THE CHALLENGE OF URBAN RAIL INFRASTRUCTURE – THE DESIGN OF WILLIAM STREET UNDERGROUND STATION

Barry Moore
MEng, AUS, MIEAust, CPEng
Maunsell Australia Pty Ltd

SUMMARY

The 72km long Southern Suburbs Railway is currently being constructed from Perth to Mandurah in Western Australia. William Street Station is located in the Perth Central Business District (CBD). It is a 138m long, 22m wide station box constructed within diaphragm walls using the “top down” technique, with excavation to 19m below ground level at its deepest point. The structural design of the station was undertaken by Maunsell Australia using a dedicated team based in Perth. The design task was influenced by a number of factors typical of urban underground construction and some factors unique to the station’s location. This paper describes how the design was undertaken and also describes the multi-disciplinary aspects that needed to be considered to ensure that a co-ordinated structural design was delivered ahead of the construction schedule.

1 INTRODUCTION

The New MetroRail (NMR) City Project consists of the design and construction of a rail link through the CBD of Perth, Western Australia and forms part of an integrated transport system being expanded from Perth to Mandurah by construction of the Southern Suburbs Railway. The design and construction of the system is being overseen by the Public Transport Authority (PTA) on behalf of the Government of Western Australia and has been divided into a number of packages for contracting purposes.

The joint venture of Leighton Contractors Pty Ltd and Kumagai Gumi Co Ltd (LKJV) has been awarded the contract to design and construct the NMR City Project, comprising the 2.3km section of railway alignment from Perth Railway Yard, north of the CBD, to the Narrows Bridge over the Swan River to the south of the CBD (see Figure 1).

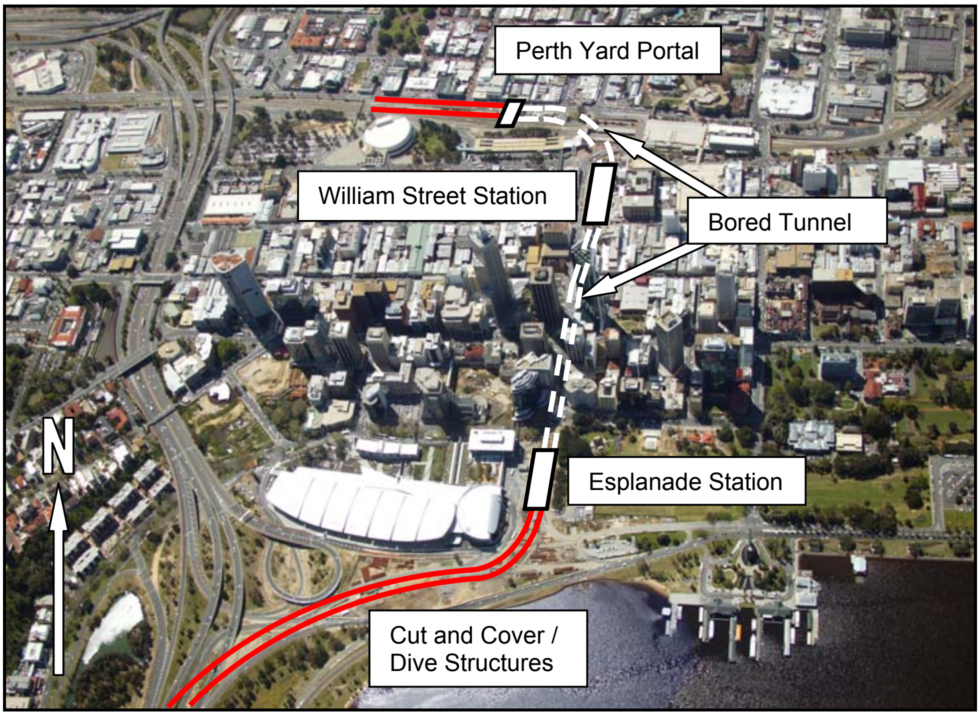

FIGURE 1: Overview of NMR City Project

The contract is inclusive of two underground stations and all associated tunnels, surface works and links to existing infrastructure.

Maunsell, as the lead consultant, are responsible for the design of the permanent works for the City Project, with assistance from their principal sub-consultant, GHD. Detailed design commenced in January 2004 and was substantially complete by the first quarter of 2005.

This paper presents the primary design aspects that have been considered for William Street Station.

2 DESCRIPTION OF THE STATION

2.1 Position And Geometry

William Street Station is 138m long, 22m wide at the southern end, stepping out to 29m wide at the northern end. The station is located beneath a precinct bordered by Wellington Street to the north, William Street to the west and Murray Street pedestrian mall to the south. Existing buildings, including Perth's central Post Office, form the eastern boundary.

The plan position and geometry of the station was subject to a number of constraints. The east-west position was dictated by the need to preserve heritage-listed structures over and adjacent to the station and to optimise development space for the William Street precinct. The north-south position was restricted by the Horseshoe Bridge, a heritage listed structure, to the north, and the Murray Street Mall to the south. The minimum length of the station is set by the need to accommodate a six-car trainset.

At the northern end of the station the Wellington Building exists, which is a three-storey heritage listed structure. This building is to be retained whilst the new station is constructed beneath it. The width of the station at the northern end was widened to enable the perimeter diaphragm walls to be constructed outside of the building's structure. Also at the northern end, a pedestrian link is to be constructed, joining William Street Station to Perth's existing central station. Figure 2 shows an overview of the station layout.

2.2 Internal Layout

The station has two main levels. There are two platforms, 16m below ground level at the southern end, serving northbound and southbound trains. Above, there is a concourse level connected to the platforms by stairs, escalators and a lift.

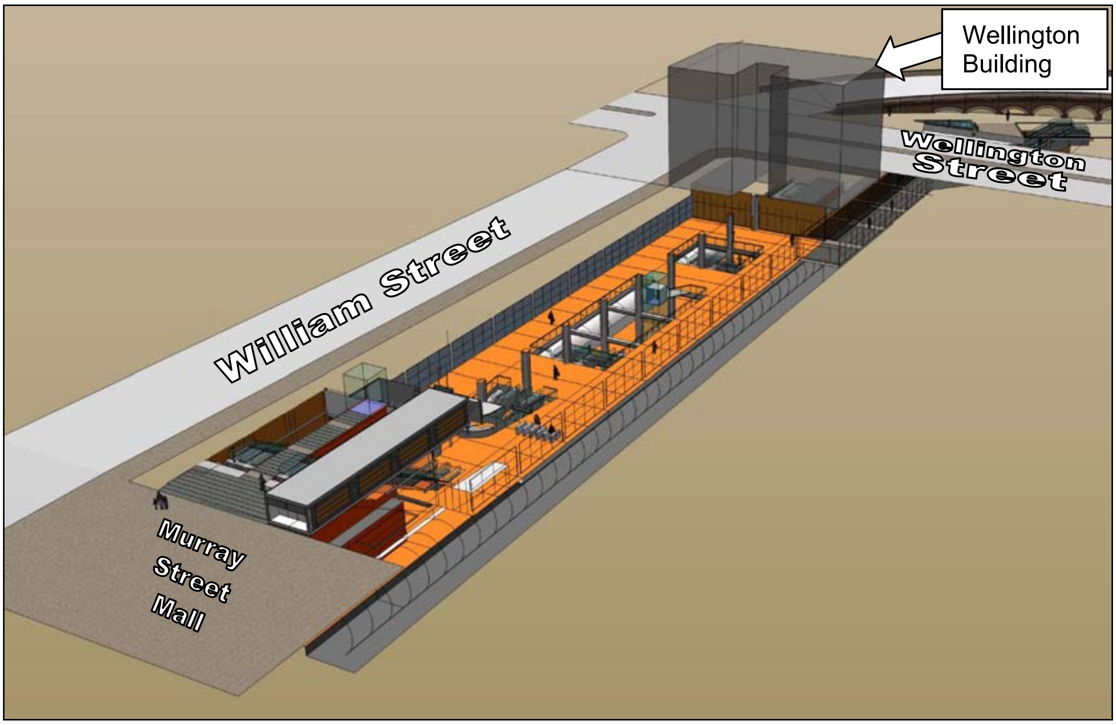

FIGURE 2: Overview of William Street Station showing concourse level exposed

The concourse, at 10m below ground, serves the purpose of providing a public area for ticketing and access, and a “back of house” area for plant rooms. Passengers access the concourse of the station from escalators, stairs or a lift from Murray Street Mall, or from the north via the underground link to Perth Station. In addition to the public access points there are emergency evacuation stairs at either end of the station. Figure 3 shows a section through the station.

2.3 Construction Technique

William Street Station is being constructed using the “top down” technique, utilising diaphragm walls as both the temporary works forming the excavation for the station, and as the permanent structure. The advantages of this methodology are that the land required for the construction of the station is minimised, it is the most effective way to build a station under an existing building and the relatively stiff diaphragm wall section acts to limit long-term settlement around the station. In addition, strict limitations were placed on noise and vibration in the CBD, making the use of sheet piles undesirable.

Two roads and a pedestrian mall, all of which must remain operational, bound the station, therefore keeping the site as small as possible was an essential requirement. In contrast, Esplanade Station, the next station to the south, is to be built using the “bottom up” technique within strutted sheet piling.

3 DESIGN CRITERIA

3.1 General

The design brief for the station stipulated that the design be in accordance with AustRoads Bridge Design Code (ABDC). It was identified that not all elements of the station could be designed using this code and alternatives were proposed where necessary.

Throughout the construction phase the northern roof slab will be loaded by the Wellington Building. The load and the resulting deflections of the roof slab will be controlled by application of reaction forces to minipiles beneath the building, through the use of flatjacks.

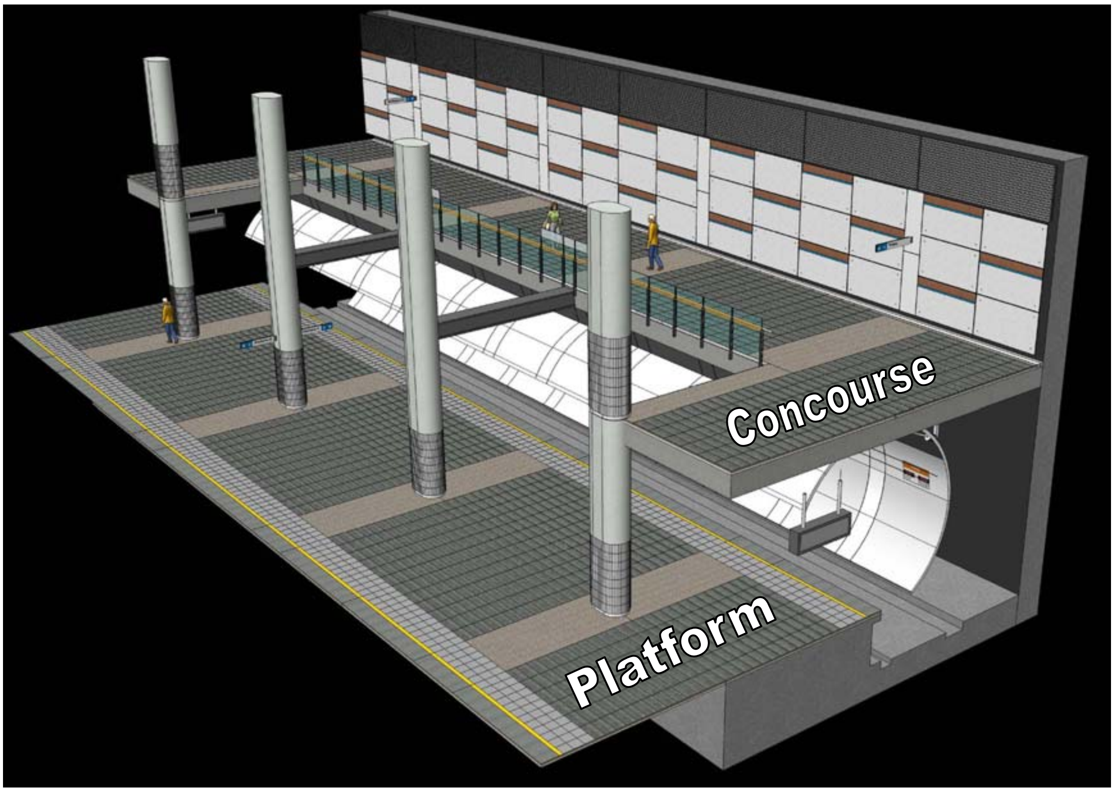

FIGURE 3: Section through William Street Station

3.1.1 Permanent case

All internal slabs and staircases are subject to pedestrian live loading of 5kPa and a finishes allowance of 2.4kPa. In plant room areas a live load of 10kPa is allowed for, increasing to 25kPa for transformer rooms.

Train loads are based on the maximum works train axle load of 190kN. In reality, due to the massive nature of the base slab, vertical train loads were not critical in the station design. However, all vertical support elements in the station, such as walls and columns are to be either protected from train impact or designed to withstand an impact load normal to the rail centreline of 1500kN, and a load parallel to the centreline of 3000kN. The central columns are protected from train impact by the platforms, which are designed to withstand these impact forces.

3.1.2 Geotechnical

The diaphragm walls are designed to resist lateral loading from the surrounding ground in both the temporary and permanent cases. It is during the construction phase, and the excavation of the station, that the diaphragm walls resist the most critical load cases. These lateral forces are transmitted into the slabs that act as props to the diaphragm walls in the temporary and permanent case. In the permanent case the concourse is designed to resist a force of 1600kN per linear metre. In addition, the station is designed to resist an uplift force generated by its displaced volume in the watertable and by soil heave due to fluctuating groundwater levels. Resistance is provided by a combination of skin friction on the barrettes and diaphragm walls and minipiles socketted into the underlying bedrock.

3.1.3 Development loads

Following construction of the station the area above will be opened up to development. The station roof, diaphragm walls and vertical support elements are designed to allow a two-tiered development of 3 storeys on the west side of the station and 6 storeys on the east. These requirements increase the vertical loads on the diaphragm walls and columns by in excess of 100% compared to an undeveloped site.

3.2 Durability

The stations and all other permanent underground structures on the project (such as the running tunnels) are to have a design life of 120 years. All critical structural elements are to have a fire resistance period of 4 hours with all other fire rated walls (for fire separation within plant areas) to have a resistance period of 2 hours.

4 GEOLOGY AND HYDROGEOLOGY

The Perth CBD is located on a terrace of river sediments, called the Guildford formation, which was formed over the last 2.5 million years. The Guildford formation is up to 35m thick and is a highly variable material. There are 3 distinct layers that vary from being clayey to sandy with states in between. An ancient sand dune system overlays the Guildford formation, forming the Spearwood Sands. At approximately 40m in depth from ground level at William Street is the King’s Park Formation (KPF), which is predominantly siltstone and shale.

The characteristics of the geological formations in which the station is to be constructed are crucial as input into the structural design. In particular, the KPF layer will be used as anchorage for the station’s foundation elements.

The watertable in the area of the station is influenced both by the level of the Swan River and a natural groundwater level at the top of the river terrace. The groundwater level over the length of the station is influenced by the flow between these two systems, and there is some evidence of perching over the clayey layers of the Guildford formation as well as under-drained conditions as a result of historic dewatering in the CBD.

5 STRUCTURAL DESIGN

5.1 Diaphragm Walls And Foundations

The foundations of the station are designed to limit settlement and to resist uplift forces resulting from the displacement of groundwater due to the station’s volume. In William Street Station the foundation system is a combination of barrettes (single diaphragm wall panels), minipiles (under the Wellington Building), and the diaphragm walls, with the base slab acting as a massive spread footing. The barrettes extend from base slab to the top of the KPF. From each barrette two minipiles extend a further 10m into the KPF.

The diaphragm walls act as a foundation element in resisting flotation and vertical load effects but primarily their design is influenced by flexural effects and lateral stability during excavation and the control of groundwater levels during dewatering. Diaphragm walls are constructed from ground level and extend to a depth of approximately 30m. A 1m wide trench is excavated by a grab and stabilised with bentonite slurry. Once the required depth is reached the reinforcement cage is lowered into the trench in two sections. The concrete is then poured via a tremmie to form a wall panel.

In order to design the diaphragm walls a detailed analysis of the construction sequence is necessary with each stage being modelled. The deformation response of the wall to bulk earthwork excavation within the station box is a complex problem of soil structure interaction. The lateral deformations and related settlement characteristics are critical aspects for supported, deep, excavations. Two-dimensional sections of the station are initially modelled in FLAC (Fast Lagrangian Analysis of Continua) [1], a finite difference program, which allows non-linear and elastic constitutive soil models and consolidation analysis. The analysis allows examination of time effects during construction and assesses seismic actions on the structure. This modelling forms the benchmark from which to assess the validity of more approximate analyses using WALLAP (a retaining wall analysis program) [2]. WALLAP is used to perform soil/structure interaction analysis for the varying conditions through the construction phase. In conjunction with the WALLAP analysis a plane frame analysis of the station box is undertaken using SPACEGASS [3]. From this analysis the loading and rotational stiffness constraints resulting from the connection of the diaphragm wall to the internal station structure will be determined and input into the WALLAP analysis. Loads are applied for stages of construction, or in the permanent case, which require a series of iterative analyses between WALLAP and SPACEGASS. The FLAC analysis and the two-tier WALLAP/SPACEGASS analyses are used to effectively verify the other's results. Figure 4 shows a typical bending moment output for a diaphragm wall resulting from this analysis. It can be seen that the design effects on the wall vary significantly during the construction of the station.

The above analysis has a significant influence on the level of the elements of the station that prop the diaphragm wall, such as the roof, concourse and base slabs and the requirement of any temporary strutting during construction. The station's internal layout cannot be determined until preliminary diaphragm wall analysis has been completed.

In order to construct the station, and limit the effects of heave on the overall station box and transmission of excessive bending moments into the diaphragm walls, a de-watering scheme is to be implemented. The Scope of Works and Technical Criteria (SWTC) stipulates that any de-watering should not result in more than a 1m drawdown of groundwater in the vicinity of the project works. This is in order to limit any settlement on adjacent buildings or structures. A recharge scheme is therefore employed so that the excavation can be maintained dry during construction whilst limiting the drawdown outside of the station perimeter.

5.2 Bored Tunnel Interface

The railway enters the station from bored tunnels at the northern and southern ends. The tunnels are constructed using a 6.87m diameter Earth Pressure Balance TBM, which will begin its bore in Esplanade Station to the south. The TBM will bore the northbound and southbound tunnels in the same direction and will traverse William Street Station twice. The structural hull of the station box will have been completed prior to the TBM breaking through into the station.

Once "breakthrough" has been completed the TBM will traverse the length of the station box. The base slab is modified to provide a 1000mm set-down for the TBM envelope, and the minimum height

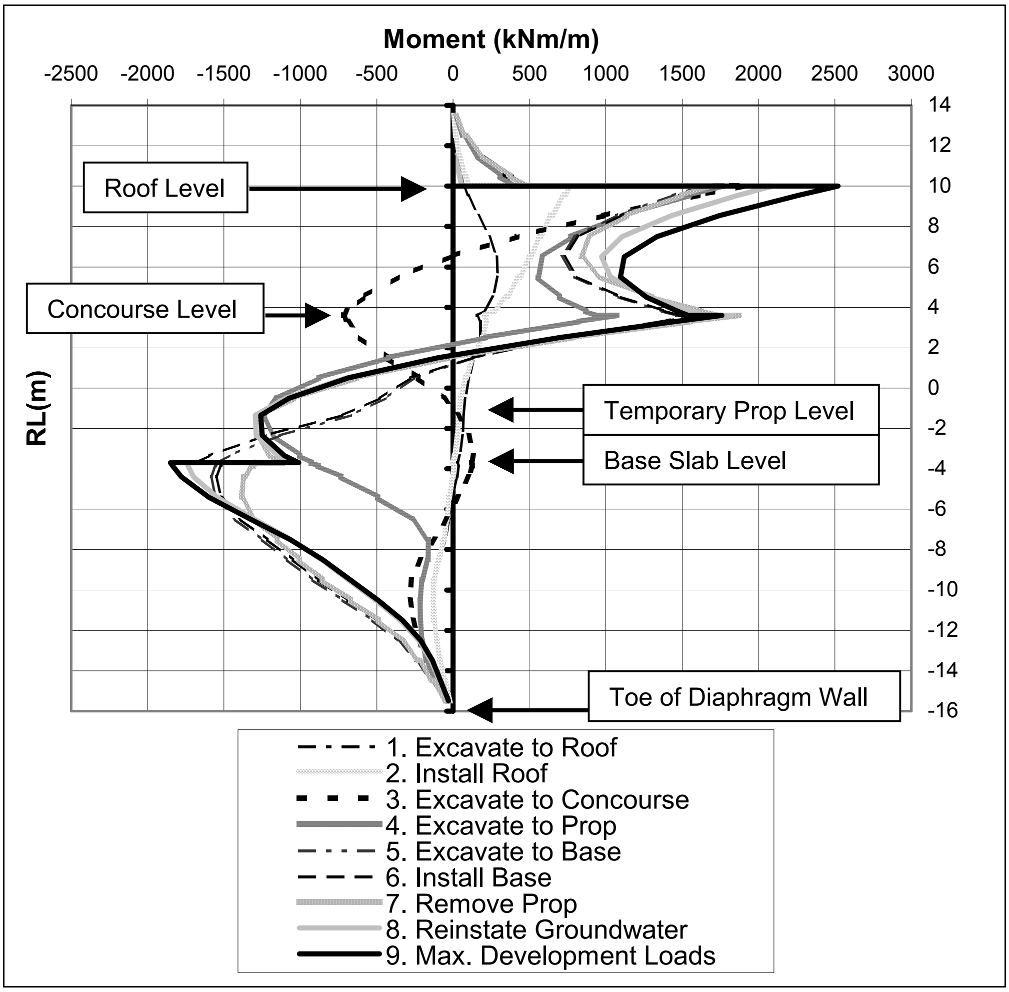

FIGURE 4: Typical FLAC output from a diaphragm wall analysis

between base slab and concourse is governed by this requirement. At the northern end the TBM launches for its next drive to the portal in Perth Railway Yard. The structure of the station must be designed to withstand the applied jacking forces of the TBM against a reaction frame. The reaction frame is bolted to the base and concourse slabs and the TBM exerts 20,000kN of thrust against it during its initial launch.

Following the passing of the TBM a waterproof seal is created between the pre-cast segmental bored tunnel lining and the diaphragm wall of the station by the casting of a concrete closure wall. This forms a rigid joint between the station and the tunnel. The magnitude of differential movement predicted between the tunnel and the station box is no more than 3mm thus negating the need for a flexible joint.

5.3 Wellington Building Underpinning

The Wellington Building is a 100-year-old heritage listed structure on the corner of Wellington Street and William Street. It measures approximately 28m x 28m in plan and William Street Station will be constructed directly beneath it.

An underpinning scheme was devised to transfer the building load onto the new roof slab and then maintain its position during excavation of the station box below. The entire ground floor of the building was removed and 21 minipiles (356mm diameter, grout filled, circular hollow sections) were installed from within the basement. These minipiles were installed within 450mm bores that extend up to 10m into the KPF layer (approximately 50m below ground level). They serve the dual purpose of supporting the building in the construction phase and then providing anchorage for the station to resist buoyancy when operational. Once installed the minipiles are topped with flatjacks capable of jacking to a force of in excess of 3000kN.

Sections of the 1.2m deep roof slab are constructed in the basement of the building. In the temporary case the building and roof slab will be supported by these minipiles. On top of the roof slab a concrete clamping panel runs around the perimeter of the building, cast against the existing brickwork on both sides. Tension tie rods are installed in a 500mm x 500mm grid, and pass through the clamping panel and the existing brickwork. The tie rods are then tensioned to a force of 210kN each, effectively clamping the perimeter wall of the building to the new roof slab. Brickwork below the clamping panel is then remove from the outside, transferring the weight of the building onto the roof slab cast in the basement. The roof slab is then completed, joining that in the basement to the diaphragm walls around the perimeter of the station. Figure 5 shows a typical detail for this work.

Before excavation below begins, the flatjacks at the heads of the minipiles are pre-loaded in the range 1500-2500kN. This serves to both take up approximately 10mm of axial shortening in the minipiles and pre-camber the roof slab by 1-2mm. A further seven 1000mm x 900mm upstand beams are cast monolithically to the top of the roof slab, spanning to the two diaphragm walls. These serve to lock the pre-camber into the roof slab and add additional stiffness in order to control deflection. During excavation, as ground support to the underside of the roof slab and the sides of the minipiles is lost, further deflection will occur. The first jacking sequence is designed to control this deflection so that it does not exceed 1/1500 over the span of the roof. Following the completion of excavation to base slab level a second jacking sequence, adding an additional 500-1500kN can be initiated, if necessary, to bring the roof back up to within +/- 2mm of its original position relative to the diaphragm walls. Permanent columns and support walls are then constructed "bottom up" within the station and the minipiles are removed, leaving the sections below the slab as part of the permanent works.

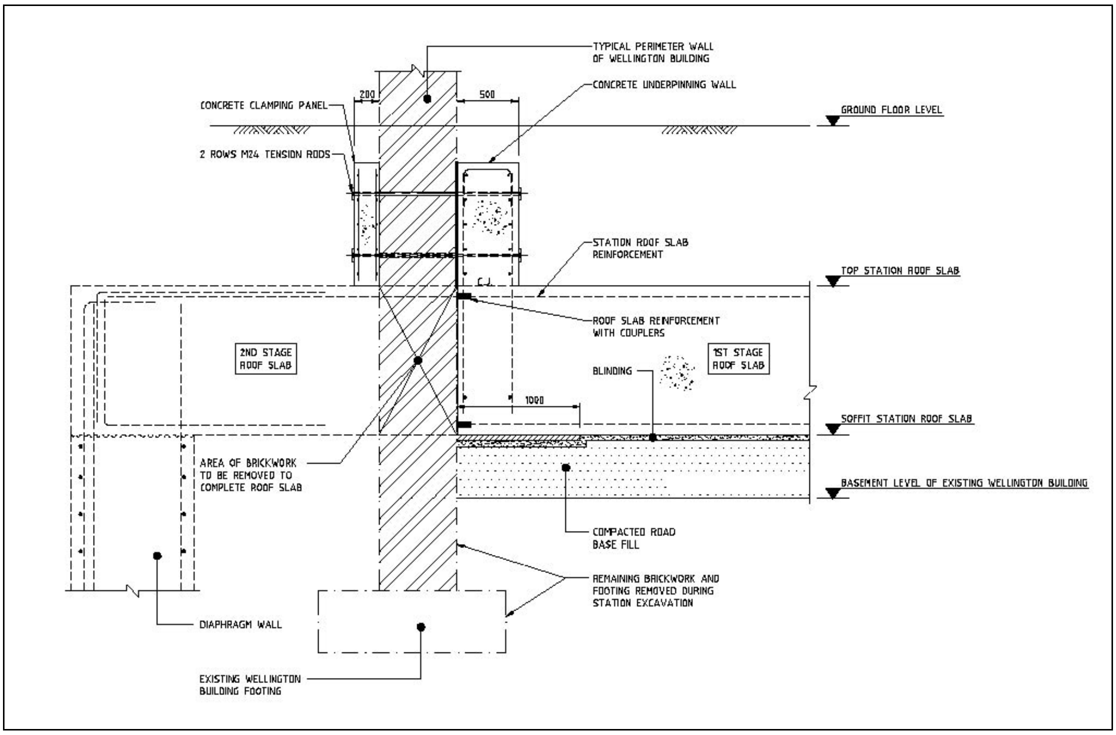

FIGURE 5: Typical detail of underpinning

A number of constraints existed that influenced the solution that could be adopted. The minipiles could only be located in zones that were not traversed by the TBM below. This resulted in longer roof spans between the minipiles and was one of the contributing factors for the requirement of flatjacks. Having to work within the basement of the building also resulted in there being restrictions on the size and position of the minipiles. All elements of the building that contribute to its structural support such as brickwork walls and piers, and steel beams and columns had to be supported with each area requiring a unique scheme to be devised. In addition to the above, the architectural and mechanical scheme for the station required that a vent shaft and the emergency stairs at the northern end of the station rise up into the existing structure of the building. Therefore, an area of the existing ground floor is to be taken up by a concrete box structure with emergency stairs exiting to Wellington Street and a vent shaft rising through the existing structure of the building and venting at its current roof level, 15m above ground. These requirements introduced additional considerations into the overall design of the roof in this area.

The design for this work was undertaken independently and was not based upon similar work undertaken elsewhere. It may not be unique in its undertaking but it is certainly a highly unusual situation that was solved using techniques developed from first principles.

5.4 Concourse

The concourse slab for William Street Station is 600mm thick in the public areas and 750mm in the plant room areas, the increased thickness due to increased loading. This slab is the most critical in the station as it acts as a permanent prop to the diaphragm walls and forms a critical part of the station's architectural and spatial concept.

In the centre of the station there is a 27m long void creating a continuous space from roof to platform level. To facilitate the propping of the diaphragm walls two steel hollow section struts constructed of 50mm and 70mm plate span from the concourse edge to the central steel columns (see Figure 6).

FIGURE 6: Typical steel strut during manufacture

These props must resist a propping force of nearly 17,000kN each. The final form of these props was chosen after an extensive review process with the project architects to work the solution into the architectural concept of the station. The steel box sections themselves are insufficient to achieve a 4-hour fire rating and they will have a fire resistant cladding and finish applied to them.

Although the props and the concourse either side of the station can resist the design forces structurally, the reduced vertical stiffness in this area resulted in the necessary consideration of the dynamic response of the concourse under pedestrian live loading. If the natural frequency of the structure is in the range 1.5Hz to 6Hz then it can become uncomfortable for passing pedestrians [5, 6]. A dynamic analysis revealed that the concourse had a natural frequency in the order of 4Hz. As a result a solution was sought that enabled extra stiffness to be added to the concourse in this area. The depth of the concourse could not be increased because a minimum height between the roof and concourse slab is required to allow the passage of the TBM. Therefore a post-fixed solution was required. The most structurally efficient solution was to install steel props to the underside of the concourse sloping back to the diaphragm wall. These props increase the natural frequency of the concourse in this area to 7.3Hz, therefore solving the problem.

5.5 Waterproofing

Waterproofing of underground stations is critical to ensure the durability of the structural elements and finishes through their design life and to ensure the viability of electrical and mechanical systems and overhead electrification. The ingress of water into William Street Station is to be tightly controlled and managed. Ingress through any structural element forming the hull of the station is to be limited to 2ml per hour per square metre. This will be achieved primarily by applying a number of waterproofing systems to the structure. In addition, there is a drainage system internal to the station to capture and discharge any such leakage.

Potentially, water could enter through cracks in concrete elements but it is the construction joints that are most vulnerable. All construction joints between elements forming the hull of the structure have at least three different water barriers. Typically, these are a combination of a waterproofing membrane, a central waterstop, strips of hydrophilic sealant and re-injectable grout tubes to allow further sealing should future leakage exceed the set limits.

Flexural and early thermal cracks in elements that form the hull of the structure are limited to 0.2mm. Where necessary the reinforcement content is increased to achieve this requirement under service loading.

6 MULTI-DISCIPLINARY INTERFACES

6.1 Architecture

The overall form of the station is driven by a combination of structural requirements and architectural concept. To determine the layout, size and thickness of all the major structural elements close co-ordination between the structural engineer and the project architects was required. This process commenced in the tender phase with further development throughout the detailed design phase.

6.2 Rail

The position and depth of the station is ultimately governed by the rail alignment and by the required transit space applicable to the system's rollingstock. Within the station, the trackform, the access gap, the overhead electrification and the requirements for control of noise and vibration all had an influence on the structural form.

The alignment through the station is flat and straight with the beginning of a transition curve that leads into the tight radius curve of the tunnels at the northern end. For maximum control of rail noise and vibration the track slab bears onto elastomeric pads fixed to the base slab to form a "floating track". In addition, acoustic panels will be fixed to the face of the under-platform walls.

The required access gap between the train and the platform is 50mm, resulting in the necessity for a high degree of control over construction tolerances for the platforms. In addition, a smokehood covers the roof of the train in the station and serves to draw smoke away from the platform area should a train fire occur.

6.3 Electrical And Mechanical

The size and shape of an underground station is heavily influenced by plant and equipment requirements. In addition to all the necessary systems to service a station, such as lighting, power, ventilation and drainage pumps, William Street Station also accommodates tunnel ventilation fans at each end. The spatial planning to accommodate these systems was undertaken during the tender stage and at the start of the detailed design phase, and occurred between the architects, electrical and mechanical designer and the structural engineers. The outcome of this exercise has an input into setting the levels of slabs and the position and thickness of the structural walls and columns.

7 CONCLUSION

Once completed, William Street Station will be one of two new underground stations in Perth. Its location in the heart of the CBD has resulted in the necessity to overcome a number of design and construction related issues. Some are typical of the challenges faced in bringing railways into urban areas, and others have been unique in the constraints that they have placed on the successful delivery of the design.

The design of a number of elements of William Street Station, notably the underpinning and the diaphragm walls, were on the critical path of the construction programme, both in terms or procurement of materials and construction activity. On all occasions the design has been delivered ahead of the construction schedule. This is largely due to the close relationship maintained between the designer, contractor and the client and an effort to keep extensive design changes to a minimum once construction had commenced. Understanding of the criticality of effective management between different disciplines to deliver a co-ordinated design was also recognised as being critical by all parties.

8 ACKNOWLEDGEMENTS

The design and construction of the NMR City Project is being overseen by the Public Transport Authority (PTA) who have kindly given their permission for this paper to be published. Acknowledgement is also given to our client Leighton Kumagai Joint Venture for their support in the preparation of this paper, and to Hassell Spowers Joint Venture (HSJV) for kindly providing some images used in this paper.

9 REFERENCES

1. FLAC v.4.0, Finite difference program, HCItasca, 2000.
2. WALLAP v.5, Retaining wall analysis program, Geosolve, 2002.
3. SPACEGASS v.9.03, Integrated Technical Software, 2003.
4. ACI440.1R-03, Guide of the design and construction of concrete reinforced with FRP bars, 2003, American Concrete Institute.
5. Stoyanoff S and Hunter M, Footbridges: pedestrian induced vibration, RWDI Technotes, Issue 15, April 2003.
6. Newland DE, Pedestrian excitation of bridges – recent results, Tenth International Congress on Sound and Vibration, 7-10 July 2003, Stockholm, Sweden.