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Management of mainline railway infrastructure during longwall mining beneath the Main Southern Railway

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ABSTRACT

Civil engineering and mine development involve activities that result in significant change to the local ground conditions and geomorphology as a consequence of both underground and surface activities. Management of these, which included a risk-based approach, is the subject of this paper. Surface subsidence produced by longwall mining beneath mainline railways produces numerous technical challenges for the engineering profession, covering *inter alia* mine subsidence prediction, world-leading civil engineering management of the track, electronic remote monitoring of the rail, and management of rail infrastructure – all in the context of maintaining operational rail safety combined with efficient resource recovery.

Near Tahmoor, NSW, subsidence of the Main Southern Railway of up to 1.2m occurs during longwall mining. This paper describes geotechnical and structural monitoring implemented to successfully manage the safety of operational mainline railway infrastructure during the underground mining.

Keywords: mine subsidence, coal, longwall mining, railway infrastructure, management

1. INTRODUCTION

Tahmoor Colliery continues underground longwall coal mining of the Bulli Seam to produce high quality coking coal for export. Mining has been managed beneath the Main Southern Railway (MSR) within Longwalls LW25, LW26, LW27 and the current (2014) LW28, with planning for LW29. The MSR is the main passenger and freight rail corridor between capital cities Sydney and Melbourne on the east coast of Australia, and the mining occurs beneath the Main Line between Picton and Tahmoor – see Figure 1. Mine subsidence changes the landform and is a 4-dimensional impact upon the ground surface, with about 1.2m vertical subsidence occurring beneath the operational Main Line.

In order to facilitate continued safe operation of the MSR, a comprehensive geotechnical and structural engineering investigation programme and design of under-track infrastructure elements was developed at the direction of Tahmoor Colliery. Implemented intervention measures were designed to manage the effects of mine subsidence upon brick arch culverts (BAC) which were constructed around 1917. The intervention measures adopted at Myrtle Creek culvert, the first to be mined beneath, were developed in advance of monitored responses. Subsequently, the intervention measures at Skew culvert were intentionally of a minimalist nature within the culvert barrel, though the wingwalls were strengthened. The experiences of mining beneath these elements, and the track itself, have been leveraged to modify and adjust designs for accommodating undermining beneath a bridge-in-cutting and another 100 year old 3m diameter BAC beneath a 20m high embankment. It is to be noted that subsidence-infrastructure interaction constitutes a strain driven system (rather than a stress-driven system more familiar to the geotechnical and structural profession) which means that when subsidence ground strains are realised they apply, and when complete, the ground strains effectively cease, together with the response of the structure.

The mine plan involves retreat of longwall panels beneath the MSR at a depth of about 440m below the track. Three longwalls at Tahmoor have now successfully mined beneath the MSR without the need for speed restrictions on the track and without restrictions upon the mining method. LW25 was mined from August 2008 to Feb 2011, LW26 from March 2011 to its completion in mid-October 2012, and LW27 from November 2012 to March 2014. LW28 is in progress (2014) and has mined beneath the MSR once already. The operation and management of the comprehensive monitoring system for LW25 was continued and augmented, as needed, for the retreats of LW26 to LW28. Management of the track system itself, through a rail expansion switch system, is not part of this paper. The track expansion switch system consists of exemplary use of intelligent engineering – reference should be made to Pidgeon et al (2014) for details of the system and the track management.

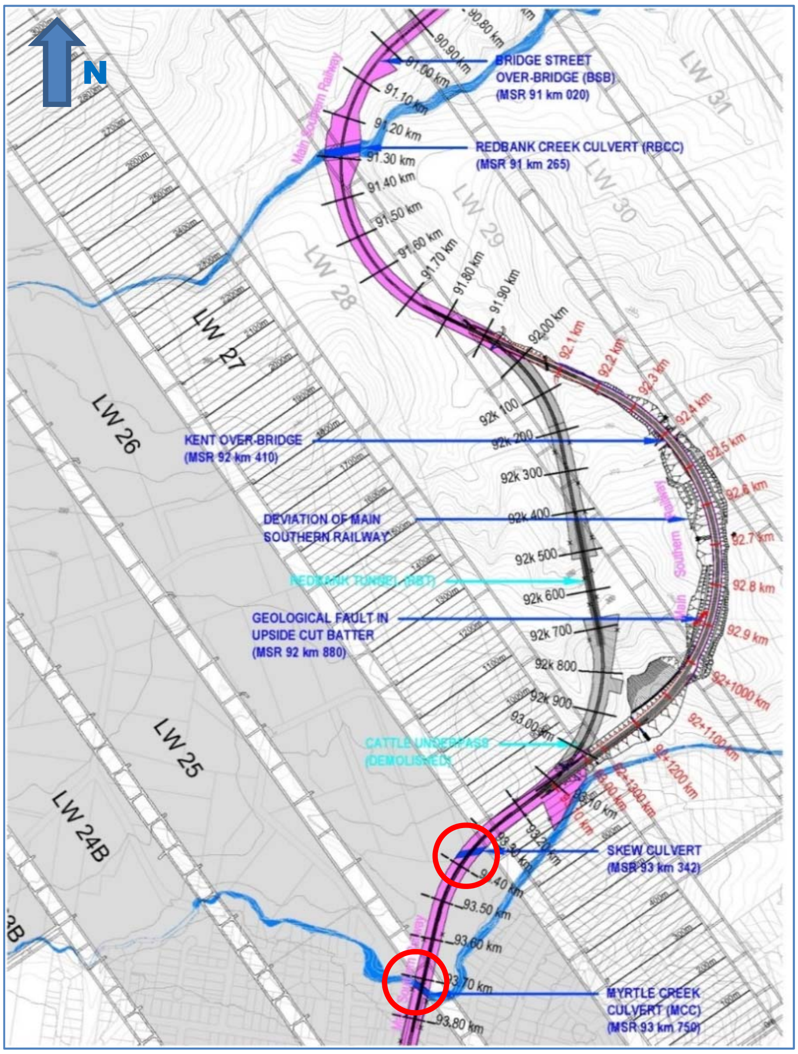


Figure 1. Location plan depicting underground mine plan and surface infrastructure with particular reference to culvert structures on the Main Southern Railway between Picton and Tahmoor about 90 track kilometres south of Sydney, NSW, Australia.

2. MYRTLE CREEK CULVERT MINE SUBSIDENCE RESPONSE

Myrtle Creek culvert (MCC) at MSR chg 93km750 is a 4.5m nominal diameter (4.4mH x 4.6mW), 22m long inverted horseshoe-shaped BAC (5 brick-on-edge thick, nominally 600mm), with its invert about 10 metres below track level. Intervention measures consist of 250mm thick steel ribs at 600mm centres together with a reinforced concrete U-shaped invert slab, passive rockbolts into the bedrock throughout the floor of the culvert (as an upsidence measure), and supporting steelwork to the headwalls. The circumspect approach included a buried 19mL x 12mW x 0.6mD steel deck to act as a baulk beneath the track. In a risk management context, the baulk installation catered for the “black swan” scenario (an unforeseeable extreme event), particularly given that this was the first BAC of this size beneath the MSR to be mined beneath. The expectation, which was realised, was that uplift of the creek embankment would occur to a measurable though minor extent.

MCC is situated above the gateroad between LW25 & LW26 which are at a depth of cover (surface to top of mining interval) of about 440m. Figure 2 provides an impression of the setting of MCC beneath the MSR, whilst Figure 3 depicts the inferred sub-surface conditions. Figure 2 also shows the intervention ribs and headwall steelwork. Reference may be made to Leventhal et al (2014) for a description of the culvert and its relative position to the track, details of the intervention measures and the response of MCC to the retreat of LW25. A nominal design life of 5 years was adopted for the steelwork in a corrosion management context and the expected duration of mine subsidence impact.

Prior to acceptance and implementation, both the intervention measures and the management through monitoring were subject to a qualitative risk assessment process involving the principal stakeholders – the rail operator, the rail regulator, the mining regulator, the colliery and various consulting engineers (structural designer and geotechnical advisor). Acceptable levels of risk were adopted by reference to Australian Rail Track Corporation (ARTC) risk management protocols for track safety. For both Skew culvert and MCC, the critical risk scenario was derailment of mainline trains. The risk levels resulting from mining impact upon the infrastructure were assigned low and very low levels (which were acceptable to the track operator) principally as a consequence of the risk management protocols that included: the nature of the intervention measures; the extensive background engineering analyses and geotechnical and structural designs; the monitoring protocol for the culverts; and the intense real-time management of the track itself accompanied by the use of expansion switches in the track (for the latter, see Pidgeon et al, 2014).

Figure 2. Myrtle Creek culvert viewed from upstream showing the steel ribs and reinforced concrete invert lining within the brick arch culvert beneath the Main Southern Railway (as indicated by the under-track baulk steelwork seen behind the fencing at the crest of the embankment). The embankment fill extends outside the field of the image to both sides, and Hawkesbury Sandstone crops out upstream.

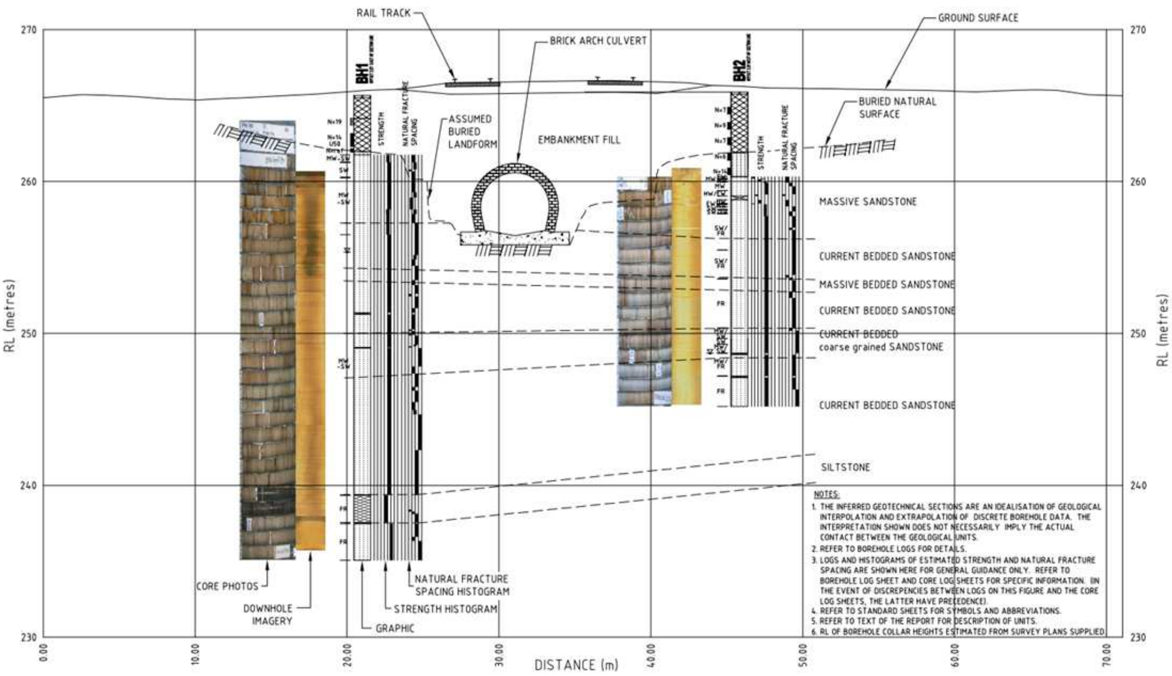


Figure 3. Inferred sub-surface cross-section at MCC.

The geotechnical and structural monitoring system included: tape extensometer readings in multiple directions in the plane of 8 ribs and between monitored ribs; high quality total station survey of prism reflectors throughout the barrel ribs at multiple locations on each rib; strain gauge monitoring at multiple locations upon 6 ribs; survey of the exposed sides of the baulk steelwork; periscopes to the baulk between the tracks; ground pegs in the local area around MCC; and frequent routine visual observations of the culvert. The track monitoring system included: real time rail stress and rail temperature readings at close centres; real-time track expansion switch displacement readings; frequent survey of ground surface within the rail corridor, and rail survey (rail top, rail level, track cant); and frequent observation of track by track certifiers and from front-of-train. Each system had monitoring review points and alarm levels established under the subsidence management plan. The reading frequencies were regularly reviewed by the Rail Management Group, and adjusted in accordance with monitored response and stage of subsidence - pre-subsidence, early subsidence (Stg 1), active subsidence (Stg 2), post-active subsidence (Stag 3) and post-subsidence.

3. LESSONS LEARNT FROM THE INTERACTION OF MINING AT MCC

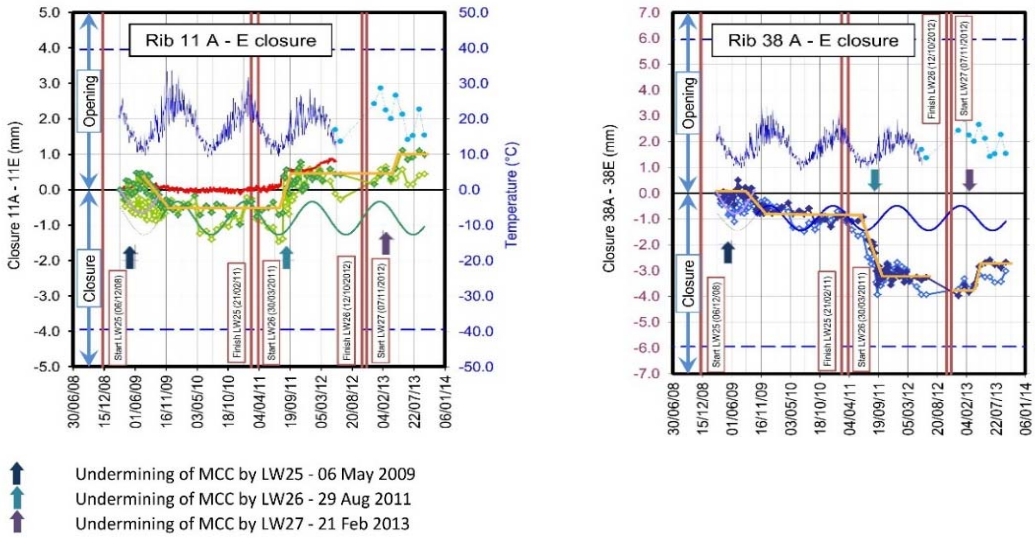
MCC has responded to environmental influences on both a seasonal and diurnal basis for the last 100 years, and has recently experienced 725mm vertical subsidence (at culvert invert). It has responded as a thick-walled cylinder returning to an orientation after mining similar to that before mining, with minor torsion developed during the 4-dimensional response to subsidence. No distress to the barrel of the brick arch culvert was identified, though vertical cracking up to 10mm wide and step shearing occurred between one of the four headwall-wingwall joints – the one visible in Figure 2.

The monitored response was attributable to closure across Myrtle Creek, which towards the end of the retreat of LW27 was between 97mm and 147mm (crest-to-crest) at locations upstream and downstream of MCC. [These represent closure strains of between 3mm/m and 6mm/m.] Closure measured along the track was less, being 65mm. By way of comparison, the response of the composite brickwork and intervention steel ribs was at a scale of only several millimetres (Figure 4).

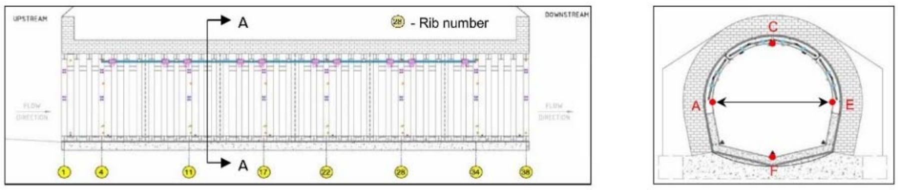
The response of the ribs within the culvert is decidedly 3-dimensional with a much greater response closer to the headwalls than in mid-section - the variable response to mining retreat provided the fourth dimension. The monitoring results were corrected for seasonal effects.

Figure 4 demonstrates the response of selected ribs during the retreat of successive longwalls. Rib 11 is near the mid-section of MCC whilst Rib 38 is at its downstream end. At the mid-section, compressive horizontal displacement was imposed during LW25, was reversed during the retreat of LW26, and further unloaded as a result of the retreat of LW27. Vertical response inversely mirrored the horizontal response, as expected. A similar response was similarly observed to various degrees throughout all ribs (except those at the end of the culvert), producing either return to a neutral position, or with a net unloading horizontally, and accompanying net neutral or downward displacement vertically. The upstream and downstream ribs responded differently with cumulative displacements during LW26 of closure horizontally and opening vertically, followed by limited unloading (rebound) during LW27. The difference in response is attributed to the strain accumulation due to the wingwalls which was not balanced by the stiffness of the headwalls, as might intuitively have been expected. Within 1 panel-width retreat of the longwall away from MCC, 65% to 75% of the creek closure occurred and virtually all closure occurred within 3 panel-widths during retreat of LW26. Strain gauge results from Ribs 7 & 11 indicated stress conditions in these ribs which mirrored the displacement response and either levelled off or reduced during Longwall LW27. These strain gauges also produced both a seasonal and diurnal response.

Surface survey monitoring results in the area about MCC were used to determine the strain field. A novel approach employed shape functions on the sides of triangles composed of monitoring points to estimate centroidal strains, which when combined with Mohr's Circle of strain, develop principal strains and their directions from this analysis. It was noted that: compressive principal strain in the direction of the creek and culvert axis was concentrated at the upstream portal; compressive strain across the creekline was present at the downstream portal area; and tensile strains were present across the middle of the culvert (parallel to the MSR). The tensile strains were consistent with unloading of the ribs as a consequence of retreat of LW26, as also observed through tape extensometer readings taken across the culvert axes.



Sources: GHD Geotechnics production run readings of Myrtle Creek culvert, and BMT WBM monitoring website - http://www.bmtwbmmonitoring.com.au/web/guest/home



Myrtle Creek culvert longitudinal section.

Section A-A: Typical section through culvert.

Figure 4. Monitored responses via tape extensometer of selected steel ribs (intervention measures) within Myrtle Creek culvert during retreat of LW25, LW26 and LW27.

*Figure 5. The upstream end of the nominal 2m diameter inverted horseshoe-shaped Skew culvert beneath the Main Southern Railway***.**

The response of the upper section of the Hawkesbury Sandstone rockmass to retreat of the longwalls, as observed in a 30m downhole inclinometer adjacent to MCC, was development of 7 discrete blocks which independently rotated and differentially displaced in response to subsidence and creek closure - both displacing towards the active mining face on its approach, and then following its retreat away from MCC, and towards the centre of the subsidence bowl (the axis of each longwall).

A significant challenge for this project was the dilemma of measuring subsidence impacts of the same magnitude as on-going environmental seasonal impacts. The requirement of identification of monitoring review levels for management produces the challenge to discriminate between the two impacts (as illustrated in Figure 4). It follows that it is important for monitoring to be established prior to expected impact occurring (in this case, mining retreat approaching the MSR). The aim should be to confidently establish existing trends and to develop an understanding of the nature and magnitudes of environmental responses before, rather than contemporaneously with, impact (in this case, impact from subsidence induced creek closure). The authors highlight the complexity of measuring and then analysing monitoring results for a BAC acting as a stiff tube, in a seasonal and diurnal environment, superimposed with 4-dimensional effects of mine subsidence-induced creek closure.

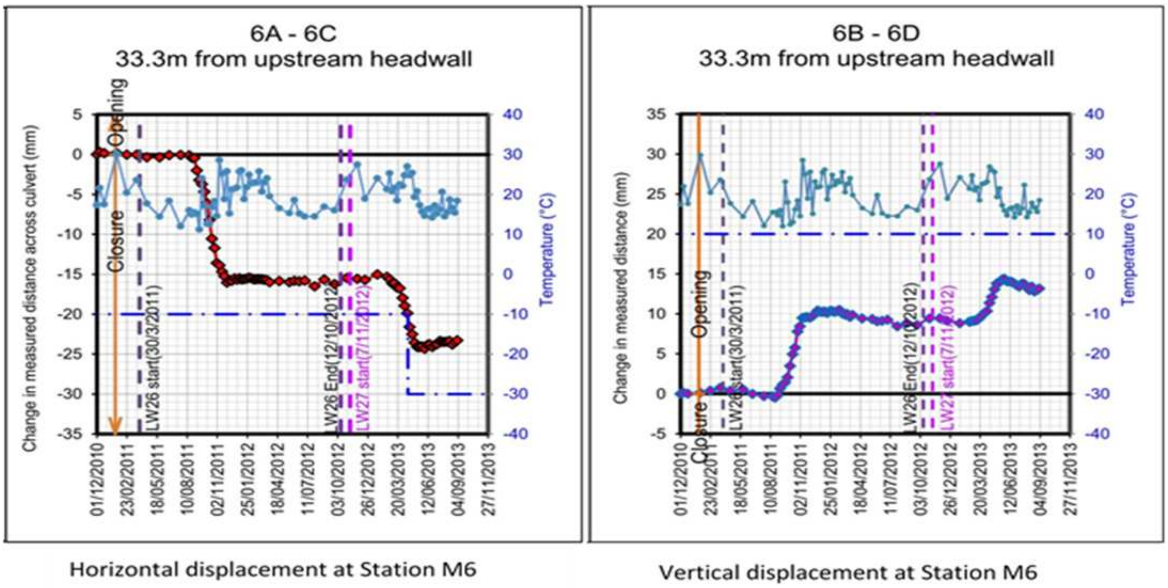


Figure 6. Trace of tape extensometer monitoring at station 3m from downstream end of Skew culvert, this being the monitoring location with the greatest response, during retreat of LW26 and LW27.

4. SKEW CULVERT MINE SUBSIDENCE RESPONSE

The Skew culvert at MSR chg 93km342 consists of an inverted horseshoe-shaped brick arch construction (4 brick-on-edge thick – nominally 470mm), and is approximately 2.0m in diameter (less than half the diameter of MCC) by 2.5m high. An impression of the setting of Skew culvert can be obtained from Figure 5. In the context of experience from MCC, a minimalist intervention was adopted – prudently with back-up and rapid-response measures. The philosophy was to permit the BAC itself to respond to creek closure. To this end, no intervention of the brickwork was undertaken. The back-up was a 20/25mm thick steel liner installed within the 36m long culvert, which did not initially support the BAC. A nominal 50mm wide annular space was left between the steel lining and the brickwork to accommodate cement-flyash grout filling at short notice which would then enable composite action. Whilst purposefully not introducing intervention to the culvert, the track-supporting wingwalls were soil nailed as an intervention measure. In addition, track baulk rails were provided to cross over the culvert. Though damage occurred to the barrel of the culvert to varying degrees along its length, the culvert remained in service, had no adverse impact upon operations of the MSR, and did not place rail safety in jeopardy. Localised stainless twisted reinforcement was required to manage upstream headwall cracking. Sawn joints were introduced in the wingwalls and underlying rockmass at each end of the culvert as a longitudinal strain management measure, as opposed to lateral creek closure, particularly at the upstream end of the culvert.

As for MCC, the Skew culvert was also subjected to multi-party qualitative risk assessment prior to acceptance and implementation of the intervention measures and the monitoring protocols.

5. LESSONS LEARNT FROM THE INTERACTION OF MINING AT SKEW CULVERT

In a similar fashion to MCC, Skew culvert has responded to environmental influences on a seasonal and diurnal basis for the best part of 100 years. Superimposed on this effect, mining induced closure responses have varied along the culvert – the greatest closure at the downstream end, and little closure in the upstream half of the culvert. Observations indicate that that damage to the brickwork has not been consistent with closure, particularly in regard to upstream creek closure in the direction of the axis of Skew culvert.

The horizontal closure of the culvert barrel's brickwork at the downstream end has been measured as 24mm (12mm/m) as per Figure 6. During the retreat of LW26, 60% of the total closure was recorded.

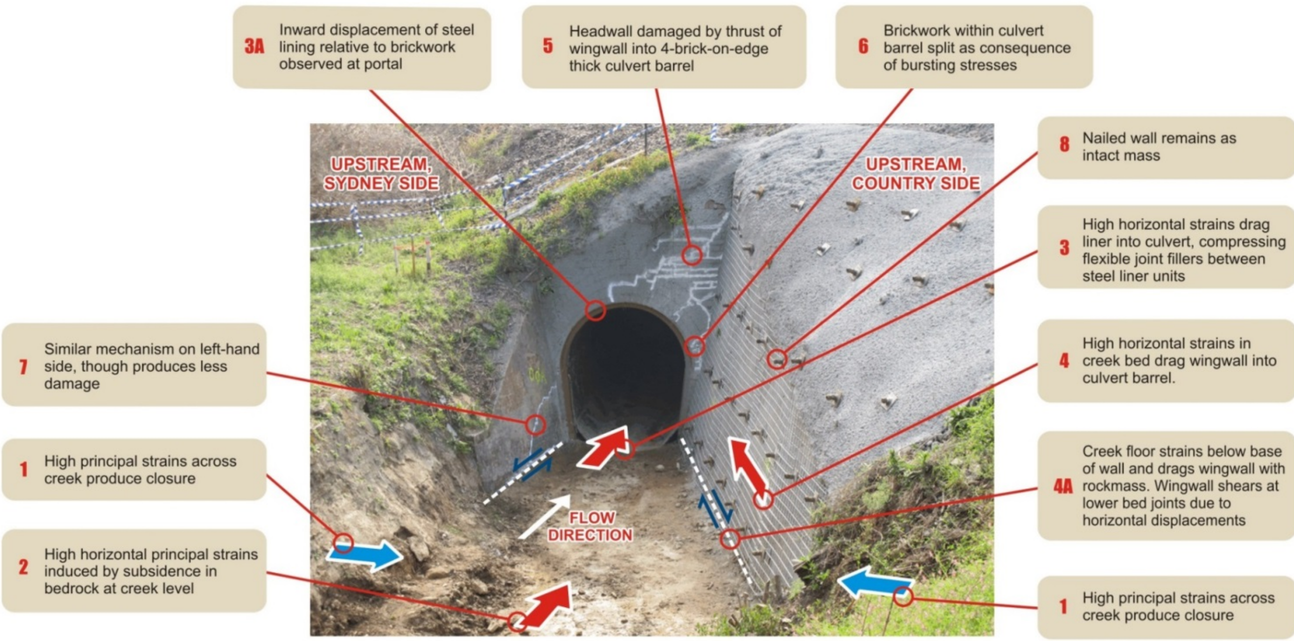
Detectable response of the culvert was observed when the active face of LW27 was still one panel width over solid coal, and the closure was complete at 1.5 panel width retreat away. The brickwork closure was accompanied by shearing and over-stepping cracks at the toe of each wall (8-10mm on the country side and 2-3mm on the Sydney side, at 2 to 3 bricks above the base of the wall), and inward displacement of a section of the culvert wall along shear crack oversteps at the arch spring-point. Tape extensometer reading closures of the wingwalls at large retreat of LW26, expressed in strain units, are: Upstream wingwalls 1mm/m; downstream wingwalls 1 to 6.5mm/m, with a median value downstream of 3mm/m.

It is believed that upsidence in the variable and relatively thin cyclopean concrete invert slab was measured at about 9m upstream of the downstream portal. [The term *"upsidence"* is the difference between observed reduced subsidence and subsidence predicted from the trend of the subsidence bowl.] Nett uplift did not occur, and damage to the floor if it occurred was not observable because of the steel liner. The estimated magnitude of the upsidence of the thin cyclopean concrete floor was 9mm over a bay length of 6m (cf vertical closure of the culvert of 8mm upstream, and 14mm downstream, whilst horizontal closure was quazi-linear).

The upstream half of the culvert suffered damage as a consequence of creek closure reporting into the culvert somewhat parallel to its axis (rather than transverse to the axis) thereby producing a tensile splitting mechanism in the brickwork of the barrel as the wingwall was brought to bear upon it on the right-hand side (looking downstream) – see Figure 7 for the mechanics. Very little closure occurred whilst cracks with a cumulative width of 13.5mm were recorded over the zone of the culvert's RHS springing-point with 5.0mm and 0.1mm cracking elsewhere in close proximity at other levels.

The soil nailing of the wingwalls was effective in producing a block of backfill material beneath the tracks composite with the brickwork of the wingwalls. Rigid block sliding was observed, which served to maintain the integrity of the walling system, and thereby did not place track safety in jeopardy.

Rock-sawn compressible joints, 1m deep by 90mm wide, were created in the wingwall brickwork and sandstone bedrock - an intervention measure implemented between LW26 and LW27 as a response to the damage of the upstream portion of the culvert's barrel. Continued straining effectively closed the saw-cut joint, such that a second sawing of the initial joint was required. Nevertheless, subsequent to the creation of the initial saw-cut, there was only a nominal increase in damage observed at the upstream end of the culvert, demonstrating the efficacy of the response measure.



Mechanics of subsidence induced damage to endwall and wingwalls at upstream end of skew culvert

Figure 7. Responses at the upstream end of the culvert due to the retreat of LW26. The mechanism involves both creek closure transversely across the creek bed, and downstream strain which has dragged the right-hand side wingwall with it.

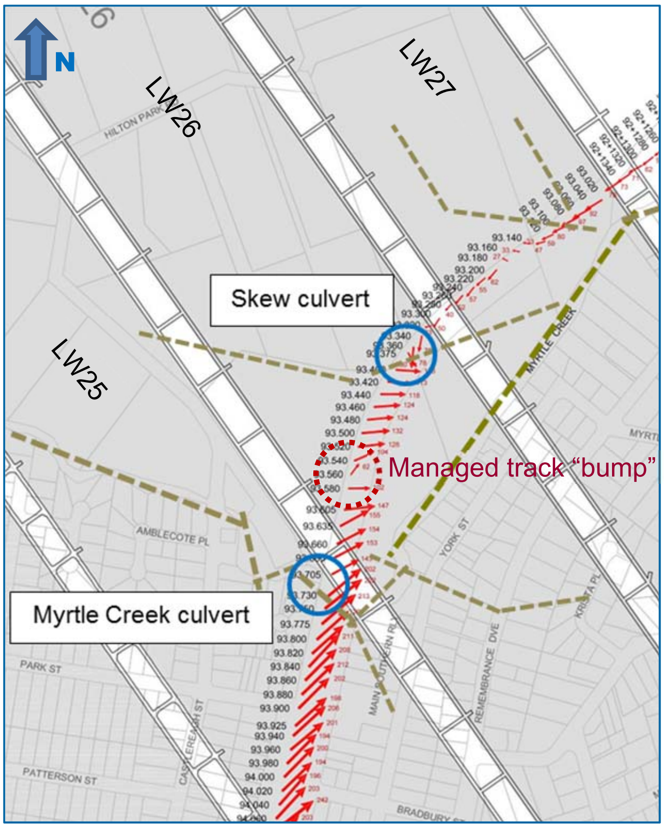


Figure 8. Tracking of horizontal displacements along MSR since the start of LW25 to completion of LW27 The readily identifiable discontinuities in displacement vectors at both MCC and Skew culvert can readily be seen, with a significant interruption to the vectors and their reversal on the northern side of LW26 at Skew culvert. The local distortion at MSR 93km560 was possibly due to the convoluted lineaments about MCC and was associated with a managed "bump" in the track.

[The API lineaments are masked to the south-west of MCC by the presence of residual Ashfield Shale and long-term residential development over the footprint of Tahmoor township.]

Wingwall closure commenced at 2 panel widths prior to mining during LW27; while effective cessation occurred at 2.5 panel width retreat away; and full cessation at 4 panel widths (panel width is 283m rib-to-rib). Saw cut monitoring commenced at 1 panel width prior to retreat beneath the culvert and effectively ceased at 3 panel widths (90%), though was still measurably closing (at sub-millimetre scale) at 5.5 panel width retreat of the active face. In contrast, creek closure effectively ceased at 1 panel width retreat of LW27. There was a clear concentration of compressive principal strains around the southern (upstream) portal, together with an area with minor strain across the central portion of the culvert – consistent with the subduction beneath that area providing strain relief.

Shearing, as indicated by displacements within three 30m deep downhole inclinometers around Skew culvert, was interpreted as a northward plunging (subducting) shear zone within the sandstone bedrock, at or about creek level 15m upstream of the culvert, and at a depths of 6m to 9m (and dipping to the north) beneath rockhead (15m below track level) on the northern side. With reference to Figure 8, the change in nature of subsidence induced horizontal displacements along the track at the culvert was considered to also reflect the presence of the subducting shear zone.

6. CONCLUSION AND CLOSING COMMENTS

It has been demonstrated that longwall mining can be conducted beneath mainline railways whilst maintaining rail safety and efficacious recovery of resources. To do this, not only is comprehensive monitoring necessary but it is required in advance of impact to enable understanding of the nature of on-going external responses which can be of similar magnitude to the expected impact.

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