Hickson Road Arch Bridges, Sydney – Analysis for Predicted Ground Movements

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ABSTRACT

The three arch bridges that cross Hickson Road at Millers Point in Sydney's CBD represent an early application of reinforced concrete for large span bridges in NSW.

The bridges were built by the Sydney Harbour Trust (later to become the NSW Maritime Services Board) and are classified as Monier arches. At the time of their construction, 1910 to 1914, they were noted as the "largest reinforced concrete bridges in New South Wales".

Due to predicted ground movements from nearby tunnel and cavern excavation work for the Sydney Metro rapid transit system, the arch bridges were structurally analysed to check their capacity to withstand the anticipated horizontal and vertical movements.

1 INTRODUCTION

A locality map of the bridges is shown as Figure 1, with the three arch bridges highlighted, noting that the bridge that supports Munn and Argyle Streets are two separate arch bridges that abut each other. Figure 2 shows a view looking south along Hickson Road, and Figure 3 shows the individual bridges in plan.

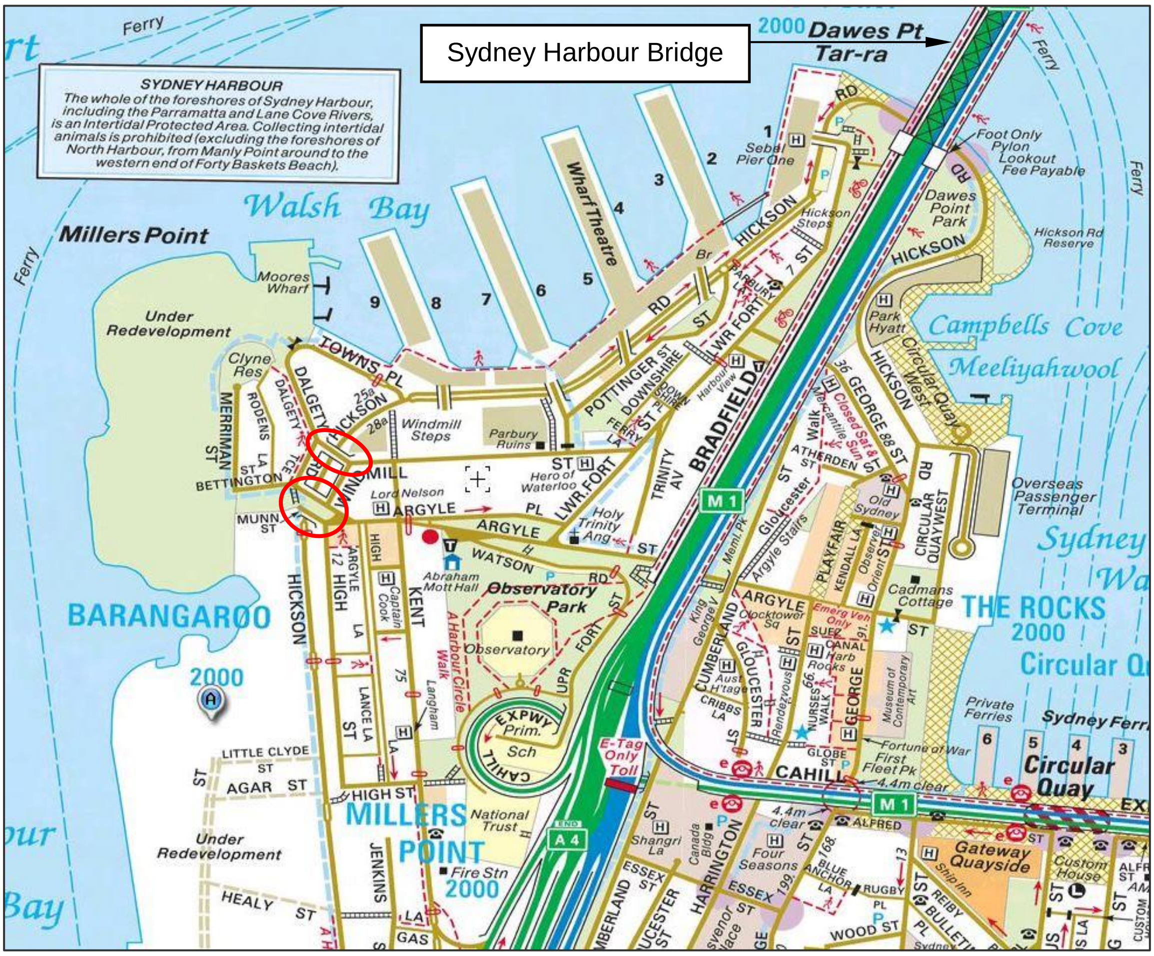


Figure 1 – Locality Map (bridge locations highlighted)

Figure 2 – Windmill Street Bridge (foreground) and Munn & Argyle Streets Contiguous Bridges (background)

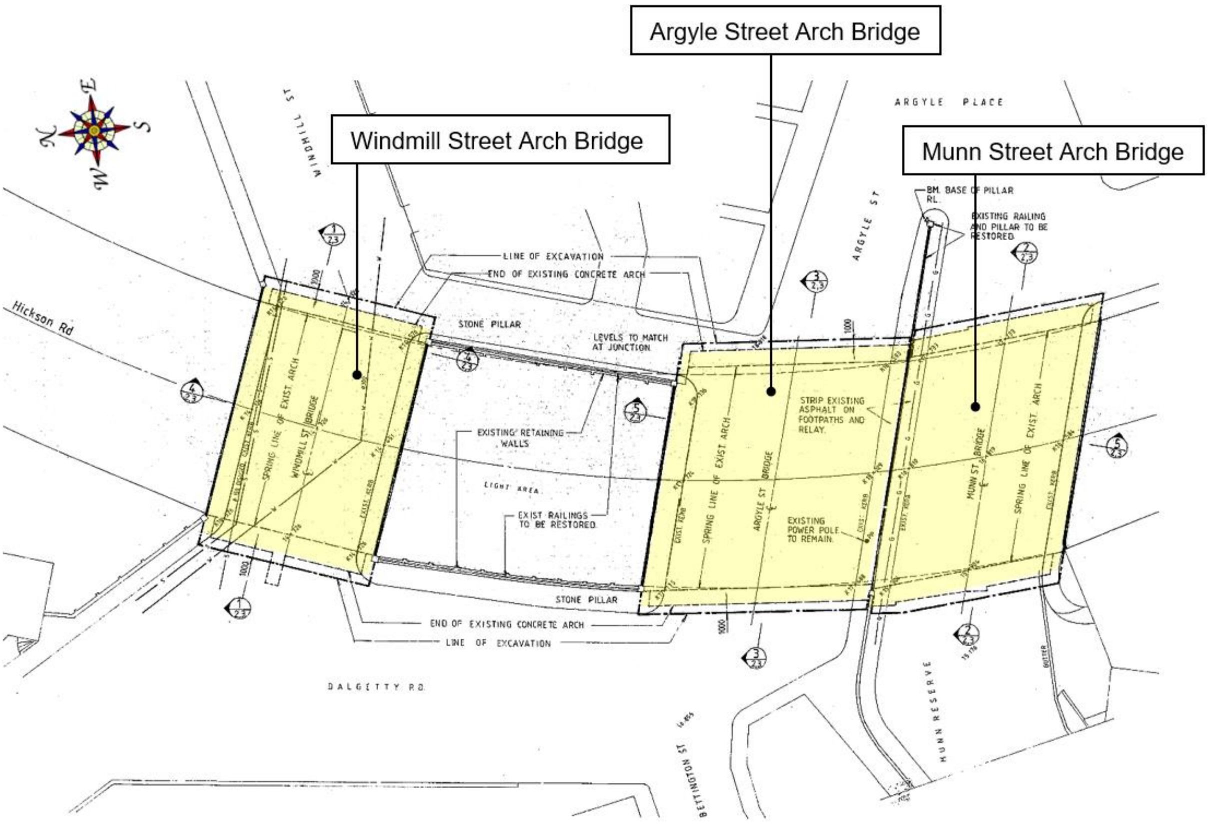


Figure 3 – Locations of Arch Bridges over Hickson Road

The three reinforced concrete arch bridges over Hickson Road at Millers Point, Sydney, were constructed between 1911 and 1914 by the Sydney Harbour Trust. All three bridges are reinforced concrete arches and of cast insitu construction, with span lengths of 24.4 m and a rise of 4.6 m at mid-span. They represent an early application of reinforced concrete in NSW.

The first bridge to be built was the one carrying Munn Street over Hickson Road, followed by Windmill Street arch bridge, then Argyle Street arch bridge, which was constructed alongside Munn Street arch bridge.

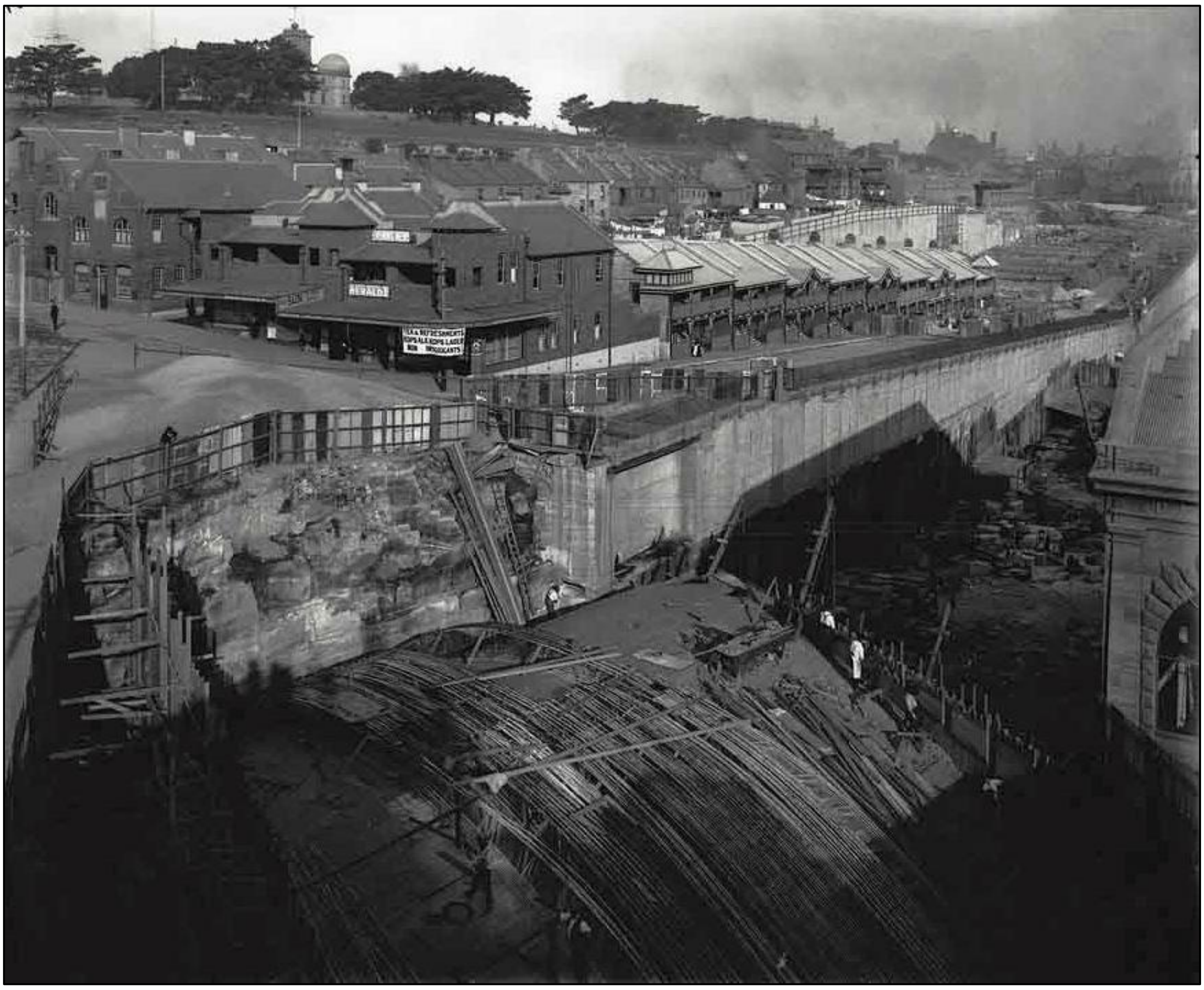


Figure 4 – Munn Street Bridge During Construction (c1911)

2 ARCH BRIDGE TYPES

The earliest arch bridges comprised individual stone blocks (known as voussoirs), and because this type of arch ring cannot withstand tension, it is essential to their stability that the resultant thrust force due to the applied loads remain within the middle-third of the arch ring cross-section. This theoretically ensures that the entire cross-section is in compression. The same theory applies to brick arch bridges, common in early NSW railway construction. As such, these arch types were more circular in geometry, thereby counteracting the adverse structural effects due to bending.

With the introduction of reinforced concrete, whereby tension in an element's cross-section could be structurally tolerated, flatter arch configuration was explored, with the 'Monier System' being the pioneering arch type. Named after Frenchman Joseph Monier, who took out patents for concrete flower pots reinforced with wire netting, the application of reinforced concrete for structural applications came known as the Monier System. For these flatter arch types, flexure becomes a more dominant load effect, however, thrust still acts to 'tone down' the otherwise adverse flexural effects, and with the presence of reinforcement (typically close to both upper and lower surfaces of the arch), any tension in the arch cross-section is withstood by the reinforcement.

In Australia, the early construction contractors of the Monier System for bridges and aqueducts were Carter, Gummow & Co (with their design engineer W.J. Baltzer) in New South Wales, and John Monash and Joshua Anderson in Victoria and South Australia.

A selection of early reinforced concrete arch bridges in NSW are: Burwood culvert under Parramatta Road (c1894), Annandale sewer aqueducts (1895-1897), Hilltop overbridge over Picton to Mittagong loop line railway (c1897), Liddell overbridge over the Main North railway (c1898), Moonbi bridge on old alignment of the New England Highway (c1900), Wallendbeen overbridge over the Main South railway (c1900), Jews Creek bridge, Larras Lee (c1903), North Richmond bridge over Hawkesbury River (c1905), Strathfield overbridge over railway(c1909), and Hickson Road arch bridges, Millers Point (1911 & 1914).

3 PREVIOUS ARCH REHABILITATION WORK

Due to the deteriorated condition of the arch intrados and the spandrel walls of each bridge over Hickson Road, City of Sydney, in the early 1990s, undertook the following rehabilitation work at all three arch bridges (Ref 1):

- Removal of fill.
- Removal of 80 to 90 mm of concrete at the arch intrados (soffit), to provide a minimum clearance behind the existing reinforcing bars of 30 mm.
- Grit blasting of existing reinforcing bars and replacement of bars (with Y24 bars) where less than 75% of their cross-sectional area remained.
- Drilling and insertion of 30 mm diameter high strength bolts through arch ring to provide composite connection between overlay and original arch ring. These bolts were anchored into the shotcrete layer.
- Shotcrete layer (110 mm thick) applied to the soffit of the arch.
- Demolition and reconstruction of reinforced concrete spandrel walls.
- Construction of 350 mm thick reinforced concrete overlay on arch extrados.
- Waterproof membrane and sub-soil drainage lines provided on the top of overlay slab, prior to backfilling.

4 STRUCTURAL ANALYSIS

4.1 Arch Assessment Loads

The arch bridges were assessed using load combinations as defined in AS 5100.2:2017 *Bridge design Part 2: Design loads*.

4.1.1 Dead Loads

The self-weight of the arch and pavement components were estimated from the drawings pertaining to the restoration of the arch bridge in the early 1990s.

4.1.2 Live Loads

For traffic loading, ST42.5 tonne semi-trailer was used in each marked lane, as this represents the heaviest legal load permitted (unrestricted travel) on NSW public roads.

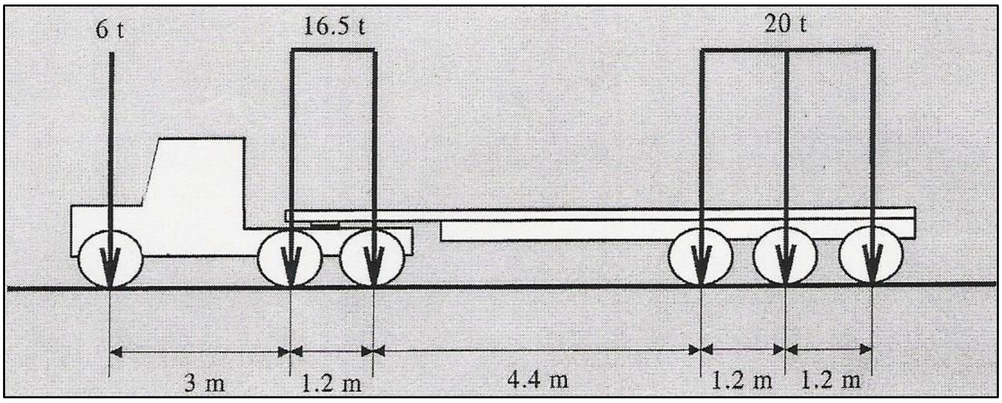


Figure 5 – Semi-trailer 42.5t

4.1.3 Predicted Ground Movements

Geotechnical engineering consultants provided Arcadis with predicted ground movements (both vertical and horizontal) at the abutments (springings) of the three arch bridges over Hickson Road, due to nearby tunnel and cavern excavation work for the Sydney Metro rapid transit system.

Vertical and horizontal (perpendicular to the arch abutment) displacements were applied to generate the maximum differential movements across the arches.

4.2 General Analysis Principles

The behaviour of a buried arch bridge represents a complex form of soil-structure interaction. When the loads are applied to the arch ring, certain portions of the ring deflect into the fill, while the other sections deflect away from the fill.

For the assessment of the arch bridges, finite element analysis utilising Strand7 software was used. Peak thrust, peak shear, peak positive moment, and peak negative moment were determined. It is noted that the existing bridge drawings were unavailable. As such, the 28-day compressive strength of concrete in the original part of the arch ring was assumed to be 21 MPa, in accordance with clause A1.4 of AS 5100.7:2017 *Bridge design Part 7: Bridge assessment*.

For each arch bridge, a 1 metre wide strip of the arch ring was modelled in Strand7 using beam elements, with both pinned and fixed conditions at the ends of the arch. In the absence of the original bridge drawings, the geometric configuration of the arch was determined graphically from the details provided in the arch restoration drawings (c1990).

Self-weight of the arch, fill, and traffic loading were applied on the beam elements.

The structural analysis of reinforced concrete arches initially involves determining the axial thrust (P) and bending moment (M) at critical sections along the arch ring. These critical sections are typically taken at the springing, crown, and between the springing and crown, as the thickness (and hence structural capacity) varies along the arch ring. Essentially, the arch behaves as a beam-column, whereby it is concurrently subjected to axial compression and bending.

The section capacity is then calculated, using reinforced concrete column theory, whereby a P-M interaction curve is developed for each critical section. For this component of work RAPT software was used.

With the critical combination of P and M identified by analysis, these points were plotted on the relevant P-M interaction diagram. Where the P-M load effects point is located within the beam-column interaction curve, the arch is considered theoretically adequate to carry the load combination considered.

4.3 Arch Design Sections

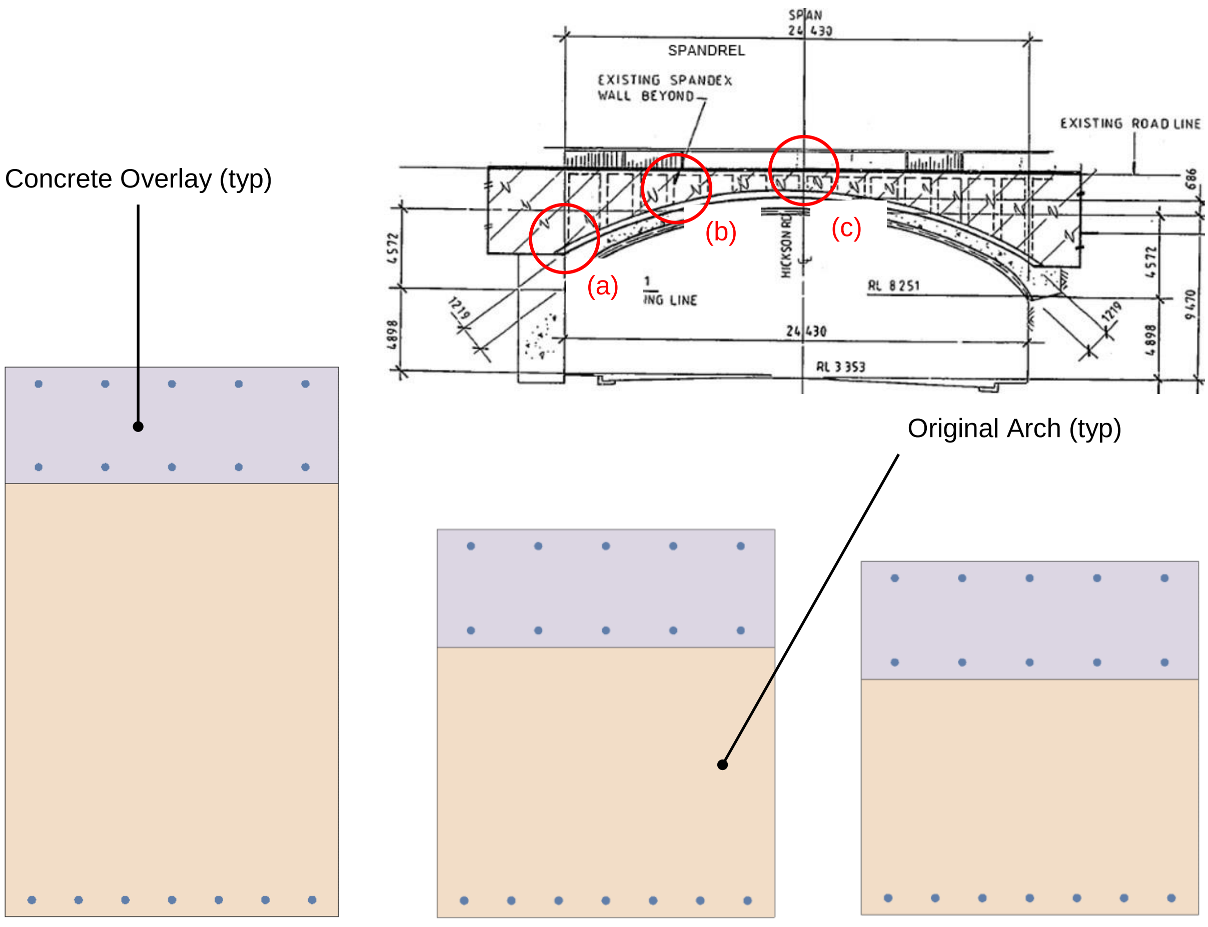
The main bridge span is composed of a reinforced concrete arch varying in thickness from approximately 1300 mm at the abutments/springing points to 700 mm at the crown, with a rise of approximately 4.6 m measured from the springing point to the highest point on the arch soffit. The abutments for each bridge are reinforced concrete and are set into cut outs in the solid sandstone.

The main arches of the original construction are reinforced with 1" diameter mild steel bars at approximately 140 mm centres longitudinally on each face of the arch. Minimal transverse and shear reinforcement has been provided throughout the arches. Concrete strength of 21 MPa was assumed.

In the early 1990s, remedial works were undertaken to strengthen the arches with a 350 mm thick reinforced concrete overlay (40 MPa), with Y24 bars at 200 mm spacing (top and bottom). In addition, a portion of the deteriorated soffit of the arches was removed and repaired with reinforced shotcrete anchored through the arch to the overlay.

Cover was assumed to be 40 mm throughout. A portion of the soffit of the arches was removed and replaced with 50 MPa shotcrete and corroded bars replaced with new Y24 bars. The analysis work treated the replacement shotcrete and reinforcement as a like-for-like replacement of the deteriorated soffit (prior to remedial works).

Figure 6 shows the various arch ring design sections. The lower layer represents the original arch section, while the upper layer represents the concrete overlay, placed in the early 1990s. The presence of reinforcement near the upper surface of the original arch section was ignored, as it was understood to have been in deteriorated condition.



(a) End of Span Design Section (b) Quarter-Point Design Section (c) Mid-Span Design Section

Figure 6 – Arch Ring Design Sections

4.4 Finite Element Analysis and Section Capacities

The arch bridges that span Hickson Road were modelled in the finite element package Strand7 Version R2.4.6. A series of 2D and 3D models were developed using beam, plate and brick elements to encapsulate the effect of the displacements induced by the proposed excavation work. The results of this analysis work are presented via the idealised 2D models (refer to Figures 7 to 10). The models have been analysed using a non-linear static analysis. As such, moment magnification effects were automatically accounted for.

Because of this modelling, key sections of the arch were identified to encapsulate the overall performance of the arches. These sections were defined at the abutments/ends of span (springing points), mid-span and close to the quarter points on each arch.

Design capacities and interaction curves were calculated using Autodesk *Structural Bridge Design* in accordance with AS 5100.5:2017 *Bridge design Part 5: Concrete*. Due to the known deterioration of the original arch structure, the upper layer of reinforcement (1" mild steel bar), located directly below the overlay, was ignored from the calculation of the theoretical capacity of the arches.

A range of arch end restraint conditions were analysed for the arches to encapsulate the varying effects of idealising the end restraints as 'pinned' and 'fixed'. The actual restraint condition could not be positively ascertained by visual inspection of the arches, nor from the provided remediation drawings. Engineering judgement assumed that idealising these structures as 'pinned' would be most appropriate for these structures, although the appreciably thicker arch ring present at the ends of the arch, compared with mid-span, would indicate they were originally designed as fixed-end arches.

Notwithstanding, the structural analysis work considered, separately, both pinned and fixed arch end restraint conditions.

It is noted that frame analysis software such as Microstran and SPACE GASS can also be used for analysing arch structures, however, moment magnification of the arch ring due to slenderness effects (as it is acting as a beam-column) must be accounted for when using this form of analysis. Ref 2 provides details of the simplified frame model analysis method for the load rating of stone masonry arch bridges, as well as reinforced concrete arch bridges.

5 ANALYSIS RESULTS

Apart from the differing arch end restraint conditions, two load cases were assessed, as follows:

- **Existing Load Condition** – This load case represents the load effects on the arch bridges due to self-weight, dead loads and live loading.
- **Predicted Ground Movement** – This load case represents the load effects on the arch bridges due to self-weight, dead loads, live loading and predicted displacements at the arch springing locations.

By checking and comparing both above two load cases, the effect of the predicted displacements was able to be appreciated.

The following shows the analysis results for Windmill Street Bridge. The same analysis work was carried out for both Argyle Street and Munn Street arch bridges.

5.1 Windmill Street Arch Bridge

Table 1: Pinned Ends – Existing Load Condition

Arch Section	**Axial Compression (kN)**	**Bending Moment (kNm) [1]**
Ends of span	3065	0
Quarter points	2650	–557
Mid-span	2437	476

Notes: 1. Positive (+) moment indicates a sagging moment and negative (–) moment indicates a hogging moment

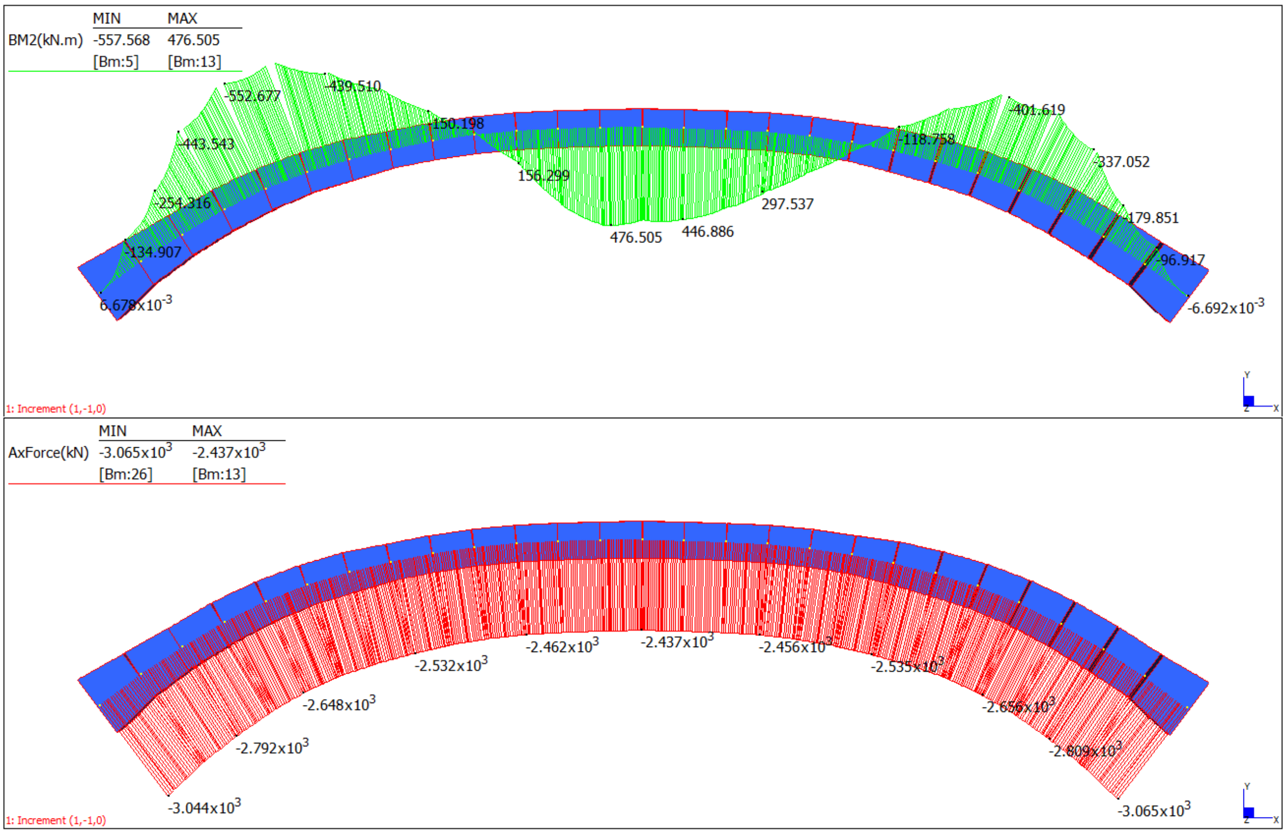


Figure 7 – Pinned Ends – Existing Load Condition: Bending Moment Diagram (upper) & Axial Force Diagram (lower)

Table 2: Fixed Ends – Existing Load Condition

Arch Section	**Axial Compression (kN)**	**Bending Moment (kNm) [1]**
Ends of span	3060	–238
Quarter points	2600	–564
Mid-span	2420	489

Notes: 1. Positive (+) moment indicates a sagging moment and negative (–) moment indicates a hogging moment

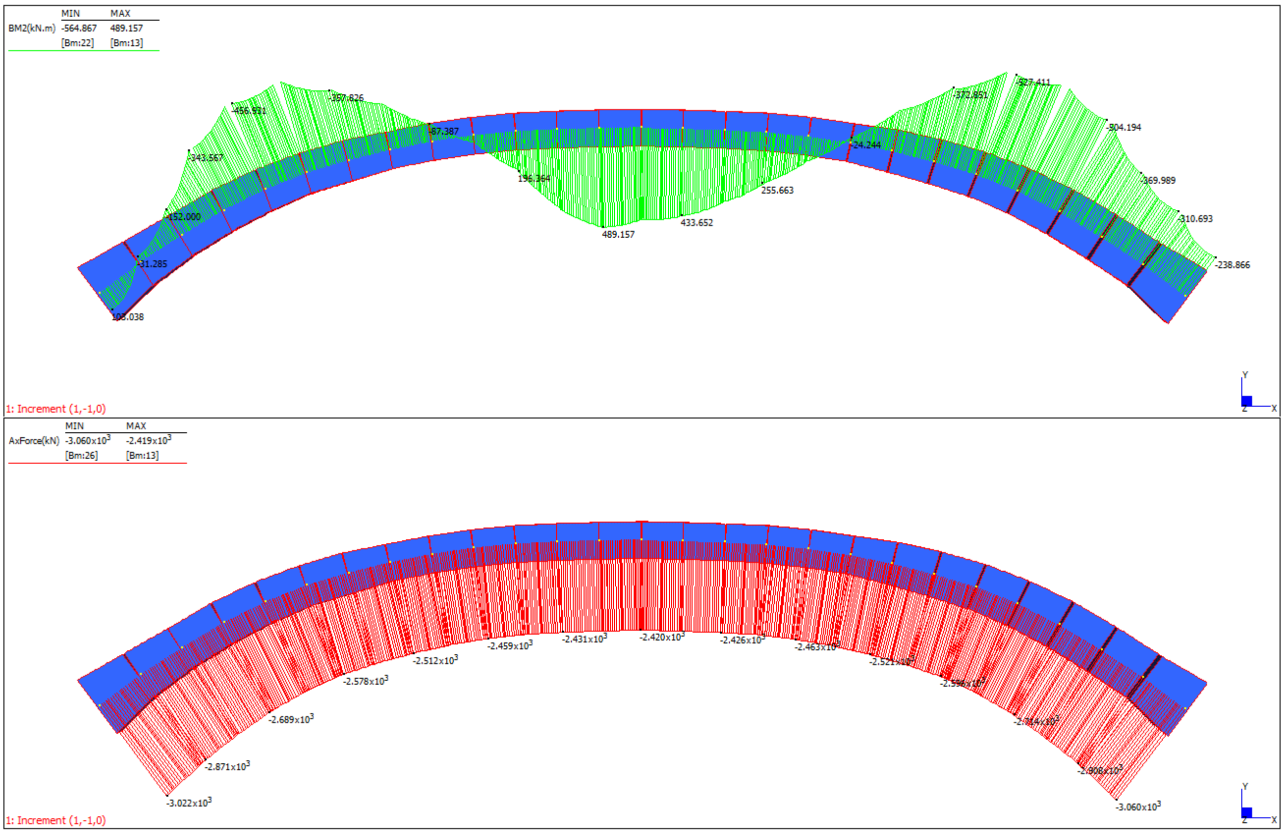


Figure 8 – Fixed Ends – Existing Load Condition: Bending Moment Diagram (upper) & Axial Force Diagram (lower)

Table 3: Pinned Ends – Predicted Ground Movement

Arch Section	**Axial Compression (kN)**	**Bending Moment (kNm) [1]**
Ends of span	3083	0
Quarter points	2600	–632
Mid-span	2460	372

Notes: 1. Positive (+) moment indicates a sagging moment and negative (–) moment indicates a hogging moment

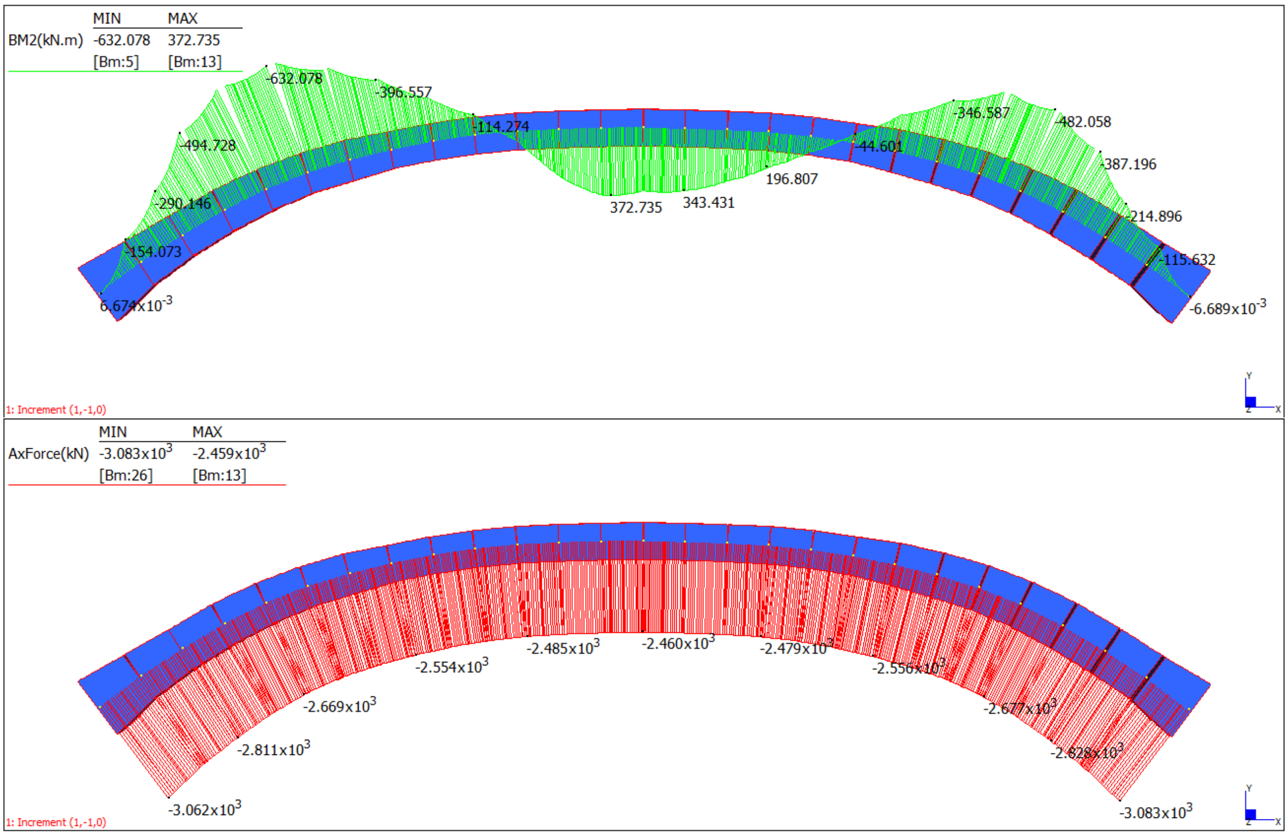


Figure 9 – Pinned Ends – Predicted Ground Movement: Bending Moment Diagram (upper) & Axial Force Diagram (lower)

Table 4: Fixed Ends – Predicted Ground Movement

Arch Section	Axial Compression (kN)	Bending Moment (kNm) [1]
Ends of span	3253	1113
Quarter points	2800	–462
Mid-span	2712	268

Notes: 1. Positive (+) moment indicates a sagging moment and negative (–) moment indicates a hogging moment

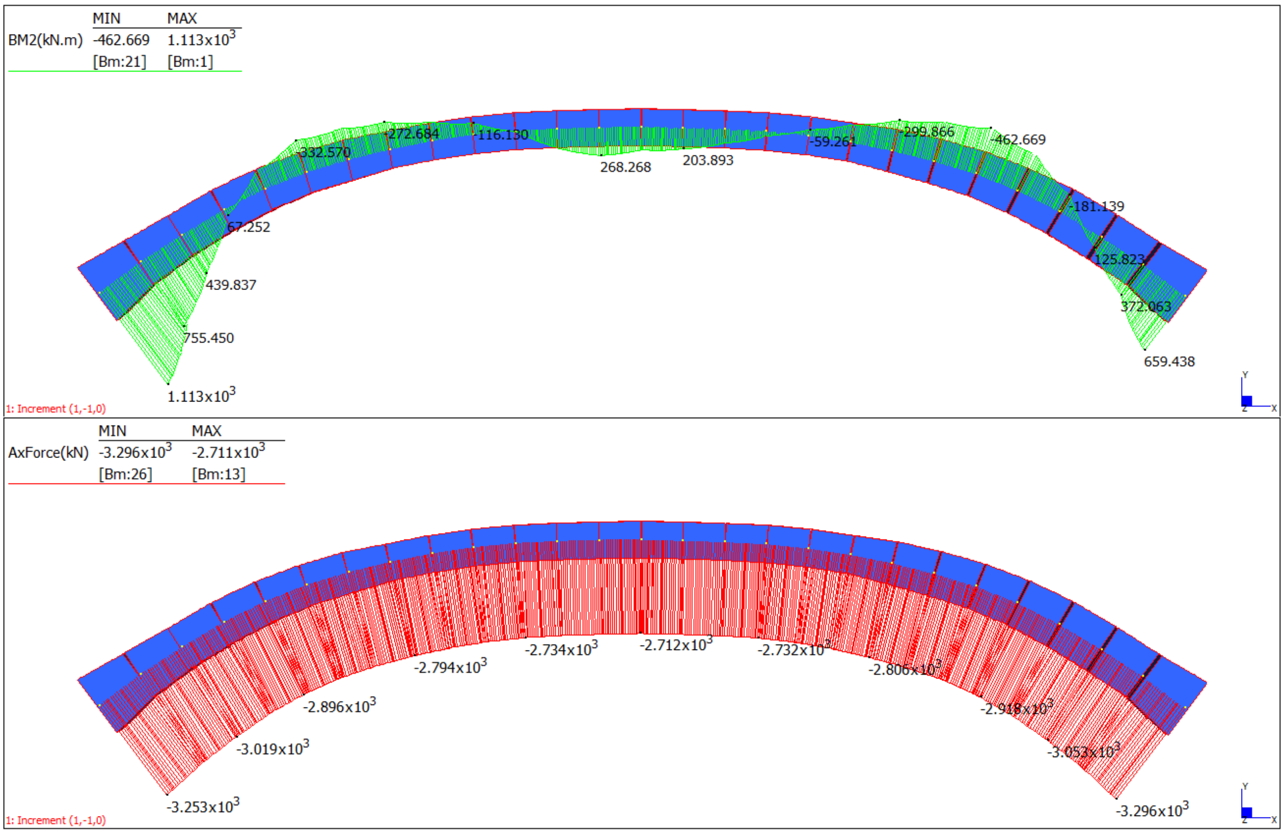


Figure 10 – Fixed Ends – Predicted Ground Movement: Bending Moment Diagram (upper) & Axial Force Diagram (lower)

5.2 Beam-Column Interaction Curves

Figure 11 shows the interaction curve (or axial load – moment diagram) for the mid-span section of the arch ring of Windmill Street Bridge. The curve was developed based on the cross-section of the arch (of unit width) at the location in question (refer Figure 6 (c) in this paper). Interaction (strength) curves were also developed for other arch sections, such as the ends and the quarter points, where the arch cross-section differed in thickness.

Each of the load effects points for axial compression and corresponding bending moment (shown in the tables in section 5.1 of this paper) were plotted on their respective beam-column interaction curves.

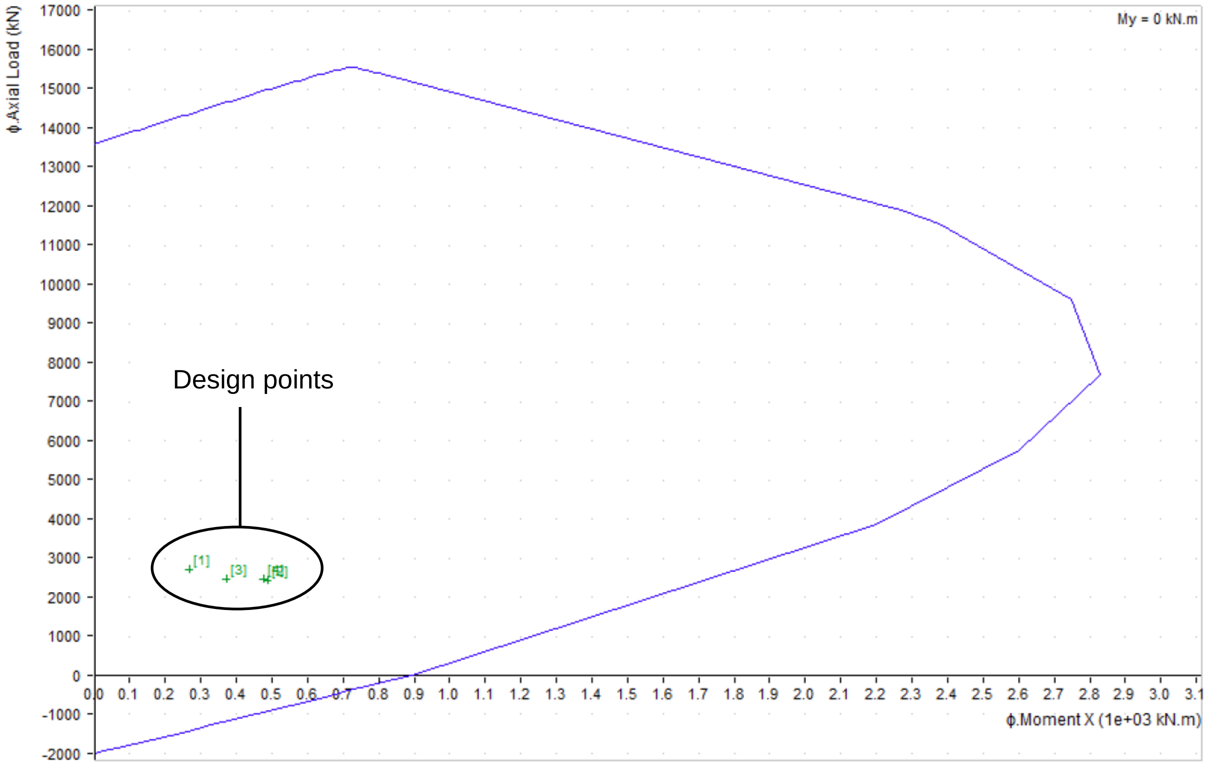


Figure 11 – Interaction Curve for Arch Mid-Span Section

The 'Design Points' shown above represent the following four load cases:

(1) Fixed Ends – Predicted Ground Movement

(2) Fixed Ends – Existing Load Condition

(3) Pinned Ends – Predicted Ground Movement

(4) Pinned Ends – Existing Load Condition

For other arch sections (ends and quarter points), the design points were re-arranged, but were all within the respective interaction curve.

5.3 Discussion

Based on the results shown in section 5.1 of this paper, the predicted ground displacements due to excavation work theoretically induce a degree of redistribution of bending moment through the arch bridges, for both arch end restraint conditions. However, although the bending moment has redistributed, it remains well within the theoretical capacity of the arch, as shown in the interaction curves.

It is noted that the 'column' interaction curves are all for positive moment capacity (that is, sagging). Although this is not the case for some sections/restraint cases, this conservatively shows that the assessments are within the bounds of the lower (sagging) theoretical capacity of the arch structures. The hogging moment capacity of the arch ring is higher throughout the arches, due to the overlay reinforcement arrangement being in the tensile zone when subjected to hogging moment.

6 CONCLUSION

Arcadis' analysis work confirmed that the excavation for the tunneling works will induce a degree of moment redistribution throughout the arch bridges, however, the theoretical capacity of these arches will not be exceeded.

7 REFERENCES

- Ref 1 – *The Structural Restoration of the Hickson Road Bridges*, Stephen Burkitt, presented at a seminar entitled *Building with Shotcrete*, jointly organised by Concrete Institute of Australia and Australian Underground Construction & Tunnelling Association, March 1997.
- Ref 2 – *A Simplified Load Rating Method for Masonry and Reinforced Concrete Arch Bridges*, J.S. Kim, R. Garro & D. Doty. AREMA 2009.

8 AUTHOR BIOGRAPHY

Ken Maxwell is a Technical Director, Bridges with Arcadis Australia Pacific, Sydney, Australia.

Ken graduated Bachelor of Engineering (Civil, 1st Class Honours) from the University of Technology, Sydney and Master of Engineering Studies (Structural and Foundation Engineering) from the University of Sydney. He has been involved in the inspection, assessment, concept design and detailed design of road and railway bridges for over 31 years, having designed over 85 bridges. Ken is a Fellow of The Institution of Engineers, Australia, a Chartered Professional Engineer (Civil and Structural) of The Institution of Engineers, Australia, and a member of the International Association for Bridge and Structural Engineering. He is accredited with Transport for NSW as a Subject Matter Expert (Structural), accredited with Australian Rail Track Corporation as Designer/Verifier/Approver of bridge design projects, and accredited to undertake Third Party Works Independent Design Review of bridge design projects on behalf of John Holland Rail.