5 m to 1.8 m above the rail to avoid adverse signal reflections from previously roughened chases. However, the point of interest for the minimum thickness was much closer to the plinth (Figs. 11-12). Consequently, the GPR data only provided an indication of the original wall thickness above the existing cut chases and further supplementary measurements were needed to obtain the minimum existing wall depths near the toe of the wall.

4.2.2 *Lining depth measurements in weep holes*

Weep holes 20 mm in diameter were drilled through the tunnel walls into rock at approximately 5 m intervals where infringements near the toe were identified. The weep holes were installed to provide drainage relief but were also utilised for endoscope measurements. The measurements involved the insertion of a small camera into a PE tube fitted with a measurement scale. The endoscope camera and tube were inserted into the weep hole until the lining extrados was observed and the corresponding depth recorded (Fig. 14). Finally, the weep holes were surveyed for inclusion in the laser scan model.

Coring through concrete and brick of the existing lining was also performed to supplement depth measurements in areas where endoscope assessments did not yield conclusive results - e.g. where vision was obstructed by murky seepage flows.

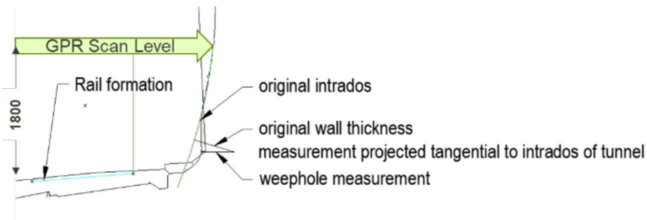

Figure 13. Measurement correlations.

Figure 14. Measurements taking place in Tunnel No. 6.

The weep hole survey and depth measurements were transferred into corresponding tunnel cross sections cut through the respective weep hole locations to infer the original tunnel wall thickness. The original tunnel lining thickness was obtained by projecting a line perpendicular to the tangent of the extended original intrados arch through the distal end of the weep hole. The original wall thickness was then derived as the distance between the tangent point and the distal end of the weep hole as shown in Figure 13. This principle enabled the determination of the original wall thickness at 5 m intervals along each of the tunnel where toe treatments were prescribed.

Because the magnitude of the infringements was also known at the weep holes, the existing residual lining thickness, $t_{residual}$, was determined with reasonable accuracy at 5 m intervals along the tunnel.

4.3 *Acceptable lining thickness*

The lining treatments needed to consider the residual capacity of the tunnel lining after trimming. The design basis needed to consider durability allowances, design fire resistance and the interaction with new rock bolts. Material properties needed to be interpreted for the existing brick/concrete, and design loads for the arch structure had to be established for design analysis.

A critical element for the design was to determine the amount of trimming that could take place before underpinning would become necessary. The target limit, t_{min}, was established based on bedded beam and 2D finite element models superimposed with multiple load cases for service and ultimate limit states.

Apart from the thickness distribution, the other major uncertainty was the existing loading condition of the tunnels. Apart from the lining self-weight and the design fire resistance, all other load cases had to be assumed based on engineering judgement. Consequently, the true loading condition in these tunnels is unknown and can range from self-weight only to self-weight with backfill, potential seepage pressure and rock wedge loading. The design loads considered in various load case combinations included self-weight, service loads, ground loads (rock wedge loads), loads from backfilling of excessive overbreak and groundwater loads. Adopting the established potential loading conditions and considering fire resistance together with the necessary durability allowances the minimum acceptable lining thicknesses, t_{min}, in concrete and brick was determined. Thus, distributions of trimming and underpinning could be identified based on the magnitude of infringements and existing lining thickness.

5 LINING TREATMENT TYPES AND DISTRIBUTIONS

5.1 *Treatment distributions*

The treatment type distributions were based on the magnitude of infringements, existing wall thickness and the minimum structural lining design thickness. Construction tolerances to be achieved within each treatment type also needed to be considered. Figure 15 shows an example of the residual and minimum lining thickness data to highlight where underpinning would be required.

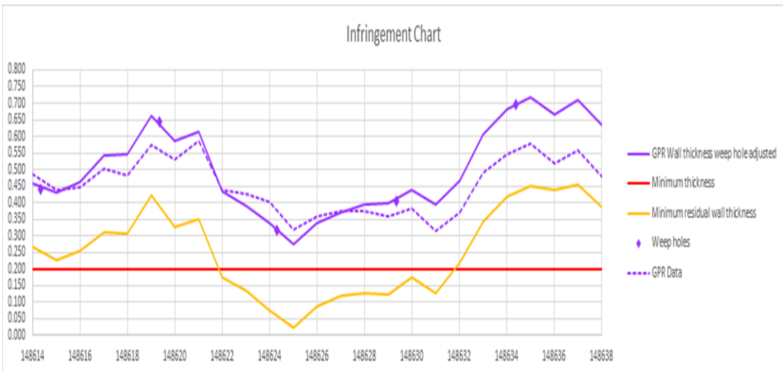

Figure 15. Infringement chart. Residual thickness distribution (yellow). Minimum required (red).

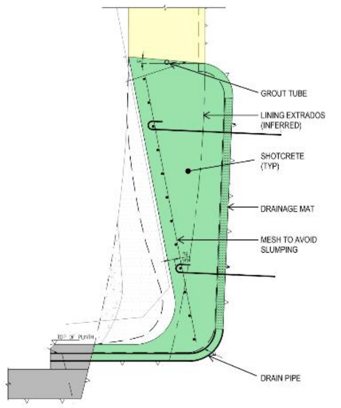

Figure 16. Underpinning typical cross section.

5.2 Treatment types

Three treatment types were designed for the BMRC project: manual trimming, mechanical trimming and underpinning. Table 2-3 summarise the key features of each treatment type in concrete and brick.

Table 2. Differences between the nominated treatment types in concrete.

Manual Trimming	Mechanical Trimming	Underpinning
		
Trimming with handheld tools/equipment for localised KE infringements up to 50 mm depth only.	Applies where $t_{residual} > t_{min.c}$ Trimming using wall shaver or rotary milling head attached to an excavator. Image shown after wall shaving.	Applies where $t_{residual} \leq t_{min.c}$ Excavation through the brick or concrete wall into rock to achieve a minimum panel thickness required for structural plinth support

Table 3. Differences between the nominated treatment types in brick.

Manual Trimming	Mechanical Trimming	Underpinning
		
Trimming with handheld tools/equipment for localised KE infringements up to 50mm only.	Where $t_{residual} > t_{min.b}$ Wall shaver or rotary milling head. Mortar repointing as required. 50 mm thick shotcrete panel.	Where $t_{residual} \leq t_{min.b}$ Hit and miss sequence. Use of temporary steel frame installed with hand tools.

Important aspects of the underpinning treatment design (Fig. 12) were to achieve the minimum section depth at the pinch point and to ensure full contact with the existing lining at the top of the panel. In addition, the toe needed to abut the existing plinth to a minimum depth of 100 mm and the rock at the back of the excavation needed to be removed to allow for a minimum lining thickness. To achieve full contact at the sprayed concrete brick/concrete interface, grout tubes were attached to the underside of the existing cut lining to enable contact grouting after concrete placement.

6 CONSTRUCTION

6.1 *Underpinning at tunnel portals*

The tunnel portals presented a unique challenge. Underpinning works at the portals was a delicate operation due to poor mortar condition, gaps at the interface between the brick lining extrados and rock, presence of loose backfill material behind the lining and the lack of longitudinal confinement at the portal face. To mitigate these risks, special construction sequences were developed for tunnel portal zones utilising temporary steel lintel beams and frames.

Figure 17. Tunnel No. 8 temporary steel frame installation prior to stage 1 excavation.

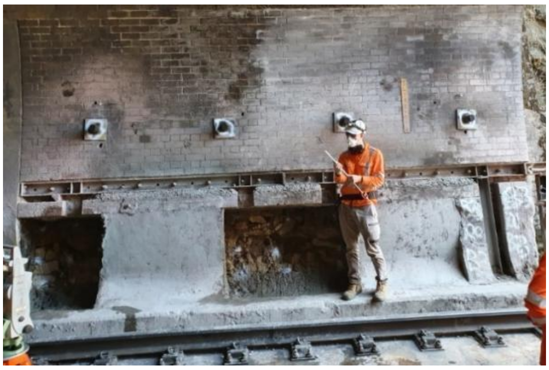

Figure 18. Tunnel No. 8 portal underpinning after stage 2 excavation and prior to shotcreting.

The purpose of the steel frames was to temporarily confine the brick lining around the excavated panels and to maintain the integrity of the portal zone during construction. The lintels were anchored into the brick lining directly above the vertical legs. Figures 17-18 both show an image taken during stages 1 & 2 of the portal underpinning sequence. In addition, permanent rock bolts were installed above the nominated underpinning zones to stabilise the tunnel wall horizontally.

6.2 *Trimming the haunch*

Trimming the haunch (Figs. 19-20) carried greater risk and required additional controls from a safety perspective due to two main reasons. The infringement locations at the haunch are in structurally unfavourable positions and can only be reached by the workforce utilising a high rail elevated work platform and any work had to be undertaken close to the OHW system which was to be protected. Shotcreting whilst possible was not desirable in this location because it would lead to additional excavation depth at the haunch to accommodate the shotcrete thickness and the associated overspray allowance. Instead, stainless steel angles were anchored to the lining in a 'hit' and 'miss' sequence prior to the removal of a single brick course. Grouting any interface gap between the lining extrados and rock was also to take place prior to brick removal (Fig. 20).

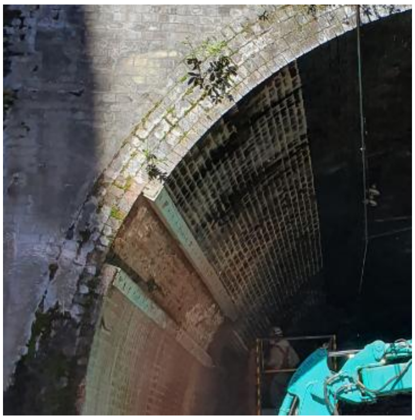

Figure 19. Completed haunch treatment between re-pointed mortar.

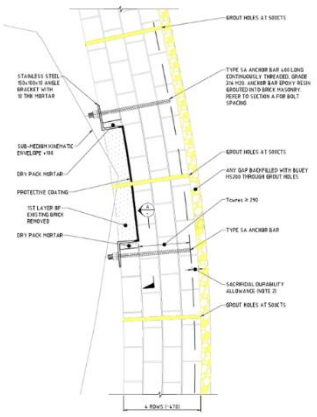

Figure 20. Haunch treatment cross section.

6.3 *Excavations in brick and concrete*

For many of the treatments involving trimming and underpinning in the walls the Continuum Alliance used a thirteen-tonne high rail excavator with a rotary milling head attachment with water spray to control dust (Fig. 21). Also in use was a trimming attachment comprising of stacked diamond discs which formed a trimming drum leaving a much smoother finish (Fig. 22).

Both methods used a machine guidance system to control trimming depths and tolerances. Controlling the profile was specifically important for trimming treatments as the design specified a minimum residual wall thickness for structural adequacy. As such, any trimming beyond the agreed construction tolerance could potentially result in the treatment type change from trimming to underpinning. Tolerances were controlled with survey set out and machine guidance.

The rotary milling head demonstrated significantly higher productivity in terms of square meters per hour compared to diamond-edged discs. It could also be positioned much closer to the toe during trimming. However, its precision was inferior due to the large cutting teeth, which often dislodged river stone aggregate from the original concrete wall. This resulted in a rougher surface profile increasing the risk of rework due to residual infringements. Notwithstanding this, the finish was no worse than the finish achieved during prior modifications.

For underpinning treatments in concrete, the rotary milling head attachment (Fig. 21) was used. Machine guidance wasn't as critical in underpinning areas as the work area was isolated and offsets to the desired depth could be set out and monitored by the operator.

Figure 21. Rotary milling head attachment. Note size of cutting teeth and roughened wall profile.

Figure 22. Wall trimming with a diamond disc drum (light grey). Note smooth but undulating surface.

Another important element for the underpinning excavation was a 100 mm deep key to be cut behind the existing concrete plinth. The diameter of the rotary milling head could not achieve type of cut. Instead, the toe was sawn near vertically at the concrete plinth and subsequently hammered out. Underpinning in brick was also undertaken with the rotary milling head, however, to minimise vibration impacts at the portals, only handheld tools were used in these areas.

6.4 *Control of water ingress*

In Tunnels 1 and 10 significant seepage water ingress had to be managed, which posed a risk for underpinning and concreting works. Where water ponding occurred at the base of the panel (Fig. 23), a drainage relief slot was cut into the existing concrete plinth to drain the water (Fig. 24). Drainpipes connected to a drainage mat at the back of the excavation ran through this slot to permit permanent seepage water discharge into the tunnel drainage system. This was particularly important in areas of running groundwater inflow to ensure that the shotcrete was not placed against running or into ponding water, which would have likely resulted in defective concrete. The slot was finally backfilled and trowelled off during concreting of the main panels.

Figure 23. Water ponding after underpinning excavation.

Figure 24. Drainage mat and drainpipe through slot in plinth.

6.5 *Concrete placement*

Concrete placement in underpinning areas faced challenges. Both sprayed and cast in situ methods were initially trialled. The first shotcrete trial panel slumped this was caused by passing freight train movements only a couple of hours after completion. To prevent this, shotcrete panels were completed away from active rails, a steel mesh was added to stabilise the face at an early age, and the shotcrete panel curing times were increased before train operations resumed on the line.

Cast in-situ panels were also trialled but were less efficient due to the need for formwork preparation and removal. Additionally, daily survey checks were required to ensure minimum clearance between the formwork and operational rolling stock has been achieved, as the formwork protruded from the existing wall lining into the tunnel.

7 CONCLUSION

The BMRC project achieved the required NIF KE clearance in the Zig Zag tunnels, overcoming various design and construction challenges. These included identifying the location, extent, and depth of existing infringements, considering different construction methods and tolerances, assessing the condition of the existing lining, and determining its thickness. Through non-intrusive and intrusive investigations, the necessary treatment types for the infringement zones were defined. These treatments were based on the original wall thicknesses, minimum structural requirements, durability allowances and the consideration of the relevant construction tolerances.

Concrete and brick underpinning was done in a 'hit and miss' sequence to maintain tunnel stability during construction. Tailored construction sequences and temporary works ensured the integrity of brick tunnel portals and buttresses during construction.

The authors hope this paper adds valuable information to the as-built records of the Ten Tunnel Deviation. The methodologies and experiences from the BMRC project offer useful strategies for similar future projects. Publishing technical papers after modifications to historical tunnels is a long-standing tradition, providing valuable insights for future engineers involved in maintenance or rehabilitation works of the Ten Tunnels Deviation.

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