# EPPING TO THORNLEIGH THIRD TRACKING PROJECT M2 MOTORWAY AND DEVLINS CREEK UNDERBRIDGE ALTERNATIVE DESIGN INNOVATIONS, SYDNEY

*Vincent Scolaro*
*Technical Director, Civil Structures Engineer*
*BE, University of NSW*
*MES(Structural), University of Sydney*
*Dip of Arbitration & Mediation, University of Adelaide*
*Beca Pty Ltd*

*Daniel Tofful*
*Civil Structures Engineer*
*Bachelor of Civil Engineering & Infrastructure (1st Class Hons), RMIT University*
*Beca Pty Ltd*

*Laura Chen*
*Civil Structures Engineer*
*BE(Hons), University of Canterbury*
*Beca Pty Ltd*

The Epping to Thornleigh Third Track (ETTT) project is a key component of the Northern Sydney Freight Corridor program. The ETTT project involves the construction of six kilometres of new and upgraded track within the existing rail corridor between the Epping and Thornleigh stations. The new third track separates northbound freight from frequently stopping passenger trains with the intent to provide additional northbound paths for freight trains, which reduces waiting times for freight trains and increases the reliability of both freight and passenger services.

Beca was initially engaged by the ETTT Alliance to carry out value engineering on the reference design and develop an innovative alternative design.

Through innovations in both the design and the construction methodology, the alternative design simplified the scale and complexity of the bridge and approach embankment works. These innovations included bridge construction staging and continuity of the girders, infill diaphragms in the girders, and the construction staging of the main retaining structure. The result was significant cost savings for the contractor and client through reducing the number of spans in the bridge and the amount of temporary works required throughout construction.

## 1 INTRODUCTION

The Epping to Thornleigh Third Track (ETTT) project is a key component of the Northern Sydney Freight Corridor program. The ETTT project involves the construction of six kilometres of new and upgraded track within the existing rail corridor between the Epping and Thornleigh stations. The new third track separates northbound freight from frequently stopping passenger trains with the intent to provide additional northbound paths for freight trains, which reduces waiting times for freight trains and increases the reliability of both freight and passenger services.

The ETTT Alliance was formed by Transport for New South Wales (TfNSW) to deliver the project with partners Leighton Contractors and Lend Lease. Beca was initially engaged by the ETTT Alliance to carry out value engineering on the reference design and develop an innovative alternative design.

The reference design consisted of a new rail bridge over the M2 Motorway and Devlins Creek, and extensive temporary and permanent retaining walls along the approach embankments. The proposed rail bridge was a seven-span incrementally launched post-tensioned concrete box girder, with an overall length of 203.8m and span lengths between 18.9m and 34.5m. The bridge was located adjacent to the existing tracks and followed the curved horizontal alignment. An additional shorter span to the north of the M2 motorway was required as the launching bed to suit the construction methodology. All spans south of the M2 Motorway are built within a steep, marginally stable existing rail embankment. Two additional spans were provided to the south of Devlins Creek to avoid interaction with the existing embankment. This resulted in extensive temporary works and retaining walls within the constrained site to facilitate construction of the bridge.

The alternative design for the M2 Motorway and Devlins Creek Underbridge has four spans with a maximum span length of 37.5m and an overall length of 136.8m as shown in Figure 1. The bridge follows a 650m curved horizontal alignment and crosses an existing culvert over Devlins Creek and both carriageways of the M2 Motorway. The existing convict-built culvert and stone causeway immediately near Abutment A are heritage listed. Abutments and piers were positioned to avoid any interaction with the existing masonry arch culvert and any works within a heritage listed zone.

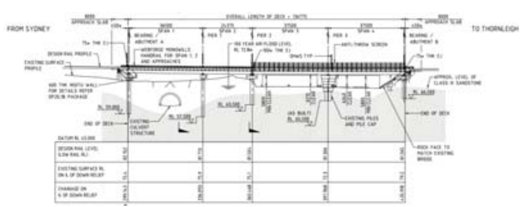


***Figure 1 – Bridge Elevation***

Figure 2 depicts a typical cross section of the bridge. The superstructure consists of three no. 1800mm deep precast prestressed Super-T girders with an insitu deck slab. The track is supported by 300mm minimum thickness of ballast below standard concrete sleepers with provision for a 50mm future ballast lift. Girders are continuous over piers P1 and P3 to sustain the heavy 300LA railway loading. A walkway is provided for maintenance access, emergency egress, to house services and support any overhead wiring structures. Protection screens are provided over the M2 Motorway to meet stakeholder requirements.

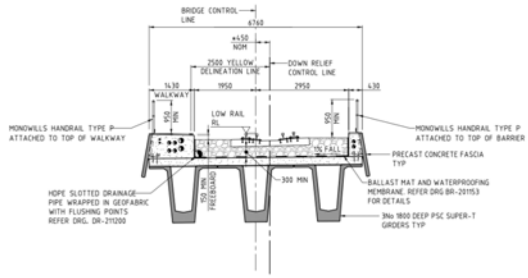



***Figure 2 – Bridge Typical Cross Section***

Abutments are cast insitu and supported by twin bored piles. Abutment A is integrated with the permanent retaining wall RW07b. Abutment B is a spill-through type abutment. Typical piers consist of insitu headstocks supported by twin bored piles. The pier within the M2 Motorway median has a precast segmental post-tensioned column and is supported by an existing foundation. This was constructed as part of the enabling works of the project. The column has a vertical taper to seat the girders on the pier without the need for skewed bearings and longer girder spans. All piles are socketed into the underlying sandstone.

Bridge articulation is controlled by pot bearings and strategically placed expansion joints to minimise rail misalignment and built-up stresses within the track as a result of rail-structure interaction. All movements are guided by pot bearings in the tangential direction. Expansion joints are provided at both abutments and pier P2. Fixed pot bearings are provided at pier P2 (southern side) and at Abutment B to direct longitudinal load back to foundations with shallow underlying sandstone.

An alternative design was also developed for the Abutment A approach embankment. This involved replacing extensive temporary works and a two-tier permanent retaining wall with a single hybrid retaining structure. The retaining structure is offset 12.5m from the proposed third track, extends approximately 90.0m south of Abutment A and is constructed at the base of the existing rail embankment. This alignment avoided any permanent works within the heritage listed zone near Abutment A and impacts on Devlins Creek. Minor temporary works were unavoidable to protect the extremities of the heritage listed zone during the construction phase.

The retaining structure consists of an upper segment of reinforced soil wall which lies on a continuous in-situ blade wall approximately 4.5m high, supported by bored piles. The reinforced soil wall height decreases along the length of the wall. The overall structure has a maximum height of approximately 12.0m near Abutment A, reducing to approximately 4.5m. Discretely spaced tie beams with bored piles were provided to resist lateral loads rather than ground anchors. Expansion joints are provided along the blade wall to minimise the effects of restrained shrinkage and reduce corrosion from stray currents and large voltage potentials. A precast capping beam is placed at the top of the reinforced soil wall to meet urban design requirements. This provides a walkway along the full length of the wall for inspection and maintenance. A drainage channel is also cast into the capping beam to convey surface runoff from the rail formation to a nearby stormwater pit. Figure 3 shows details of the retaining structure

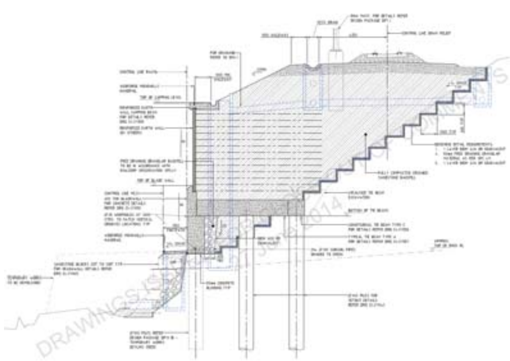


***Figure 3 – Retaining Structure Typical Cross Section***

This alternative design simplified the scale and complexity of the bridge and approach embankment works. This resulted in significant cost savings for the contractor and client. The alternative design has the following benefits:

- Bridge construction possible by crane erection rather than the incremental launching
- Reduced overall bridge length by removal of the launching bed and an additional two spans south of Devlins Creek. These spans were replaced by the permanent retaining wall RW07b
- Removal of the retaining wall ground anchors. These would have been stressed anchors extending beneath the existing and proposed rail tracks
- Relaxed inspection and maintenance requirements for the retaining wall with the removal of ground anchors. No need to perform routine inspections and testing of ground anchors. These would have been located high above ground level and difficult to access
- Solution addresses the stability issues of the existing marginally stable rail embankment
- The design provides a method to construct the bridge in a steep existing embankment

Beca was subsequently awarded the design of the M2 Motorway and Devlins Creek Underbridge, approach retaining walls and associated temporary works. The ETTT project is currently under construction with an anticipated 2016 completion date.

## 2 DESIGN CRITERIA

The M2 Motorway and Devlins Creek Underbridge was designed for the following criteria:

- Single track with 300LA railway loading including derailment scenarios. Mainline freight track classification for fatigue assessment
- Ballasted deck with 300mm minimum ballast beneath sleepers with allowance for future 50mm lift
- Track is continuously welded with standard concrete sleepers and 60kg/m rail
- Maximum train speed of 75km/hr
- Maintenance walkway live load of 5kPa
- Bridge classification Type III for earthquake assessment
- Road traffic collision loads considered for the pier within the M2 Motorway median
- Piers designed for earth pressures from the marginally stable existing rail embankment

The hybrid retaining structure was designed for the following:

- Pressures from backfill and groundwater

- Nominal surcharge of 20kPa from construction equipment
- Railway traffic surcharge due to proximity with the new third track
- Localised pressures from special construction equipment including piling rigs
- Loads transferred from the Abutment A bridge piles

## 3 INNOVATIONS

### 3.1 Bridge Construction Staging and Girder Continuity

Standard simply supported Super-T girders were found deficient for flexure under the alternative design span arrangement and heavy 300LA railway loading. In an effort to overcome these deficiencies girders were made continuous over piers P1 and P3. This was achieved by longitudinal post-tensioned stressbars and passive reinforcement within the deck slab as shown in Figure 4. Additional prestressing strands and passive reinforcement were provided in the bottom flange of the girders to improve sagging capacity. This required the standard bottom flange to be thickened. Fully bonded strands were also utilised as positive moment reinforcement over the continuity joint. These projected from the rear face of the girders and were detailed with swaged ends.

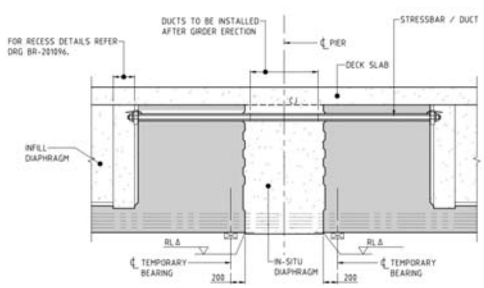



***Figure 4 – Continuity Joint Detail***

Careful consideration was also given to the construction sequence of the girders with the intention to reduce the magnitude of stress ‘locked-in’ on the simply supported non-composite girder. The following construction sequence was developed to fully harness the advantages of continuity:

- Construct retaining wall RW07b and temporary crane pads to facilitate piling
- Perform piling and construct abutments and piers
- Install permanent bearings at continuous piers
- Crane erect precast Super-T girders with permanent bearings attached to the simply supported end. Girders to be placed on temporary bearings at continuous piers
- Cast continuity joint at continuous piers. Perform longitudinal post-tensioning over the continuity joint
- Release temporary bearings
- Cast infill diaphragms once the continuity joint has achieved full strength
- Cast deck slab between 60-100 days after girder casting
- Install precast fascia panels
- Cast walkway and ballast upstand
- Install ballast mat, waterproofing membrane and deck drainage
- Install protection screens, handrails and overhead wiring structures
- Construct approach slabs and off-structure access
- Install ballast and track
- Open bridge to rail traffic

### 3.2 Infill Diaphragms

Conventional precast Super-T girder webs were found deficient under the heavy 300LA railway loading. An innovative solution using infill diaphragms was developed. This involved filling the end bays of the precast Super-T girders with insitu concrete after erection.

Infill diaphragms were provided to:

- Overcome web shear crushing failure under combined shear and torsion
- Comply with crane lifting limits. The use of longer precast end blocks was not feasible
- Reduce reinforcement congestion in the precast girder webs by providing supplementary shear reinforcement in the infill diaphragm

The contractor and precast manufacturer were involved in the development of the infill diaphragms. Special consideration was given to the arrangement of shear reinforcement within the infill diaphragm, shown in Figure 5. In an effort to utilise standard Super-T void formers, supplementary shear reinforcement was confined within the infill diaphragm. Full depth shear reinforcement extending into the bottom flange of the Super-T girders with or without couplers was considered. The precast manufacturer deemed this too difficult and expensive.

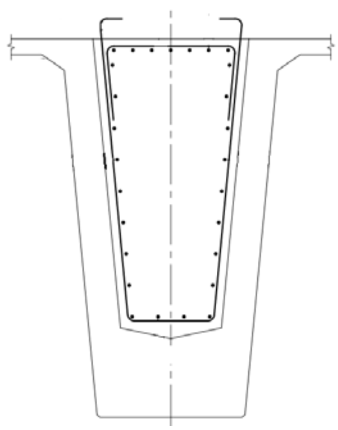


***Figure 5 – Infill Diaphragm***

Infill diaphragms were provided for all girders except the simply supported end of the shorter span. For these, the precast girder webs alone were found to be sufficient. The design of the infill diaphragms was based on the preceding methodology.

Consider the following free body diagram of the composite Super-T girder over the length of the infill diaphragm at a continuous pier:

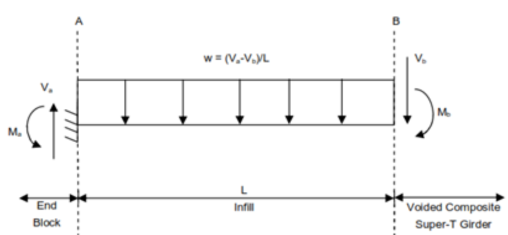



***Figure 6 – Free Body Diagram at Infill Diaphragm***

- Without an infill diaphragm the composite Super-T would resist the total shear force
- With an infill diaphragm the total shear force is resisted by both the composite Super-T and the infill diaphragm. The distribution of shear force between each component depends on relative stiffness and deflection compatibility along the length of the infill diaphragm
- The infill diaphragm must act compositely with the Super-T girder to distribute shear force between each component and prevent overstress of the precast Super-T girder webs. To achieve this all interfaces between the composite Super-T girder and the infill diaphragm must be capable of transferring horizontal and vertical shears
- The amount of shear force resisted by the infill diaphragm may be limited by transfer of vertical shear at A or B if solely reliant on interface friction
- The infill diaphragm must be 'locked' with the Super-T girder at section B to ensure deflection compatibility before and after the deck is cast
- Differential shrinkage between the infill diaphragm and precast Super-T girder will result in interface slip, separation and loss of composite action with the infill diaphragm if unrestrained. Potential separation is demonstrated in Figure 7:

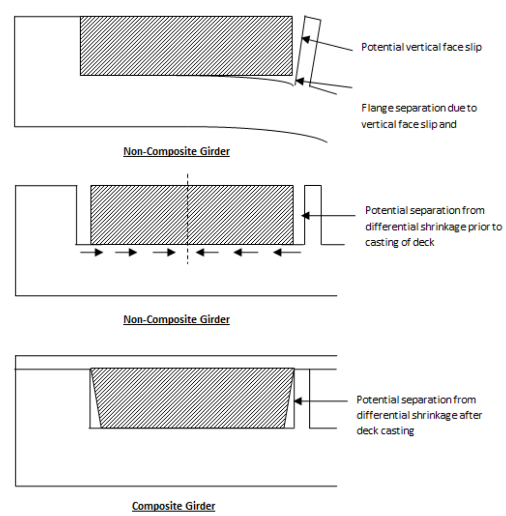



***Figure 7 – Potential Separation from Differential Shrinkage***

The infill diaphragm has been designed with the following features to promote composite action with the girder:

- Deflection compatibility and transfer of vertical shear is achieved at section A by coupled reinforcement bars projected from the end block and concrete friction
- Deflection compatibility and transfer of vertical shear is achieved at section B by concrete friction alone. A recessed shear

key may be provided in the vertical face of the intermediate diaphragm should vertical shears be large. Coupled reinforcement bars cannot be used given the 150mm thickness of the intermediate diaphragm

- The non-composite precast Super-T girder is designed to resist the shear force from the wet weight of infill diaphragm concrete
- Once the deck is cast the infill diaphragm is 'locked' with the composite Super-T girder and deflections become compatible. Shear reinforcement ties the infill diaphragm and deck to the precast Super-T girder. The deck slab is designed to resist a clamping force as a result of deflection compatibility along the length of the infill diaphragm
- Longitudinal shear at the interface between the precast Super-T bottom flange and the infill diaphragm from the design shear force is resisted by concrete interface friction. All internal faces of the end Super-T void are deliberately roughened.
- Longitudinal slip from differential shrinkage is resisted by a recessed shear key formed into the precast Super-T girder at each end of the infill diaphragm. The key follows the profile of the Super-T void. The tensile force generated by differential shrinkage of infill diaphragm is resisted by bearing of the infill diaphragm concrete onto the formed recess. Adequate reinforcement has been provided to prevent shear key failure.

A simple frame model was developed to investigate the vertical shear force transfer between the infill diaphragm and composite Super-T girder. The model was based on the Vierendeel truss mechanism shown in Figure 8.

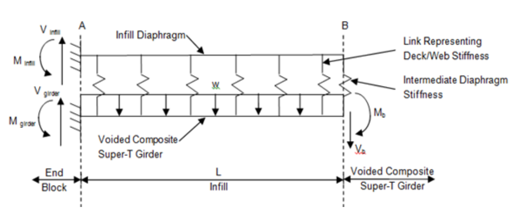



***Figure 8 – Free Body Diagram of Vierendeel Truss Mechanism***

All loads were applied to the composite Super-T girder. The model relies on link members to transfer shear from the composite Super-T girder to the infill diaphragm. If the link members do not have adequate stiffness no shear force will be transferred to the infill diaphragm. Link members were applied along the full length of the infill diaphragm to represent the clamping force of the deck slab. An additional link was provided at section B to represent the stiffness of the intermediate diaphragm.

Applied loads were based on the shears and moments taken at each end of the infill diaphragm from the global grillage model. Shear force was assumed to vary linearly along the girder and was applied as a uniformly distributed load. Support reactions were used to confirm total shears and moments and ensure the model behaved consistently with the global grillage.

Additional finite element modelling (FEM) was undertaken to verify the results of the above Vierendeel Truss mechanism model. Strand7 was used to develop a three-dimensional brick model of the composite Super-T girder with the infill diaphragm shown in Figure 9. Loads and boundary conditions are consistent with the previous analysis.

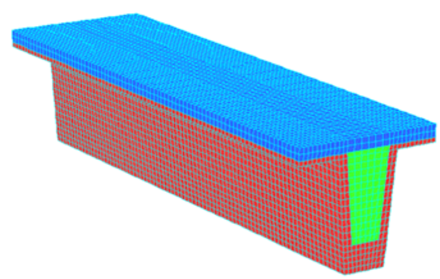


***Figure 9 – Brick Model Geometry***

The model was found to correlate well with the simple Vierendeel truss model. Support reactions were checked and agree with the global grillage model. Furthermore flexural stresses are in agreement with those computed manually for the girder design. The Vierendeel truss model slightly overestimated the shear carried by the infill diaphragm. Model results for a continuous pier are provided in Table 1 below for comparison:

***Table 1 – Model Results***

| Action | Element | Vierendeel Truss | FEM Model |
|---|---|---|---|
| Shear | Infill Diaphragm | 1660 kN | 1400 kN |
| | Composite Super-T | 2755 kN | 3015 kN |
| | Total | 4415 kN | 4415 kN |
| Moment | Total | -28010 kNm | -28040 kNm |

The FEA shear stress distribution results are shown in Figure 10 and Figure 11.

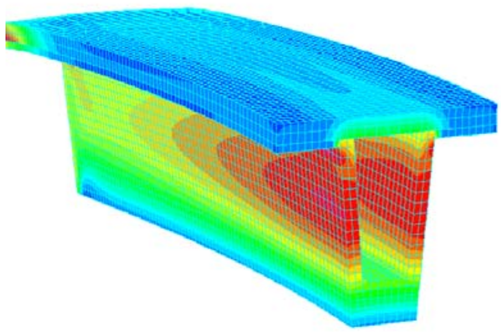


***Figure 10 – Shear Stress Distribution (Composite Super-T)***

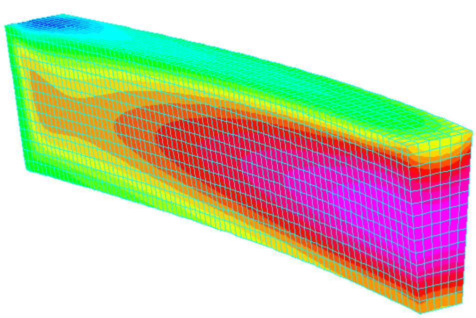


***Figure 11 – Shear Stress Distribution (Infill Diaphragm)***

### 3.3 Retaining Structure RW07b Construction Staging

The retaining structure is constructed within a complex and constrained environment. The solution was developed through extensive collaboration between the construction and design teams.

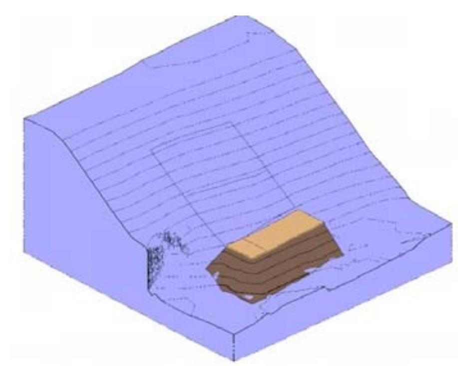
The solution accommodated the following constraints:

- Located within a steep existing rail embankment with a 1:2 slope
- Close proximity with Devlins Creek
- Close proximity to the heritage causeway and convict-built stone culvert
- Presence of existing and decommissioned services
- Requirement for the existing local council access road to be maintained
- Permanent access path required along the full length of the structure for future inspection and maintenance
- Avoid the use of active ground anchors beneath existing and new tracks

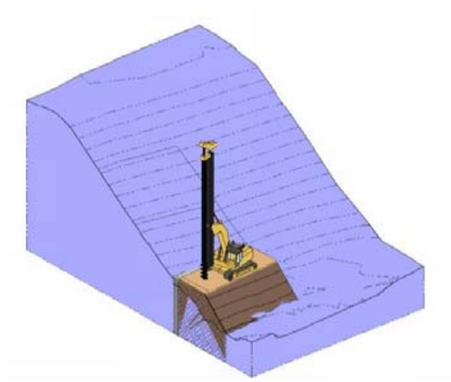
The design of this structure was heavily influenced by the construction sequence of the approach embankment. The blade wall was designed as a vertical cantilever prior to the casting of tie beams. Under this partially constructed condition the wall was designed to support backfill to the underside of the tie beams and surcharge pressures from any construction equipment including the piling rig. Once the tie beams achieve full strength all proceeding loads are applied to the continuous frame system. Resultant design actions are based on the summation of these stages. The system experiences some long-term redistribution as load initially applied to the cantilever wall creeps onto the continuous frame system.

The hybrid retaining structure is constructed in the following sequence:

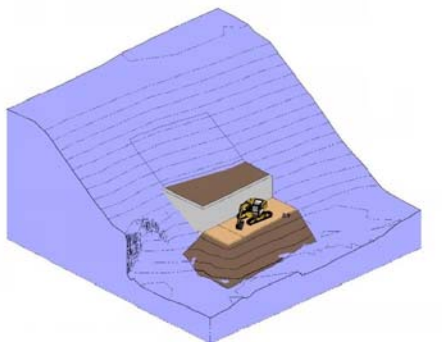
1. Install protection for heritage causeway near Abutment A
2. Perform temporary works



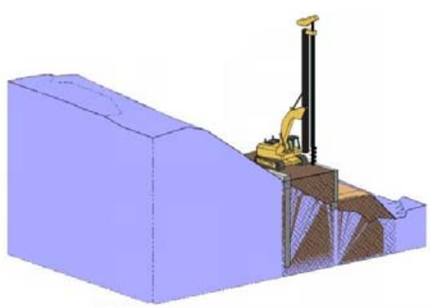
3. Carry out lower level piling works



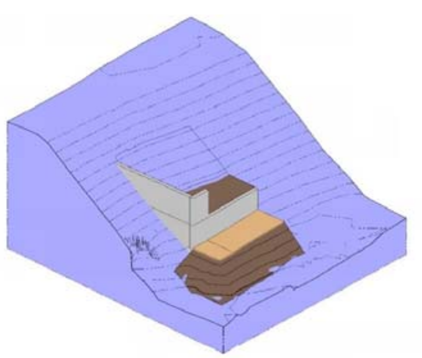
4. Construct pilecap and blade wall to reinforced soil wall level
5. Backfill behind blade wall to underside of tie beams



6. Carry out piling works for tie beams

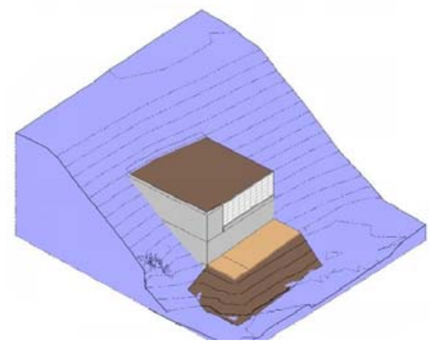


7. Construct tie beams
8. Backfill behind blade wall to reinforced soil wall level

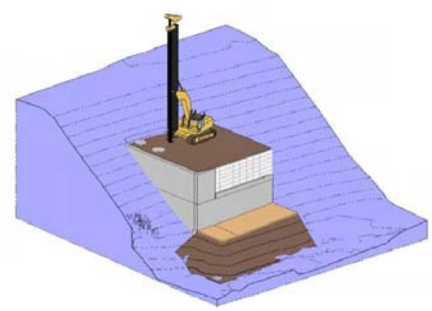


9. Construct reinforced soil wall for remaining wall height. Backfill and compact progressively as panels and soil straps are installed.

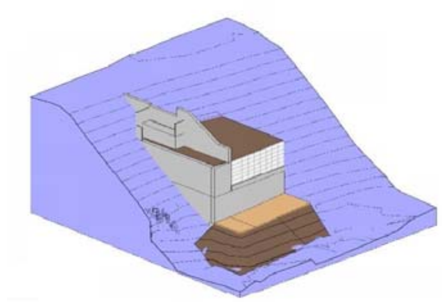
   Sequence stages 5 to 9 will repeat along the wall as the blade wall and tie beams step up in increments.



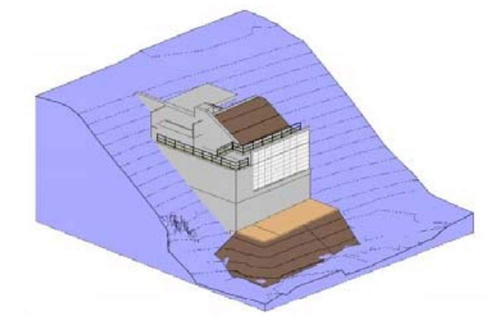
10. Advance piling rig and carry out Abutment A piling works



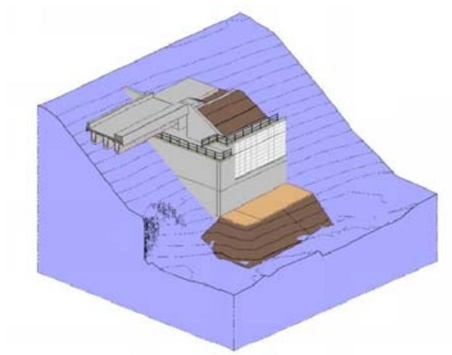
11. Construct Abutment A including wingwalls and access platform



12. Install precast capping beam
13. Construct rail formation
14. Construct bridge approach



15. Construct bridge



A temporary crane pad was required to facilitate the construction of pier P1 and erection of girders for the two southern spans. Pier P1 is positioned half way up the existing rail embankment. The temporary crane pad consists of an embankment formed to the underside of the pier headstock and is constructed beside the westbound carriageway of the M2 Motorway. A temporary retaining wall was required to prevent the crane pad formation from spilling out onto Devlins Creek. The crane pad is also located over an existing drainage retention basin. The basin was covered by a temporary platform before backfilling. This protected the basin from any damage and ensures it remains operational during the construction stage.

***Figure 12 – Temporary Crane Pad***

## 4 CONCLUSION

The major outcome of this work involved the simplification of the reference design, a large incrementally launched post-tensioned concrete box girder to a shorter four span Super-T bridge. The project was delivered in a tight timeframe and resulted in significant cost saving for the contractor and client. The design facilitated construction of a bridge within a steep marginally stable existing rail embankment. The design also addressed stability issues associated with this embankment.

## 5 REFERENCES

[1] TfNSW Services Brief, Document no: 1812574_14 V3.0, September 2012.

[2] AS5100-2004 Bridge Design Set