

Innovative Engineering to replace Small Bridge Structures

Peter Marchant¹ Product and Development Manager ITS Pipetech Pty Ltd¹
Lachlan Drake ² Lyndsay Dynan Consulting²
Doug Jenkins³ Interactive Design Solutions³

ABSTRACT:

Replacing complex and aged sub surface structures to meet the never-ending need for faster, smarter and innovative delivery often involves considerable disruption of day to day business for the infrastructure operator. The search for non-disruptive and cost beneficial rehabilitation technologies therefore remains a high priority in today's demanding maintenance programs especially in remote and harsh locations.

Innovation and adapting existing technologies using concrete and steel reinforcement as functional rehabilitation techniques for new approaches in infrastructure maintenance is high on designers' and contractors' priority targets and is seen as key to keeping costs and disruption down to a manageable level to remain competitive in the rehabilitation market.

The logistics management for much of Australia's transport infrastructure is fundamental to the National economy such that interruptions to the surface traffic is always to be avoided unless physically impossible, however as the sub surface infrastructure ages the repairs to overbridges, underbridges and sub surface tunnels, including large profile culverts require more innovative solutions in order to achieve this.

This paper reports on the unique application of a tunnel and culvert structural remediation technology addressed to a multi span corrugated steel plate bridge that was showing advanced stages of metal corrosion having been in service for over 45 years. This triple span bridge with each arch spanning 8.0m wide and 4.0m high, is located to the south of Wickham in the Pilbara, WA, and services the main Iron Ore route to Cape Lambert. With axle loads set to approach 50 T and facilitating the transport of over 180 million tonnes of Iron Ore per year, the drive to develop a suitable structural rehabilitation without affecting or slowing down the movement of the traffic above became a key deliverable in the overall work proposal.

The ability to use innovative design combined with FE Modelling techniques enabled the development of a high strength reinforced concrete solution to surpass the Clients requirements without any surface disruption. This combined with a specially designed light weight modular panel formwork facilitated the installation of a fully structural concrete multi span bridge lining, resulted in zero interruptions or speed restrictions to the operation and delivery of freight to the ore terminals.

Keywords: Corrugated Steel Plate Bridge, Tunneline, Finite Element Analysis,

1. INTRODUCTION

Today, the majority of the heavy haul rail systems in Australia are now at or rapidly approaching 50 years of operational life and the demands that are required on the infrastructure continue to increase as the drive for economies and efficiencies, to get more from less are the key drivers in today's business world.

Modern technology has developed larger transport cars increasing axle loading at up to 50 tonnes in certain cases. The existing rail infrastructure is therefore required to meet these demands and similarly, the undertrack structures, the bridges and culverts, need to be sufficiently robust and competent in order to handle the increased loading. Unfortunately, many are already at or rapidly reaching the end of their serviceable life and unless renewed, upgraded and strengthened these structures present a substantial risk to the daily operation of the railways.

Preventing the potential of failure and minimising any disruption to the operation of the railway is a fundamental consideration for any infrastructure operator, as is the need to install a rehabilitation that will last the tests of time both with regards to the aggressive environment as well as with the developments in technologies loading and supply demands.

Innovative design and reviewing conventional construction techniques are the tools that Engineers have to use and develop to overcome these issues and combining Finite Element Analysis methodology together with adapting a pressure placed concrete technology system referred to as Tunneline is now able to develop and install structural cast insitu elements inside degrading culverts and non-circular bridge spans to rehabilitate and provide a serviceable asset with a design life of up to 120 years (based on UK and European standards)

Current Australian standards do not specifically address the remediation and rehabilitation of culverts or arch spanning bridges, the current standards used are for new constructions and are generally adapted to apply for rehabilitation projects, therefore alternative design approaches need to be considered.

Using a Finite Element Analysis approach and addressing the soil structure interaction together with guidance from the Australian Bridge Design standard AS/NZS 5100^[1] (2004) and the design for the installation of buried concrete pipes, AS/NZS 3725^[2] (2007), ITS PipeTech and Designers Lindsay Dynan with FEA input from specialist Engineer, Doug Jenkins of Interactive Design Solutions, were able to develop a unique solution to rehabilitate a structure that otherwise may have had to be completely rebuilt.

2. THE PROJECT

2.1 Existing Structure

The existing structure built in 1970, consists of a triple parallel arch span fabricated from corrugated steel plates bolted together to form the profile. Each of the spans measuring 8.0m in width, 4.0m in height (see figure 1) and had a depth of 17.0m. The strip foundations were reinforced concrete structures comprising 4 in total running under the foot of each arch and the up and downstream vertical face was infilled with concrete.

Each arch had a reinforced concrete base that was extended with inlet and outlet aprons.

Soil infill had been placed between each arch span to the level of the Obvert then 2.0m of fill above this to the underside of the track formation.

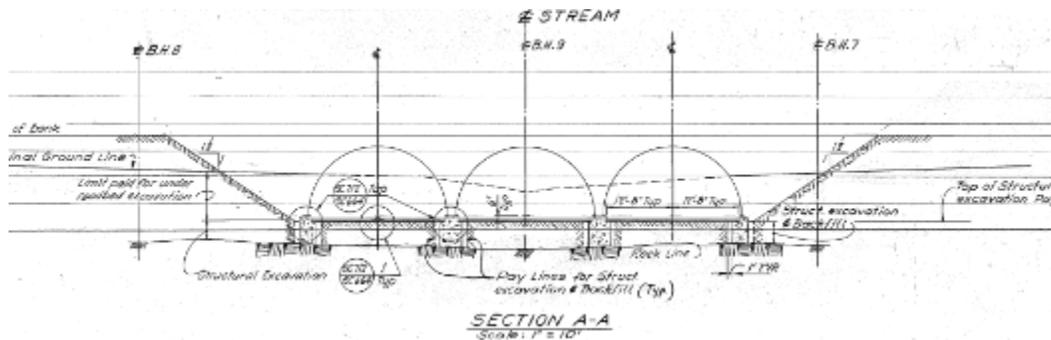


Figure 1 Original 3 arch bridge



Figure 2 Original Bridge before relining

2.2 The Intended Design

The original rehabilitation concept was to design and install a new corrugated steel plate culvert inside the existing spans and then to structurally grout the annular void between the old and the new to create a new structure. Design had been specified to AS/NZS 2566 pt 1 as a flexible construction.

The intention was to use the flexible design code to provide a structural lining solution that would extend the life of the bridge by 50 years and also to strengthen the structure for future loading.

The initial surveys and inspections of the bridge had determined that decomposition of the existing arch was present both internally as well as externally with visual evidence of rust patches and delamination of the corrugated plates (*Figure 5*).

Cracking and spalling was evident on the concrete surfaces to the inlet and outlet headwall and core sampling had determined that cover to the reinforcement was generally less than acceptable to today's standards. Cracks observed at the culvert apexes and across the tops of the foundation levels (*figure 4*) endorsed the belief that movement was evident and commensurate with a general structural deterioration. Further carbonation and Chloride content testing confirmed that chloride induced corrosion to the existing steel reinforcement was also present in the structure



Figure 4 Cracks across the foundation level
CSP



Figure 5 Advanced corrosion to CSP

2.3 The Proposal

Reviewing the requirements of the project, ITS decided against approaching the design using AS/NZS 2566 pt 1 as there were questions on using a flexible design code combined with a rigid, grouted extrados so instead chose to develop a solution based on the principles of a fully rigid structure using established Australian Standards codes AS/NZS 3725^[2]: "Designs for installation of buried concrete pipes" with additional guidance from AS/NZS 1597: "Precast reinforced concrete box culverts" together with Finite Element Analysis to model both the design concept and construction process as well as the load distribution through the soils into the completed structure.

ITS PipeTech Pty Ltd (ITS), together with their structural design partners: Lindsay Dynan Consulting Engineers Pty Ltd (Lindsay Dynan), and specialist FE Designers, Interactive Design Services Pty Ltd (IDS), proposed a design and construct solution to rehabilitate this arch bridge using their Tunneline structural lining system which utilises conventional steel reinforcement together with a special prescribed design concrete mix that is pressure injected inside a unique formwork assembly, creating a dense highly compacted concrete lining that can withstand the live and dead

loadings without any recognition of any inherent strength of the existing host structure.

Due to the distortion in the existing culverts the lining thickness was established at a minimum of 200 mm in the affected rail zone providing a nominal finished internal arch span of 7600 mm by 3800mm.

The design also needed to explore the potential for utilising the existing strip foundations to see if there was scope for harnessing these into the base support for the new concrete arch structures.

The design called for a 40 MPa special prescribed concrete mix together with a double reinforcement arrangement comprising of N16 curved arch bars, N16 distribution steel and N20 L shaped bars where the arches transitioned into the foundations.

On site investigation and testing confirmed that the existing foundations were sufficiently competent to be utilised in the design and a suitable design was produced to tie the arch into these as detailed below in figure 6 below.

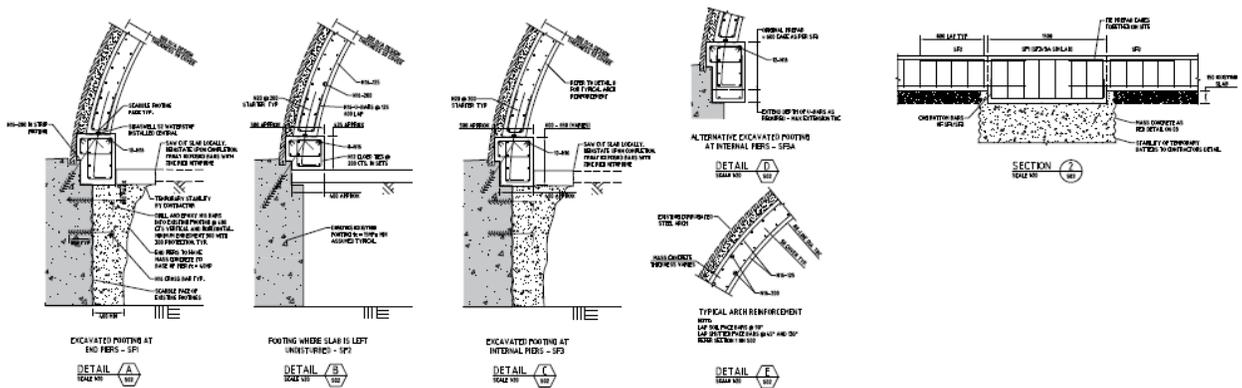


Figure 5: Foundation development

3. DESIGN

3.1 Design Philosophy

Tunneline is a technology to install a structural concrete element that is designed as a buried concrete pipe in accordance with Australian Standards. Applied loads from the soil and railway traffic, as well as road vehicle traffic are reviewed and are calculated in accordance with AS/NZS 3725^[2]. This standard provides a method to determine a uniform pressure at the top of the culvert, and an equivalent point load to be applied to the top of the culvert based on compaction of the surrounding soils.

The lining is then designed in accordance with the point load test procedure outlined in AS/NZS 4058^[4] to determine concrete design actions (bending moment, shear force, axial force, etc.) The reinforced concrete structure is designed in accordance with the requirements of AS/NZS 3600^[3], or AS/NZS 5100^[1] where a 100-year design life is required.

In addition to this Finite Element Analysis was applied using 2 alternative methods:

- A simplified frame analysis, with applied loads due to fill dead load and rail live loading in accordance with AS/NZS 3725^[2]
- A 2D finite element analysis, modelling the culvert and surrounding fill, with the lining construction modelled in a staged analysis to assess transient loading across the structure.

3.2 Design Parameters

Parameters included in the arch relined design include soil cover from obvert of the existing arch to railway sleeper, the arch span, the arch height the degree of deformation (from existing survey), the railway traffic live load, the soil type and density, the original host arch installation condition and support zone compaction as well as the FEA parameters listed above.

3.3 Information provided

The Client provided a comprehensive report which was prepared as part of their maintenance asset assessment. The report included photographs of the culvert showing the condition of the existing structure and degradation of items such as the steel plates, the headwalls and connections to the foundations, corrosion around joints and bolts, and penetrations through the host arch caused by corrosion. A detailed survey of the structure foundations was also completed, post award, to determine the competence of the foundation for incorporation into the new design.

3.4 Live Load Requirements

Design scope for rail is generally in accordance with the live load requirements of AS/NZS 3725^[2]; which adopts the 300LA (30 tonne axle load, 30 TAL) vehicle from AS/NZS 5100^[1]. However, this project called for a bespoke design in accordance with client requirements with a maximum axle load of 353 kN, similar to 350LA passive load requirements.

Soil loads on the arch are determined in accordance with AS/NZS 3725^[2]. The soil load calculation considers: soil cover from obvert of the existing arch to railway sleeper, arch width, trench width, soil type and density, existing host installation condition and compaction of the support zone and side zone material surrounding the existing structure.

3.5 Design Considerations

In the design assessment the following issues were reviewed:

- The original construction method of the Bridge, i.e. embankment fill, trenched excavations and foundations and the effect on calculation of soil load;
- The likelihood of cavitation, external voiding or undermining around the arches and loss of side zone and bedding support and the effect of this on bedding factor and soil load; and
- The effects of a new CSP arch with solid concrete surround inside an existing arch and the ability to behave as a flexible structure under transient loading interacting with the other arches.

3.6 Design Assumptions

In the absence of exact data, assumptions were made in the initial detailed design phase for soil density, trench width and side zone compaction. These assumptions were confirmed prior to construction following further soil investigation and subsequently analysed using the FEM and the final design modified as necessary.

3.7 Engineering Considerations

Due to the variability of the existing bridge profile, the thickness of the final design varied considerably around the circumference and along the length of the structure. The reinforcement design considered this and all conditions were accounted for with an economical reinforcement detail agreed between Lindsay Dynan and ITS.

3.8 Modelling

Established procedures for the design of corrugated steel culverts allow large span structures to be constructed with a structurally efficient membrane that attracts very small bending moments, but corrosion has proved to be a problem, especially for structures carrying a waterway or flood water flows. As a result, many existing structures, where continued reliable performance is a requirement, are being replaced, or provided with concrete liners.

Since the early 1990's precast concrete buried arch structures have made use of finite element analysis in the design process, modelling both the construction process and the loads in the completed structure, application of a similar process to the design of an in-situ concrete lining system was undertaken and the results analysed and compared with code-based simplified methods, showing significant improvements in the ability to achieve design efficiency.

The culvert was modelled using the finite element (FE) analysis program Strand7. A two-dimensional beam model is used to represent the point load test procedure outlined in AS/NZS 4058^[4], with point loads applied to the top of the culvert, as calculated in accordance with AS/NZS 3725^[2], and the invert of the culvert restrained as required by AS/NZS 4058^[4].

The Strand7 finite element models are shown in Figure 6 for the Arch Structures. Differences from standard procedures for analysis of precast arch structures are discussed below:

- Dead load actions in the corrugated steel culverts, prior to lining, were modelled in a single stage, including both the culvert and the fill material. For precast concrete arches it is normal practice to apply the fill elements in layers, modelling the construction process, resulting in locked in stresses in the fill, which have a significant effect on the actions in the arch. This process is different for circular culverts due to the following considerations
 - For fill elastic modulus values typically used in concrete arch analysis the staged loading resulted in unrealistically large deflections in the culvert, and associated convergence problems, due to the much lower flexural rigidity of the corrugated steel section.
 - The low flexural stiffness of the steel section results in greatly reduced locked in stress in the fill.

For the simplified analyses the culvert and liner elements only were modelled in a frame analysis program, with loads applied directly to the structure. Applied loads were calculated in accordance with Clauses 3.2.1 and 3.2.3 of AS 1597.2 (2).

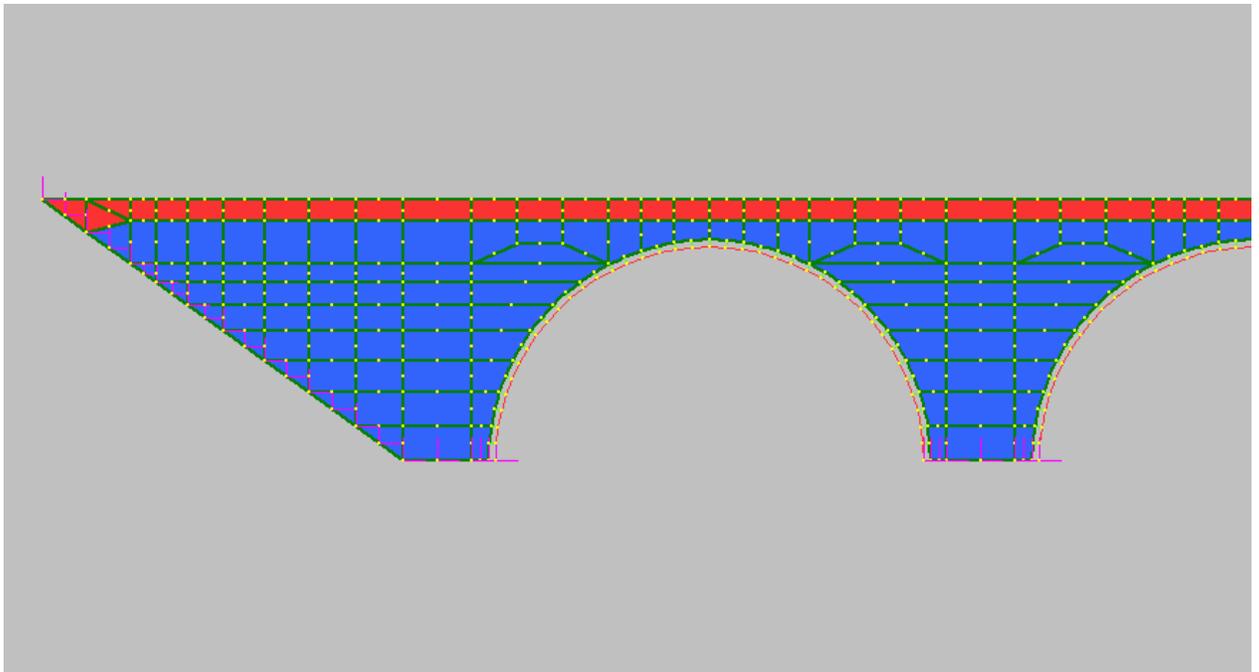


Figure 6: FE Modelling the Arch loading

In using this approach, the Designers followed the methodology typically used for the design of buried concrete arches but considered against and with:

- The existing structure and surrounding embedment modelled as a 2 dimensional analysis, using beam elements for the arch and plane strain plate elements for the embedment.

- The concrete liner beam elements were placed on the centroid of the concrete section, and connected to the plate nodes with short friction elements, allowing slip between the soil and concrete surface.

The lining process was then modelled in four stages:

- Steel arch and embedment fill;
- Addition of the internal concrete liner;
- Removal of steel culvert, modelling corrosion to the extent that the original culvert provided negligible strength to the combined system; and
- Application of rail live loads to the top surface of the fill, with pressures adjusted to allow for transverse distribution of loads and transient movement through the fill.

3.9 Formwork Design

The proposal for the formwork was to adapt the long established Tunneline shutter system; which comprises a plural of small pre-formed panels that link and clip together to form (in this case) an arch section shutter, that is then compressed as a single construction to form a rigid element that is locked into place inside the host span. Once locked the formwork is braced with internal steel supports for additional security and is capable of taking the internal loading during the concrete infill without distortion or movement.

Each complete shutter panel is two (2.0) metres in length and five sets (10.0 m) were used on each pour for this project. Generally, the hydraulic flow of a completed Tunneline is more efficient than the host structure as the friction coefficient of the new lining is superior to corrugated steel- recognized both by Mannings and Colebrook White calculation

One of the key benefits of using a cast in place lining that is constrained behind a fixed rigid formwork, is that it quickly adopts the structural properties of an arch which is an ideal element for the application to reinforced concrete. Concrete trial mix tests undertaken in advance of the works commencing were indicating 24-hour strengths in excess of 10 MPa. Design checks taken in accordance with 353 kN railway loading indicated that the shutters could be struck within 18 hours and subsequent cylinders taken from the actual site mixings confirmed this to be acceptable.

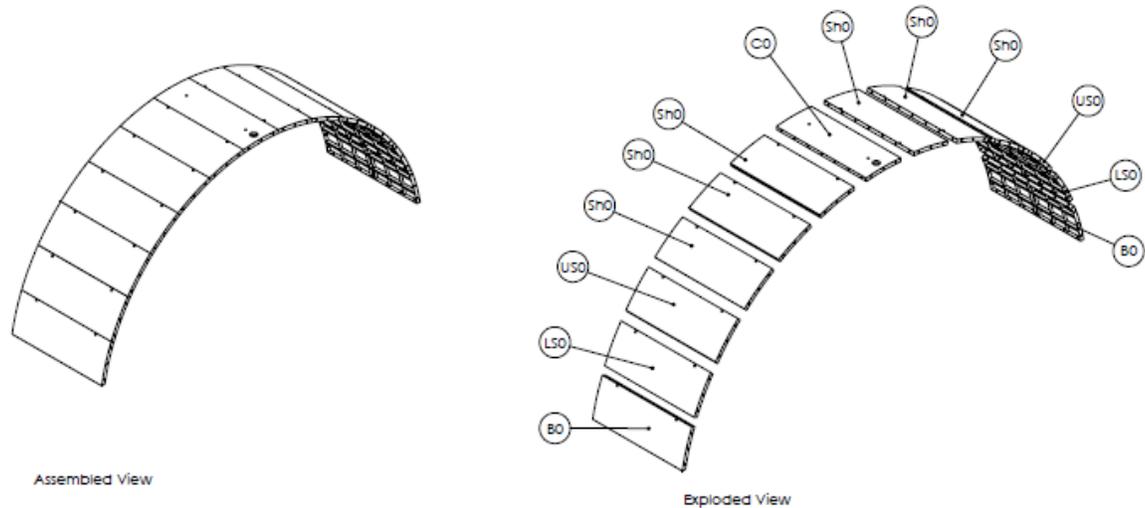


Figure 7: Formwork assembly

3.10 Concrete Design

A fundamental element of the design is the concrete mix and after many years of installing Tunneline, experience has concluded that if anything is going to go wrong it will be due to the concrete. Determination of the right mix and maintaining a rigid quality regime is therefore paramount to the success of this type of project.

Most clients have a suite of preferred design mixes however not all of these will be suited to the Tunneline technology so it is vital to establish the performance requirements and environmental class of the structure and how it will be exposed in the life cycle of the structure.

For this project, a bespoke design mix was developed in accordance with the parameters of AS/NZS 3600^[3] with a minimum cement content of 450 kg incorporating 25% fly ash replacement and a water cement ration (WCR) of 0.4. The slump range was set between 200 to 280 mm with an optimum target of 240 mm directly into the pump.

Mix proportions called for a blend of fine aggregate, coarse sand and fine sand in the ratio of 795 kg/387 kg/473 kg per m³.

A further stipulation was that 90% of the coarse aggregate had to pass the 9.5 mm sieve in order to maximise the penetration of the mix around the host unit.

A water reducing additive and a superplasticiser were added at 1.5 and 1.0 l/m³ respectively for workability.

4. SITE WORKS

4.1 Foundation

Having ascertained that the existing foundations were suitable for incorporation into the permanent works the first operation was to excavate 5 off, 2.0m by 1.0m openings (*figure 8*) along either wall of the central span alongside the existing foundations onto the rock head. These openings were then used to construct the tie ins to the existing foundation in order to develop the cantilevered support for the new arch lining (*figure 9*).

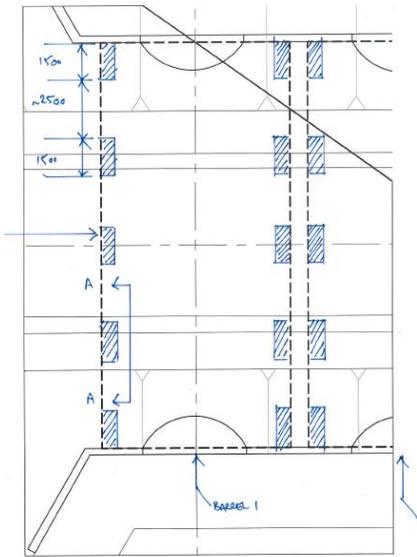


Figure 8 Foundation excavations

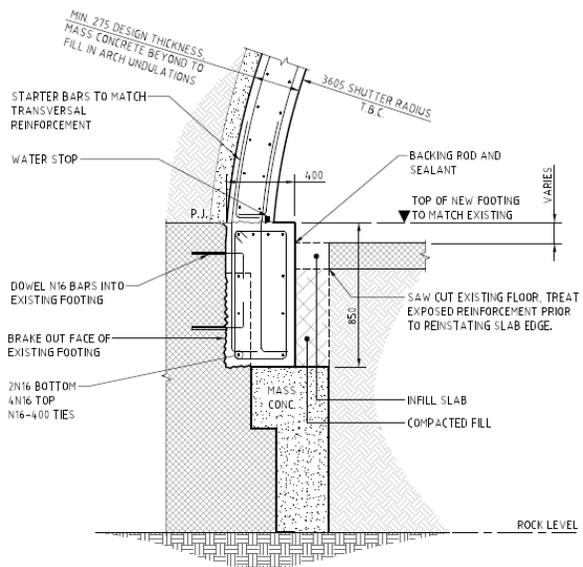


Figure 9 Tie into existing Foundations

Once these had been completed a ground beam (*figure 10*) was developed, harnessing the foundation cantilevers along the base wall extending this above the existing slab which then formed the kicker off which the main arch would be cast.

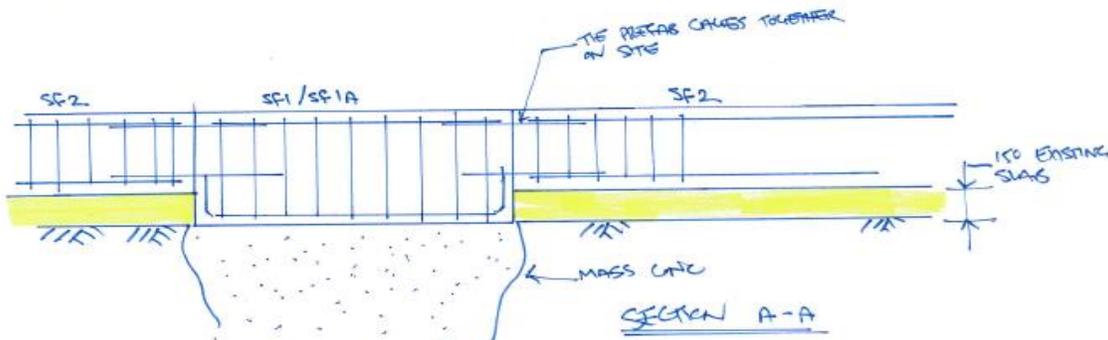


Figure 10 Ground beam concept.

4.2. Lining Installation

The twin cage reinforcing design was fully installed in each span prior to assembling the Tunneline formwork which was braced and supported in accordance with the temporary works design.

The Formwork was designed to the Tunneline Formwork Design Manual, issue 3, 2016^[7] and the system was verified compliant to the requirements of AS/NZS 3610: Formwork for Concrete 1995.^[8]

The formwork together with supporting bracing was checked and verified using FEA to ensure that no movement would take place as the shutter was loaded or when full and under load from overhead traffic movement.

Erecting the formwork required the placement of additional support ribs at 2.0m intervals along the depth of the span. These were also utilised to accurately position the Tunneline panels as the build progresses through the arch.

When all of the formwork is installed the line and level is rechecked, adjusted where necessary before the screw bars are fully tightened to lock the formwork into place. On completion of this, the final brace supports are installed and tightened and the stop-end is set to complete the sequence. Again, throughout the formwork installation process constant QA checks are undertaken and recorded to confirm that the correct cover is maintained to the reinforcement at all times.

Concreting is undertaken by placing the concrete into the formwork through a purpose made injection port, the first of which is located at one end of the shutter in the obvert. Concrete is pumped in through the port and the shutter is progressively filled from this end port until it is full and begins to travel along the formwork.

Ports are established every 2.0 m along the shutter however the pump line is not moved to the adjacent port until the concrete has travelled past this point such that, when moved and reconnected concrete is then pumped into the previously placed concrete continuing to push it further along the shutter therefor eliminating the potential to create trapped air pockets. Observation ports were installed along the formwork to check that the concrete was flowing well through the pour.

As the concrete is pumped into place inside the compressed rigid shutter the effect of this creates intense compaction that requires no vibration. On completion of the pour the screw bars are removed as the concrete is retaining the formwork.

Striking the formwork was undertake the following day after the pour is complete, and test cylinders verified the strength prior to this operation commencing. Initial trials on the concrete design had previously established the mean strengths at 12, 18 and 24 hours.



Figure 11 Installing Formwork Panels



Figure 12 Installing supports



Figure 13 Arches complete

5. SUMMARY

The use of Finite Element Analysis in the design stage enabled the designers to fully consider the effects of the soil interaction and the significance that this had on the development of the bending moments in reinforced concrete liners to corrugated steel liners both for dead loads and high live load effects resulting from heavy rail load with limited cover above the structure.

Finite Element Analysis procedures for pre-cast concrete buried arches are well documented but the works undertaken on this project can be applied to insitu cast members to provide a structured dependable design solution.

The use of the Tunneline system, originally developed for circular and ovoid pipe and culvert lining, can be engineered to develop arch spans which in this case

resulted in significant time and cost savings over conventional rebuild or steel lining systems with no impact to the operation of the railway above.

Using pressure placed concrete to the Tunneline technology there is no need to undertake any pre-remedial works. The host structure acts as a temporary external formwork for the new structural lining.

The system has a reduced carbon footprint from less site traffic and vehicle operation and benefits from a reduction in noise and general disruption all round.

The highlights of the project can be summarised as:

- Providing a 120-year design life.
- Full Compliance with Australian Codes and Standards.
- No disruption to the operational Railway.
- Flood immunity was not compromised
- No track closures.
- No speed restrictions.
- No LTI's or accidents.
- Completion ahead of schedule.

6. ACKNOWLEDGEMENTS

The author would like to acknowledge the help and co-operation of the parties engaged in the design of the structure described in this paper: Structural Engineers Lindsay Dynan Consulting, and Doug Jenkins of specialist FE Designers, Interactive Design Services.

7. REFERENCES

- [1] AS 5100 – 2004 Bridge design
- [2] AS/NZS 3725 – 2007 Design for installation of buried concrete pipes
- [3] AS 3600 – 2009 Concrete structures
- [4] AS/NZS 4058 – 2007 Precast concrete pipes
- [5] AS/NZS 2566 – 1998 Buried Flexible pipelined, Structural Design
- [6] AS/NZS 1597 – 2013 Precast reinforced box culverts
- [7] Tunneline Formwork Design Manual rev 3 2016
- [8] AS/NZS 3610 – 1995 Formwork for Concrete

Figure 9 Expanded

