Design of Cut and Cover Structures for Legacy Way, Brisbane

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Abstract The Legacy Way tunnel, constructed by Transcity JV (Acciona / BMD / Ghella) for Brisbane City Council, will commence at the Western Freeway at Toowong and extend 4.6km to the northeast, joining the Inner City Bypass at Kelvin Grove. The mainline tunnels for Legacy Way comprise two bored, two lane tunnels. The tunnels will be driven from west (Mount Coot-tha Road) to east (Victoria Park Road). This requires below ground box structures at the western and eastern portals to facilitate launching and extraction of the Tunnel Boring Machines, respectively. Transition structures are required to lower the road alignment on either side of the tunnel. Directly in front of the tunnel portals cut and cover structures are constructed. On the western side this cut and cover structure is situated at the edge of Mt Coot-tha Botanical Gardens and supports a landscaping area. On the eastern side Victoria Park Road will be supported by this structure. The cut and cover structures are designed as two span roof structures with precast, prestressed, Super T girders supported on secant pile walls on either side of the buried structure and a central support on discrete columns. Critical details for the design were the water tightness of the structure as well as achieving a durable low maintenance construction. A low maintenance solution was found by fixing the girders to the headstocks which form the connection between the precast girders and the secant pile walls and central support. As a result, bearings and expansion joints are not required. This paper describes the design principle and details of the connections of the roof structure to the substructure. It reflects on the design process as well as detailing of the connections.
Introduction

Sustainability is one of the main goals for designs of engineering structures and hence, also of the Legacy Way Tunnel project in Brisbane. Although the conference is addressed to sustainable bridge design, the same principles apply to the design of underground structures. For the design of the cut and cover structures of the Legacy Way tunnel design principles have been used to achieve a durable design with a 100 year design life for major structural components. An integral structure was designed, i.e. the main structural components are rigidly connected. As a result, components which require maintenance over its lifetime, expansion joints and bearings, have not been used in the design. The structural integrity is achieved with careful detailed reinforced connections. By using precast members where possible high quality is guaranteed. For example, the majority of the roof structures comprise precast, prestressed concrete girders (Super Ts). The composite slab as well as the connections to the headstock is cast in-situ to form a rigid connection.

The project is constructed by Transcity JV (Acciona / BMD / Ghella) and designed by an alliance of Cardno, GHD and URS. Construction started in April 2011 and completion is planned for the end of 2014.

It is noted that there is some detailed discussion around design elements that are included on the following pages and yet to be certified by the Independent Verifier and approved by Brisbane City Council, and hence some of these details could change in the coming weeks during design documentation review.

Project Overview

The Legacy Way Tunnel is the third major tunnel project in Brisbane in recent years. A previous major tunnel project was the CLEM7 tunnel which connects Brisbane’s north with the southern suburbs providing a tunnel under the Brisbane river. Currently also under way is the Airport Link project which connects Brisbane’s Domestic and International Airports with the Inner City Bypass. The Legacy Way project is regarded as the continuation of the Airport Link project connecting the Inner City Bypass with the Western Freeway.
Major sections of the Legacy Way are the western connection, the main tunnel and the eastern connection. The western connection comprises the transition from surface level of the Western Freeway to a depth of approximately 10m at the western portal including a 170m long cut and cover structure. This transition comprises the overpass of the Eastbound carriageway of the Western Freeway, an open roof section and the main cut and cover tunnel including the launch box which provides the facilities for launching the Tunnel Boring Machine (TBM) during construction. As a transition of the cut and cover structure a reinforced concrete portal block and a pipe umbrella is constructed which supports the soil near the surface before the tunnel is fully captured in rock and the TBM, as well as later precast segments, are sufficient to support the rock. The main tunnel comprises two bored tunnels with a diameter of 12400mm and a length of 4.6km. On the eastern side the tunnel portal enters into a 20m deep cut and cover structure to provide the transition into an open trough structure. In addition, this section supports the Inner City Bypass and the connection to Victoria Park Road.

To provide sufficient clearance for the Inner City Bypass realignment two bridges have to be extended. Of those two bridges the elevated Inner Northern Busway is closer to the cut and cover structure and has to be extended by an additional span of 20m. Parallel, only 5m apart, a pedestrian bridge connecting the Brisbane Grammar School on the southern side with their sport fields on the northern side is extended also by approximately 20m.

**Western Connection**

The western entry to the Legacy Way Tunnel comprises the transition of an open trough structure constructed with secant pile walls on either side into a partially buried box structure. The secant pile walls are continued in this section and form the abutments of a two span roof structure comprising a reinforced concrete slab with a central support on discrete columns. The western part of the overpass is covered with a landscaping formation accentuating the entrance to the tunnel.
where the central section accommodates the overpass of the Eastbound of the Western Freeway.

**Fig. 2.** View on Daylight Portal Western Connection

**Fig. 3.** View on Pergola Section and Western Freeway Overpass

Before entering the main cut and cover tunnel a section comprising discrete concrete beams is constructed which is similar to a pergola and allows ventilation. This section was introduced to shorten the length required to be artificially ventilated. The pergola beams act as a prop to reduce deflections and moments of the secant pile walls.

The main cut and cover tunnel is approximately 140m long and comprises secant pile walls, a central support on discrete columns and a roof constructed with prestressed, precast Super T girders completed with a cast in-situ composite slab. A waterproof membrane is provided to protect the structure against water ingress and a 125mm thick concrete protection slab constructed to ensure that the membrane is not ruptured when excavation takes place in the future.
A section of approximately 70m is left open during construction to allow assembly of the TBM. A concrete slab is cast as a base slab for the launching procedure. TBM sections and precast segments are lowered into this section with a heavy lift portal crane.

The TBM portal comprises a reinforced concrete block which provides sufficient capacity to withstand the loads acting during the launching process of the TBMs into the main tunnel. Initially, sheet piles are driven into the ground to support the loads of loose soil overlaying rock. Temporary anchors are required to ensure stability of the sheet pile wall. The portal block is constructed in front of the sheet piles. Once the ground anchors and sheet piles corrode, the earth pressure is acting on the portal block which is supported laterally by the secant pile walls and the central column support. In addition, rock dowels are provided to mitigate the risk of wedge failure.

**Eastern Connection**

Similarly to the western connection the transition at the eastern end is performed with a secant pile wall trough structure which leads into a cut and cover section. However, as the western cut and cover structure covers the same lengths of the East- and Westbound carriageway the covered sections of the Eastern cut and cover structure are significantly different. At the Eastern portal the roof over the westbound carriageway is approximately 125m long and the roof over the eastbound carriageway 63m. Furthermore, the major design constraint for the construction of the eastern cut and cover structure is the interface with the Inner City Bypass (ICB) and hence, the requirement of diligent traffic staging to perform the works. This staging includes that sections of the cut and cover structure have to be provided during construction to divert the traffic before final backfilling and construction of the final road alignment can take place. In addition, recovery of the TBM’s is a major constraint which has to be considered. It is planned to disassemble the TBMs just outside the Westbound daylight portal independent of the works occurring on top and around the cut and cover structures.
Fig. 4. View on Daylight Portal Eastern Connection

**Other Structures**

Both cut and cover structures include a separate tunnel section on the northern side which is used to extract air from the road tunnels. Those ventilation sections are connected to ventilation buildings on either side of the main tunnel with ventilation tunnels with an area of 40m². The ventilation tunnels are constructed cast in-situ as closed box structures. During construction they are used to accommodate construction traffic.

Finally, two bridge extensions are part of the project. Both bridge extensions are required at the eastern end. The extension of the Inner Northern Bus way (INB) bridge comprises a post-tensioned concrete trough structure with precast units spanning laterally. The major benefit of this structural layout is the opportunity of construction with the least impact on bus traffic. The second bridge extension is required for a pedestrian bridge which runs parallel to the end of the Inner Northern Busway bridge and comprises a steel through truss with a composite, concrete slab.
Structural details cut and cover structures

Secant Pile Walls

The retaining structural element on either side of the cut and cover structures is a secant pile wall. The wall consists of 1200mm diameter piles which are spaced at 1030mm. The overlap is designed to ensure water tightness of the walls considering also tolerances during construction. The horizontal set-out tolerance has been assumed with 25mm. To achieve this higher than commonly allowed accuracy 1000mm deep concrete guide walls are provided for drilling of the secant piles. The secant piles comprise bored, cast in-place piles. Firstly, the firm piles with no or small reinforcement are constructed with 2060mm spacing. Secondly, hard piles are subsequently constructed with a steel casing that cuts through the firm piles and the surrounding soil or rock. The hard piles form the main structural element. They are designed to carry the majority of the load and are therefore more heavily reinforced and extend as deep into the rock as required for lateral and vertical loads and structural stability. In turn, the firm piles are designed to arch between the hard piles and to extend sufficient under excavation level to ensure the required water cut off. At Legacy Way high moments have been calculated in the top of the secant pile walls in some areas which required firm pile reinforcement in the top 5.0m of the wall.

The exposure classification of the secant pile walls is B2 to Australian Standard AS5100. Consequently, the minimum concrete strength for reinforced items is 40MPa. The concrete for reinforced primary piles have been designed with a delayed strength gain of 56days for ease of drilling secondary piles. Unreinforced primary piles consist of 25MPa concrete to reduce the strength gain further. A minimum strength when drilling the secondary piles of 5MPa is required to ensure that the strength of the primary piles is higher than the surrounding soil/rock. In addition to the spacing requirements of the piles, it is planned to drill through firm piles and grout behind the wall in case leakage occurs.

It is planned to erect the girders into place as soon as possible. In sections where no anchors are required the girder/headstock connection is constructed before excavation occurs. In anchored wall sections excavation and installation of anchors is required before the girders are fixed to the headstocks to reduce opening moments. Final excavation is planned once the fixity is achieved.
Secant pile walls have been selected over diaphragm walls as diaphragm walls are not commonly used in Australia and have been assessed to be not cost-effective for this project. Other techniques such as contiguous piles, soldier pile walls or cantilever concrete walls have been disregarded as cost intensive groundwater management on site would have been necessary.

**Roof Structure Western Freeway Overpass**

The geometric constraint for the spans of the Western Freeway Overpass is the clearance envelope for the two carriageways of the Legacy Way which results in a spacing of the supports of approximately 13m laterally to the Legacy Way alignment. The geometry of the roof structure is dictated by the clearance envelope of Legacy Way under the structure and the road geometry of the Eastbound of the Western Freeway. A highly skewed main slab in plan and a deck with varying thicknesses are therefore required to address these constraints. It was decided to construct this part of the cut and cover structure with a cast in-situ, reinforced concrete slab. The loading of the structure comprises besides self weight, traffic loads and other transient effects a soil cover which was introduced following the landscape and urban design and to achieve an impressive entry to the Legacy Way project from the Western end. Following the high skew of the roof slab and the varying loads including traffic loads a 3D-beam model was used for the design which allowed accounting for non-linear soil behavior, i.e. compression only springs have been used to model the soil. Images of the structure are provided in Figures 2 and 3.

Top-down construction is adopted for this overpass. Once the secant pile walls and the central supports are constructed the roof is reinforced and cast on ground.

**Roof Structure Western cut and cover section**

The roof structure consists of two spans supported at the ends by the secant pile walls and in the middle by a continuous suspended headstock on columns. The main supporting elements are pretensioned Super T girders which are made composite and continuous with a cast in-situ slab. A typical cross section through the cut and cover tunnel is shown in Figure 5.

The figure shows a section through the launch box, i.e. the section where the Tunnel Boring Machines are assembled. During construction this section of the roof will not be completed until the TBMs have been assembled and launched.
Tunnel and precast segments for the fit-out of the tunnels are lowered into the box with a portal crane at this location.

The method of construction was chosen considering the following:

- The benefits of using precast elements for speedy erection have been considered as Super T girders are well established and cost effective.
- The in-situ slab over the Super T girders has been detailed in a way to ensure the composite girders become integral with the supporting pile walls at the ends and continuous over the middle support. The continuous structure is more effective in supporting all subsequent loads, some of which are substantial, e.g. nominal 1m of fill and 25kPa to cater for possible future development loads.
- Making the roof structure integral with the supports is favorable as no bearings are used and therefore bearing maintenance and replacement requirement is eliminated. The roof structure is buried and bearing replacement would be practically impossible.
- Waterproofing membrane details are also simplified by making the roof structure integral with the supports as there are no joints which can move and rotate.

Due to clearance requirements the spans vary along the length of the cut and cover structure. Based on span arrangement, sequence of erection and geotechnical conditions, seven representative locations have been selected for analysis in order to rationalize the design process.

The computer models were created in RM bridge analysis software as two dimensional frames incorporating a slice from the tunnel length equal to the 2.2m overall flange width of one typical Super T girder.

Only the roof structure was modeled. The interaction with the pile wall and the central headstock was accounted for by introducing supports at these locations.

The translational and rotational stiffness of these supports, particularly at the interface with the secant pile walls, was proportioned to account for the soil structure interaction between the piles and the adjacent soil. A separate model for the above mentioned chainages was created by geotechnical engineers using the software package Phase 2. The support stiffness in the RM models was calibrated to ensure the two models, if loaded with the same loads, calculate forces of a similar magnitude at the interface junction. A few iterations were required until this was achieved with reasonable accuracy. Allowance was made for some sensitivity by varying the stiffness of the supports.

Any load effects resulting from activities within the pile walls, e.g. excavation and anchor stressing or backfill operations, were calculated using Phase 2, and applied to the RM model as imposed support displacement and rotations.
All remaining load effects were applied directly to the RM models, taking into account the sequence of construction and the time dependent effects, resulting from the girders becoming composite and integral with the pile walls, which changes the structure from simply supported to a statically indeterminate, continuous structure. The ability of the software package RM Bridge to handle such complex problems has been utilized.

**Girder / Headstock Connection**

Converting simply supported pretensioned girders like Super Ts into continuous structures occurs rarely in everyday practice and presents some challenges. Firstly, constructing the connections is complex due to access and construction staging requirements combined with the need for cost effective and timely delivery. Secondly, consideration has to be given to the sequence of the structure build-up and all time dependent effects associated with it.

In detailing the connection between the roof structure and the secant pile walls the requirement for flood protection during construction, particularly along the open box for the installation of the TBM's, had to be considered. A temporary bund wall was incorporated in the headstock to achieve flood immunity at an early stage. The wall limited further the access for fixing the reinforcement connecting the roof girders with the headstock particularly the bottom reinforcement. Therefore the capacity of the connection to take positive (opening) moments was of concern. The analysis showed that once the 1 m backfill is placed, the joint is no longer subjected to opening bending moment; however it had to be ensured that during the intermediate stages such situation did not occur. The level of excavation and the timing for permanent anchor installation had to be considered in order to limit the chances of inducing an opening moment in the connection.
Within the eastern part of the western connection it is not possible to install the backfill within two years after the connection was cast to ensure there was no obstruction for the discharge of flood waters. In this case the bottom reinforcement of the Super T girders has been extended using coupled reinforcement bars to withstand opening moments. This section of the cut and cover structure did not require a bund wall and hence access to install the coupled bars after erection of the Super T girders was achievable.

![Figure 6. Headstock Detail](image)

Figure 6 shows details of the connection between the secant pile wall and the roof structure through the continuous headstock. A single steel dowel was detailed at each girder end which has several functions. During installation it serves as a safety feature preventing the girder from displacement, especially in locations where the girders are installed on a longitudinal slope of the headstocks. In service, the dowel, in combination with the bottom reinforcement where installed, acts in resisting the opening moment in the joint.

The Super T girders are initially erected on steel shims and only the formed holes are grouted to prevent the girders from sliding. Once the central section of the composite slab, inside of 1.5m strips over the headstocks, is cast the space between the girder soffits and headstocks is grouted and the slab/headstock
connection concreted. As a result, of this construction sequence as much rotation of the girders as possible has occurred before making the connection integral.

**Composite Slab design**

The in-situ slab acts predominantly as part of the composite girder cross section as local bending is limited in service when the structure is loaded with 1 m of backfill. The slab is mainly utilized as a container for reasonably heavy reinforcement required for girder hogging moments at the supports. The thickness of 225mm of the slab is selected to accommodate this reinforcement considering congestion.

Due to sudden changes of girder span length and support offsets, there are some locations where two adjacent girders would have a significant differential deflection over a short distance. If the slab is made continuous over these regions, this may lead to overstressing of the transverse slab, and in some instances, the girder flange reinforcement. In order to prevent this overstress, deflection joints between two adjacent girders have been introduced where a sudden change of span length occurs. The joint has been detailed for a 100year design life and is covered with the waterproof membrane. Maintenance issues which occur with expansion joints are therefore not of concern in this instance.

The following Figure shows where the deflection joints are required.

![Fig. 7. Deflection Joint Locations](image-url)
Western TBM Portal

During the tender design the Western TBM Portal was designed to comprise of a secant pile wall and stub tunnels which results in a very time consuming process to launch the TBM. Discussions regarding an improvement of this procedure resulted in an innovation comprising the use of sheet piles, a pipe umbrella (canope tubes) and a reinforced concrete block as shown in Figure 8.

![Image](image.png)

**Fig. 8. Cross-section Western TBM Portal**

Initially, sheet piles are installed to support the higher lying soils and a road overpassing the tunnel entry. Temporary ground anchors are required to ensure lateral stability. The soil in front of the sheet piles is then excavated and when the roof level of the tunnel is reached steel pipes are installed and filled with concrete to support the loose soil above the first section of the tunnel before radial precast segments are installed. Once the excavation in front of the sheet piles is finished a concrete block is cast to facilitate launching of the TBMs. The concrete block is reinforced to control cracking and to withstand the loads during the launching process and the soil pressure in service.
Once the TBMs have passed the critical first section, a headwall is constructed on top of the concrete block to ensure stability of the loose soils in service. To ensure a safe work environment the lower rows of temporary anchors will remain in place. They will corrode over time which is not critical as the anchor heads are captured in the portal block and headwall. Only the top row of anchors will be destressed and removed at the final stages of the project to achieve clearance for future services. Furthermore, reinforced concrete culverts are used as void formers to reduce the load of fill on the roof. In addition to the above mentioned loads, forces which act on the portal during launch of the TBMs have to be considered. Following detailed discussions between tunnel and structural engineers the corresponding forces have been identified and the structures have been designed for these forces. Forces to consider are thrust forces longitudinally to push the TBMs forward but also forces to resist the torque of the TBMs when drilling. Figure 9 shows a TBM with brackets which act on rails to resist the torque.

Fig. 9. Section through launch slab
Construction

Construction of the cut and cover structure at the western connection by Transcity JV (Acciona / BMD / Ghella) for Brisbane City Council started in April 2011 near the Mt Coot-tha botanical gardens. Piling works commenced in June 2011. Construction of main components of the western cut and cover sections were planned to be finished by end of 2011 to allow launching of the Tunnel Boring Machines. At that point in time the entire shoring works and approximately 60% of the roof structure will be finalized. Construction of the eastern connection started in July 2011.

Conclusion

The main challenges have been to achieve a design which ensures water tightness of the structure and the design of an integral connection of precast girders with secant pile walls. To ensure water tightness of the walls diligent set-out of the piles is required. In addition, repair methods with grouting through the secant pile walls had to be designed.

For the design of the integral corner connection between Super T girders and headstocks thorough calculation of all construction stages including stressing of the anchors in the secant pile walls and the timing of backfilling was considered to achieve a constructible design.

By utilizing secant pile walls and precast girders quick construction is ensured. More importantly, a safe work environment is achieved as no falsework supporting the roof with corresponding safety issues is required.