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DESIGN AND CONSTRUCTION OF THE NORTHERN APPROACH TRENCH, WATERVIEW CONNECTION

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SUMMARY

Perhaps the best known feature of the NZ Transport Agency's Waterview Connection project is the construction of the twin tunnels being bored in Auckland by the Tunnel Boring Machine (TBM) named Alice. Situated at the northern end of the twin tunnels is the Northern Approach Trench; the structure from which, upon completion of the first tunnel, the TBM was retrieved, turned around and subsequently re-launched to undertake mining of the second tunnel.

This paper outlines the key aspects of the design and construction of the trench's variety of primary structural elements, as well as offering the designer's perspective on the challenges associated with accommodating the TBM and the adopted construction sequence.

INTRODUCTION

Costing NZ$1.4b, the Waterview Connection project in Auckland is New Zealand's largest and most ambitious roading project. By connecting the Southwestern and Northwestern Motorways (State Highways 20 and 16) the project will complete Auckland's Western Ring Route. In doing so, it will provide a motorway alternative that will enable road users to bypass the city centre, easing pressure on State Highway 1 and the Harbour bridge.

The project is being constructed for the NZ Transport Agency by the Well-Connected Alliance which comprises the Transport Agency, Fletcher Construction, McConnell Dowell Constructors, Beca, Parsons Brinkerhoff, Tonkin and Taylor and Japanese construction company Obayashi Corporation.

Half of the new motorway – 2.4km - is situated underground. Through this zone, twin tunnels are being bored by the Tunnel Boring Machine (TBM), named Alice. With a cutting diameter of 14.4m, the world's tenth largest Tunnel Boring Machine is currently constructing the largest road tunnels in Australasia. The TBM was initially launched from the southern end of the project, tunnelling firstly towards the northern portal. In October 2014 it broke through into the Northern Approach Trench, a NZ$50m "cut and cover" structure that provides a transition for SH20 from the bored tunnels to surface level.

This paper focuses on the design and construction of the Northern Approach Trench (NAT) structure. It commences with a high level review of the NAT's function and structural form, before continuing to outline key aspects of the design and construction of the trench's primary structural elements. The paper also highlights the variety of ways in which concrete was used in the trench's construction. It discusses the constraints that made the trench a challenging structure to design and build, as well as offering the designer's perspective on the challenges associated with accommodating the TBM and the on-going tunnelling operations.

SITE DESCRIPTION

The NAT is situated at the northern portal of the bored tunnels in the suburb of Waterview. Its location was governed by the tunnel's vertical alignment and the proximity to the existing SH16. In particular the location was constrained by the need to bring the new section of motorway over and across SH16 whilst also bringing the TBM underneath Great North Road. The NAT is bounded by the presence of Waterview Primary school to the west and Great North Road to the east.

Typically ground conditions consist of Tauranga Group Alluvium overlying competent (SPT N>50) East Coast Bays Formation Rock. The alluvial deposits vary in depth between approx. 8 and 16 meters and typically comprise clay, silts and pumiceous sands. In some areas a layer of weathered ECBF is also present.

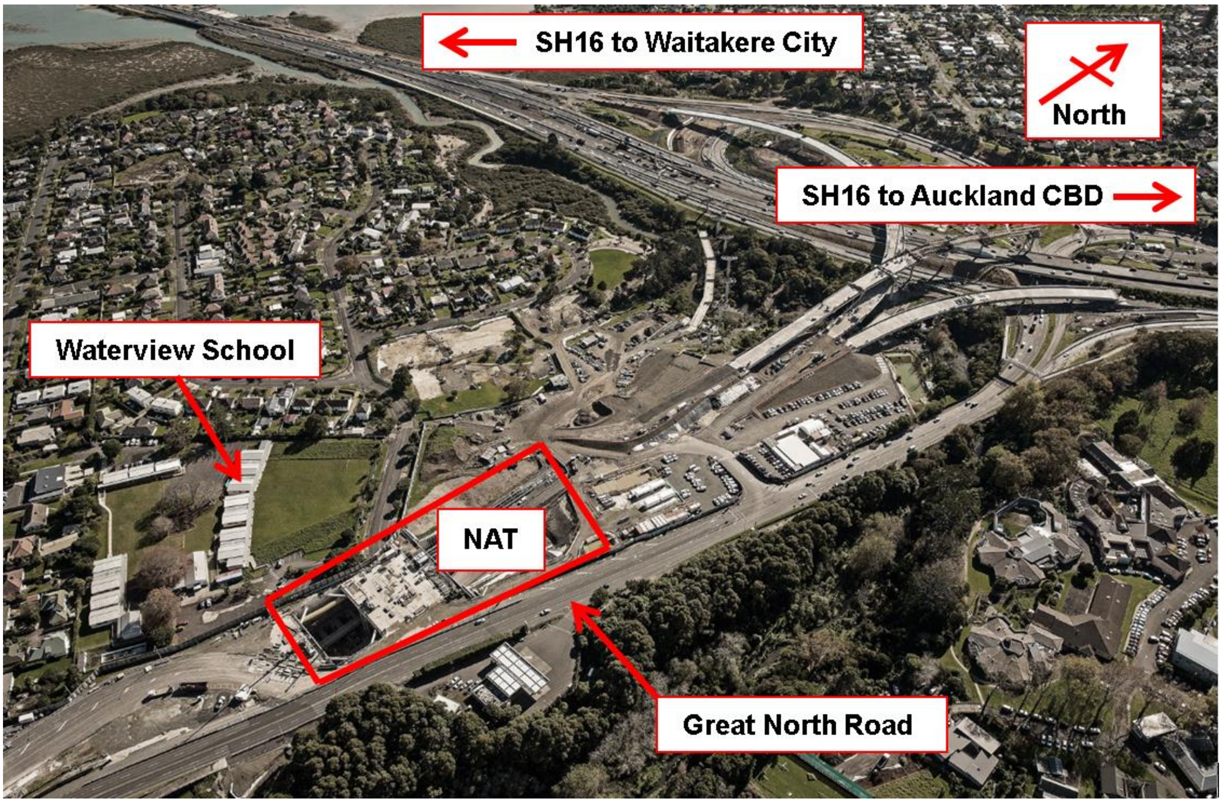


Figure 1. Aerial View of the Northern Approach Trench

FUNCTION & PROJECT REQUIREMENTS

Once completed the Northern Approach Trench will provide the following functions:

- Provide a transition for SH20 from the underground bored tunnels to surface level
- House mechanical & electrical equipment that services the tunnel
- Form part of a ventilation plenum that extracts exhaust fumes from the tunnel
- House a portal drainage sump below the carriageway for collection of stormwater and groundwater inflow to the NAT
- Provide support for a local road (Herdman Street) where it bridges across the structure

During construction the structure also provides a space for the retrieval, turnaround, and subsequent re-launch of the TBM as well as accommodating a number of temporary road diversions where they cross the structure.

The Project Alliance Agreement also included the following constraints on the design and construction:

- Great North Road must remain operational throughout construction
- The trench structure is to be ‘watertight’ to control groundwater levels and flows and ensure that there are no detrimental effects on adjacent properties, buildings, infrastructure and utilities

Figure 2. Architectural Render of the NAT

STRUCTURAL FORM

The NAT is a “cut and cover” structure that comprises of an 83m long section of covered trench and a 40m long section of open trench. The width of the trench varies from 39m to 45m, and it is up to 24m deep at its deepest point. The trench was largely constructed using top-down construction techniques. Consequently a large number of structural elements were installed either before or during the main excavation. The basic structural form of the trench is depicted in Figure 3. Figure 3a comprises elements installed both before and during excavation, whilst Figure 3b illustrates the completed trench, minus architectural cladding & building fit-out.

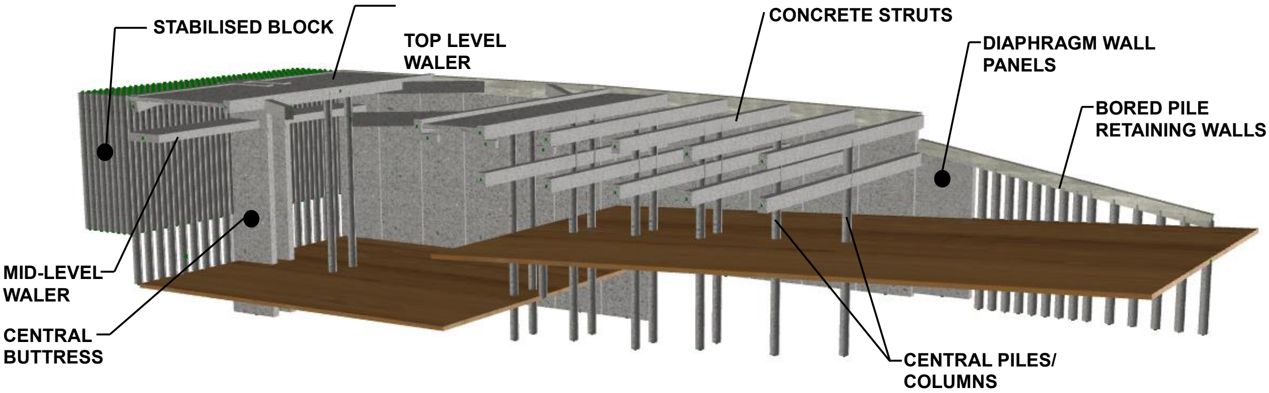


Figure 3a. Structural Elements installed before & during excavation

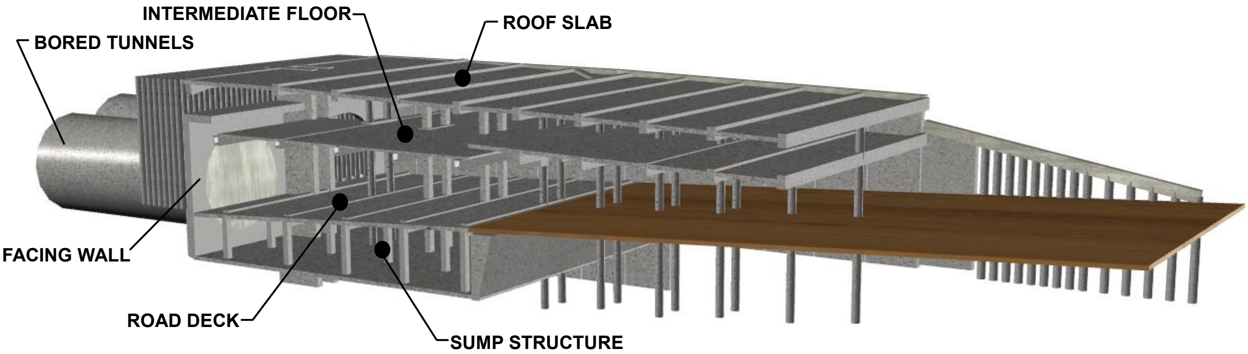


Figure 3b. Completed Structure (minus Architectual cladding & fitout)

The trench is a drained structure and as such does not require a base slab to resist hydrostatic pressures. Instead a network of subsoil drains was provided beneath the carriageways to collect groundwater and drain it to the structure’s drainage sump. Although the trench is drained, the project alliance agreement (PAA) required that ground settlement due to groundwater drawdown be limited to consented limits. The PAA also specified limits as to the amount of allowable water ingress into the structure.

Side Walls

Depending on the retained height, the sidewalls of the trench consist of either a configuration of diaphragm walls; or, where the retained height is sufficiently low, bored pile walls with shotcrete arches. Diaphragm walls are reinforced concrete wall panels constructed in the ground prior to excavation. The walls are propped by a series of reinforced concrete struts or tied back by a configuration of permanent ground anchors, both of which were installed as the excavation progressed.

The toes of the diaphragm wall panels are founded in ECBF rock, and act as cut-off walls to groundwater flow, reducing the amount of water ingress, drawdown, and ground settlement experienced. They are considered to be largely impermeable, however provision was made to collect any leakage through the panel joints and drain it into the structure's drainage sump. Vertical strip drains were provided behind the shotcrete arches of the bored pile walls, these in turn connect into the network of subsoil drains.

Portal Headwall

At the interface between the trench and the bored tunnels (the headwall), the primary framework for resisting retained loads consists of two central buttresses, formed from diaphragm wall panels, and a top level waler, formed by constructing the first section of the structures roof, both of which were constructed prior to excavation. As the excavation progressed a second mid-level waler was also installed just above the crest of the bored tunnel. The framework spans load to the sidewalls and to the base of the excavation.

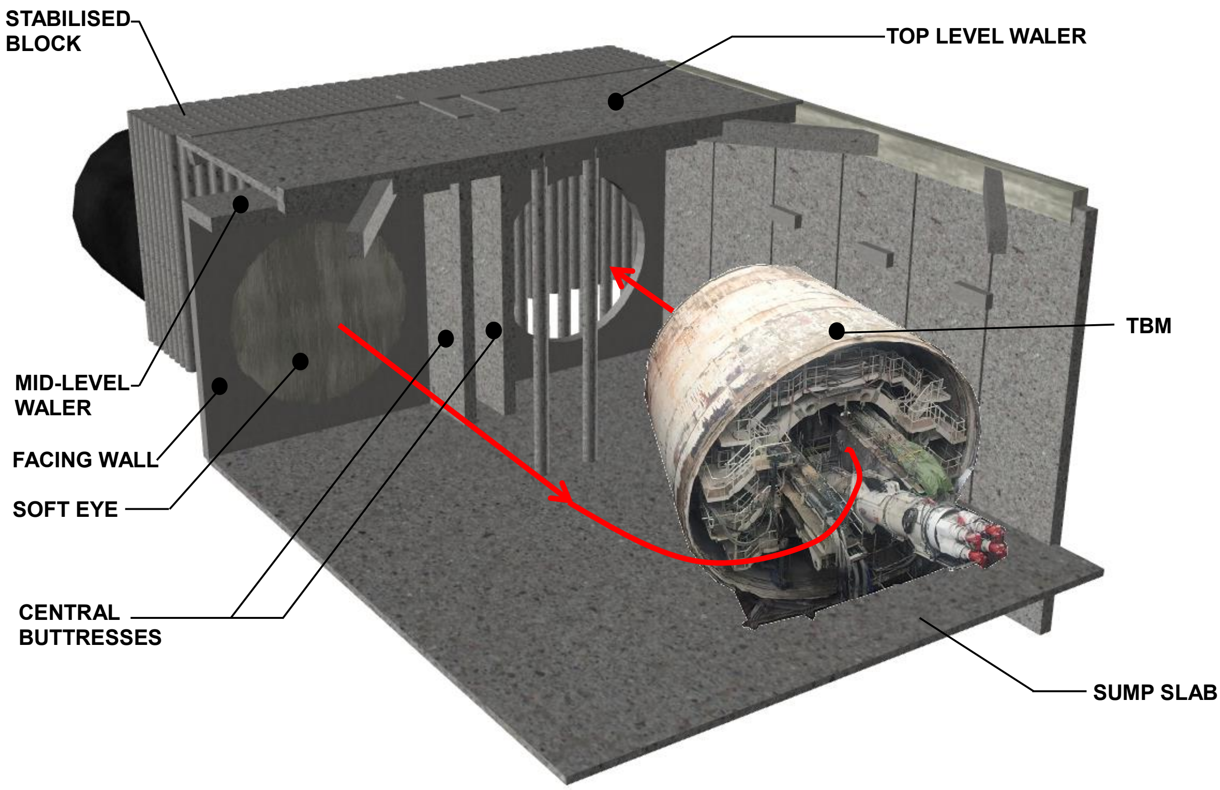


Figure 4. Structural Elements present at the time of TBM breakthrough

At the headwall, the ground in front of the trench was treated by installing a cement stabilised block (Figure 4) The block was constructed from original ground level using a configuration of interlocking Continuous Flow Auger (CFA) piles. In addition to providing a stable face during excavation, the block also provided a zone of stabilised material for when the TBM broke in and out of the trench. During these operations, the TBM was required to run under reduced face pressures. The block enabled the TBM to reduce pressure without generating excessive settlement in the above region of ground.

Upon completion of the trench's excavation, a reinforced concrete facing wall was constructed "bottom up" in front of the stabilised block. The facing wall was installed prior to the TBM's arrival as a means to resist loads generated during the TBM's breakthrough and subsequent re-launch. For the retrieval side, the facing wall included a soft eye: a circular zone of unreinforced low-strength concrete that the TBM could pass through with relative ease.

At the base of the excavation a 500mm thick in-situ slab was installed in order to support the heavy loads generated during the TBM's turnaround. The slab ultimately also forms a part of the structure's drainage sump.

Internal Structure

The turnaround of the TBM required a large zone to be temporarily left clear of structure. Consequently only a limited amount of the trench's internal structure was installed before the TBM's arrival. This included a number of reinforced concrete "propping" beams that were installed by casting against ground as the excavation progressed. In addition to resisting lateral earth pressures, these beams also carry gravity loads from the adjacent floor spans. To support the beams, a number of central columns were also installed "top-down" as bored piles from original ground level. Since the turnaround zone was unable to accommodate the construction of these elements until after the TBM's departure, the sidewalls in this region were instead tied back by a configuration of permanent ground anchors.

After the TBM's departure from the NAT, construction of the remainder of the internal structure commenced. This includes construction of:

- the structures drainage sump,
- a roadway that bridges across the sump
- an intermediate floor suspended above the carriageways
- the remainder of the structures roof

These elements are currently being constructed bottom-up amidst on going tunnelling operations, and are discussed further in the following paragraphs.

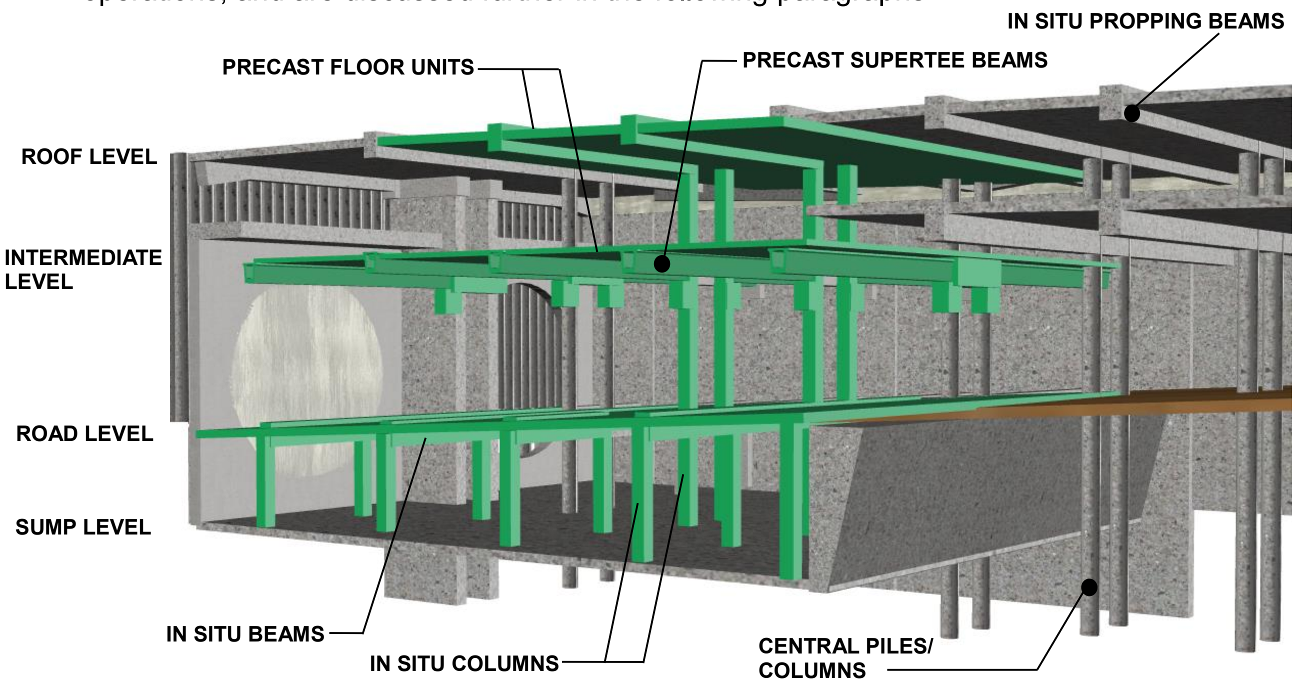


Figure 5. Structural Elements installed after the TBM's departure (elements are highlighted in green)

Drainage Sump

The portal drainage sump is located below road level immediately adjacent to the twin tunnel portal. The size of the sump was largely dictated by the spatial requirements of the TBM. Once complete, the sump will collect stormwater from the trench's catchment area, as well as groundwater inflow from beneath the slab and carriageways within the trench. The collected stormwater and groundwater will be pumped from the sump to a nearby wetland situated to the north of the NAT.

Road Deck

A road deck will bridge over the sump area, ultimately supporting two three-lane carriageways as well as a central corridor that will provide access between the sump, road and intermediate level. The deck comprises of precast prestressed hollowcore units, tied together by a cast in situ topping. The road deck will be supported on reinforced concrete beams which are in turn supported by concrete columns extending from the underlying sump slab.

Intermediate Floor

Situated above the carriageways will be an intermediate suspended floor. Similar to road level, the flooring at this level comprises of prestressed floor units with a cast in situ topping. Typically the flooring will span onto the "propping" beams constructed during the excavation. However, the exception to this is through the turnaround zone where units will instead span onto a configuration of precast Supertee beams. These beams will be craned in from above via the opening at roof level. Once complete, the intermediate level will comprise of two distinct areas; a ventilation plenum that extracts exhaust fumes from the tunnel and a separate area that houses mechanical & electrical equipment.

Roof Level

Finally the opening at roof level will be closed in by constructing the remaining propping beams. These will be constructed at height by temporarily propping back down to the underlying intermediate floor. Flooring, similar to those used at road level (precast planks with in situ topping) will ultimately be installed between the beams. Once complete, Herdman Street, a local road, will be reinstated to run across the roof of the main trench.

SIDE WALLS ANALYSIS & DESIGN

Modelling of the trench was carried out using a combination of both the geotechnical software FLAC & the structural analysis software Spacegass.

The geotechnical model analysed the soil-structure interaction to determine the effects of the lateral earth pressure on the walls. It was also used to determine the required embedment depths of the walls. The analysis took into account each stage of construction and excavation. The full cross section of the NAT was included within the analysis model to account for any out of balance loads acting on the structure. Specifically the geotechnical analysis modelled the following loads

- Static earth pressure
- Earth pressure due to surcharge loads
- Seismic loads due to an assumed acceleration profile of the soil and structure

The Spacegass analysis modelled the gravity loading acting on the floor and roof structures, which also induce bending moments and shears into the side walls. Pattern load checks were carried out to ensure that worst case design actions had been determined. Lateral springs were added to the model to represent the increased stiffness of the walls due to the soil-structure interaction. The Spacegass analysis modelled the following loads

- Dead loads applied to the structure
- Live loads (including traffic) applied to the structure
- Thermal expansion of the structure

The design and detailing of the sidewalls was undertaken following the provisions of NZS3101:2006. The walls primarily span vertically. Crack width limitations of 0.3mm were applied to the design for both durability and to limit permeability.

The design of the diaphragm wall's transverse reinforcement was based on the minimum quantities required for walls by NZS3101:2006 to control concrete shrinkage and temperature related effects. Shear keys were provided between adjacent D-wall panels to prevent any 'unexpected' differential displacement. The dimensions of the shear key were primarily derived to suit the 'stop-end' arrangement used in construction and to accommodate the PVC water stop.

SIDE WALLS CONSTRUCTION

To construct the trench, concrete was used in a variety of different ways.

The diaphragm wall panels were built by undertaking a series of local wall excavations using rope suspended hydraulic grabs operated by heavy cycle cranes. The grab buckets measured 3m in width, were approx. 9m tall and weighed in the order of 19 tonnes. Stability of the local excavation was achieved through the use of the support fluid bentonite. Pre-fabricated reinforcement cages were inserted into the excavation before concrete was then placed via tremie pipes. The lower end of the pipe was kept immersed such that when the concrete rose from the base of the excavation it displaced the bentonite without washing out the cement content.

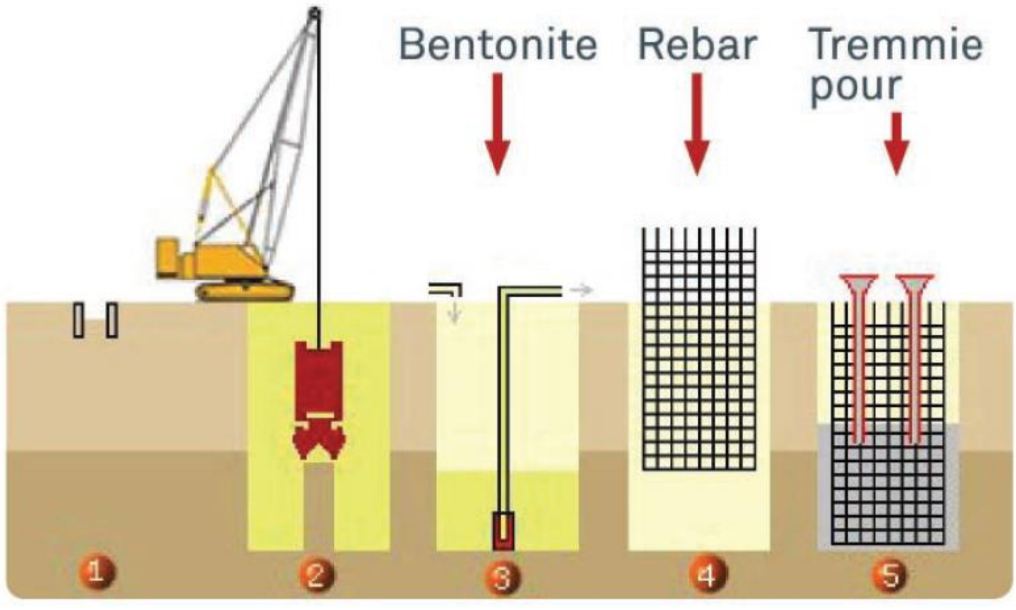


Figure 6. Diaphragm Wall Panel Installation

Diaphragm wall construction is relatively new to New Zealand. It has been used by the Fletcher Construction Company previously, to construct the New Lynn Rail trench and more recently the Victoria Park Tunnel.

The concrete mix used to construct the diaphragm walls had a relatively high cementitous content of 380kg/m^3 to allow for additional fluid inclusion during the tremie pour and a high slump of 220mm to ensure adequate concrete flow given the method of placement. Following this methodology concrete is cast directly against the existing ground; consequently the quality of the wall's surface finish is largely dependent on the type of ground the excavation passes through.

Pile construction was undertaken using conventional bored piling techniques. Similarly to the diaphragm wall panels, the concrete was placed using a tremie pipe and used bentonite slurry to maintain the excavation's stability.

PORTAL HEADWALL ANALYSIS & DESIGN

As discussed previously, a number of structural elements within the headwall area were constructed prior to excavation as a means to resist lateral earth pressures. Once excavated, an additional facing wall was also installed as a means to resist loads generated during the TBM's breakthrough and subsequent re-launch

As the TBM approached the NAT, it applied load to the structure both via the cutting face of the TBM (shown in red) and via friction between the TBMs contact area with the surrounding soil (shown in blue). Whilst operating at full face pressure the headwall was propped by a steel reaction frame that transferred load into the NAT sump structure. The overturning moments on the reaction frame were resisted by a combination of passive resistance on the sump back wall and a configuration of ground anchors stressed through the slab.

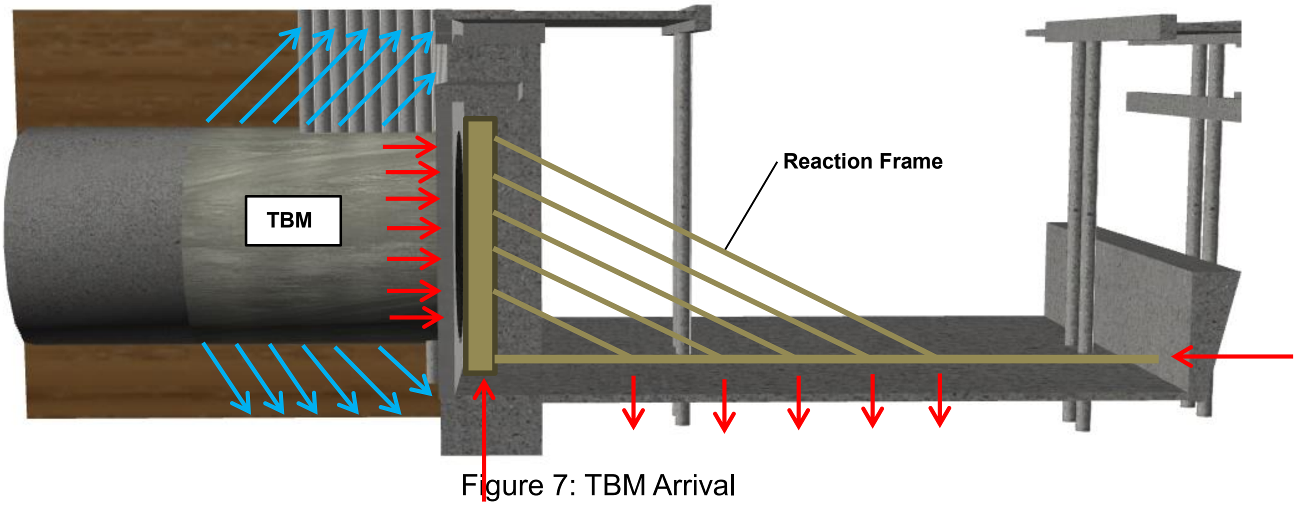


Figure 7: TBM Arrival

Upon entering the stabilised block, the TBM's face pressure could be reduced without generating excessive settlement in the above region of ground. At this point the reaction frame was removed such that the TBM could undertake final breakthrough. During this stage only the cutter head advanced forward, the main body of the TBM remained stationary, minimising the amount of friction generated. Once extracted the TBM was trafficked across the sump slab before being re-launched back towards the south. A similar reaction frame was used during the re-launch.

Analysis of the portal headwall, including the stabilised block, was carried out using the geotechnical software FLAC 3D. The analysis took into account each stage of construction and considered the effect of the TBM at various distances from the NAT. A separate structural model, used as a means of verifying the behaviour of the structure was also prepared using the software SAFE.

As the TBM generated load on structural elements that form part of the permanent structure, it was necessary to impose suitable design criteria on TBM loads. This ensured that upon completion of the TBM's operations, structural elements were left in a condition that enabled them to ultimately form part of the permanent works. Headwall elements were designed to behave elastically under TBM loading. At serviceability limit state the maximum stress in the reinforcement was limited to 0.8fy, whilst crack widths were limited to less than 0.4mm.

PORTAL HEADWALL CONSTRUCTION

At the portal headwall, the stabilised block was constructed from original ground level using a configuration of interlocking Continuous Flow Auger (CFA) piles. The two central buttresses were constructed as diaphragm wall panels following the same technique used to construct the sidewalls. The walers were constructed during excavation by casting against ground.

The facing wall in front of the stabilised block was constructed after excavation had been completed and the sump slab had been installed. The wall was constructed bottom up as a series of 2m high concrete pours. For each pour, timber formwork was erected and supported off of the previously poured concrete below. This sequence required the upper most portion of the facing wall to be cast directly against the underside of the existing waler. In order to achieve this, the waler was cast with a number of penetrations, enabling fresh concrete to be placed from above (through the waler).

Figure 8.Facing Wall Construction

On the retrieval side, the facing wall comprised of two distinct zones of concrete: a reinforced zone that formed part of the permanent works, and a temporary 5MPa unreinforced soft eye that the TBM passed through. The two areas were both poured during the 2m lifts and were separated by a circular perimeter formed using cast-in formwork made from expanded steel mesh (stremaform). The use of this formwork was well suited to creating the required circular shape. It also minimised the amount of work required on-site, helping to reduce the construction time of this critical path activity. At the interface between the facing wall and the stabilised block, the stremaform was cut to shape and sealed with a run of expanding foam. Prior to construction, trials were undertaken in order to ensure that this interface did not permit concrete to bleed excessively from one zone to the other. Constructing the facing wall in this manner worked well, contributing to a hugely successful breakthrough, as evidenced in Figure 9.

Figure 9. TBM breakthrough

INTERNAL STRUCTURE ANALYSIS & DESIGN

The majority of the NATs completed internal structure will comprise of precast prestressed floor systems which span onto a configuration of main beams. At roof and road level, the main beams will be constructed from cast in situ concrete whilst at intermediate level, the beams will be precast, prestressed, closed-flange Supertee beams.

The Supertee beams were designed following the provisions of NZS3101:2006. A partial prestress design approach was adopted, for which the fluctuation of stress range was checked using the software application RESPONSE. This software performs an elastic analysis on a reinforced and prestressed concrete section. Using the stress at the level of the reinforcement crack widths were checked in accordance with NZS3101. Creep and shrinkage strains were estimated following the provisions of RRU Bulletin 70, in order to assess long term prestress losses. At either end of the Supertee, the beam will sit on low friction bearing pads. The beams have been detailed as being pinned at both ends and hence will not attract bending moments from the side walls.

Once placed inside the trench, the flooring will be tied together by means of a cast in situ topping. At all levels the flooring is detailed as being semi-integral with the main beams (connected at in situ topping level only). The in situ topping will typically also be connected to the sidewalls meaning that globally, the floor slab will be restrained against longitudinal shortening.

Once composite action is achieved, the redistribution of stresses between the precast units and the topping slab were evaluated using the provisions of AS5100, considering the effects of residual creep in the precast and differential shrinkage between the precast unit and topping in the following two extreme cases:

(i) Final residual creep acting with final differential shrinkage
(ii) Zero residual creep acting with zero differential shrinkage (representing the conditions at a time shortly after achieving composite action)

INTERNAL STRUCTURE CONSTRUCTION

The majority of the NAT's internal structure is currently being constructed around on-going tunnelling operations. Although the TBM has now left the NAT, at the time of writing this paper, a number of support services for the TBM still run through the structure. These include a conveyor, which extracts material excavated by the TBM, and Multi Service Vehicles (MSVs) used to deliver tunnel lining segments to the TBM. This, coupled with the fact that parts of the NAT were constructed top down has impacted the way in which the remaining internal structure is being built.

In order to accommodate the continued presence of the MSVs, the road deck is currently being built in stages. Initially after breakthrough, in order to continue production of the second tunnel, the MSVs were trafficked across the sump on temporary staging platforms. The presence of the staging limited the amount of road deck that could initially be built. As a consequence, an initial portion of the NATs road deck was built around the staging. The MSVs were then moved onto the newly completed section of deck, so that construction of the remaining area could commence. The on-going presence of the MSVs has meant that the remaining area is constrained, limiting plant access and manoeuvrability. In order to avoid competing for operating space, it has been necessary to stage construction activities.

Figure10. Construction of the internal structure through the turnaround zone

The intermediate level through the TBM turnaround zone will be constructed above the road deck whilst the MSV operations are still on going. During this time in situ concrete works will be installed at height by propping back down to road level. The precast Supertee beams will be craned in from above via the opening at roof level. Once the Supertee beams have been placed, the precast floor units will be landed in a similar manner, using cranes setup at either road or roof level. The fact that portions of the roof were constructed "top down" prior to excavation makes it difficult to access some areas of the intermediate level. Consequently a number of beams will be slid into place using load skates set up on a configuration of temporary beams.

CONCLUSION

The Waterview Connection's Northern Approach Trench (NAT) is a complex structure, fulfilling many different requirements both during construction and in its completed state. The adopted construction sequence, the need to accommodate the TBM and the requirements of the completed structure each presented a number of different challenges. In each case a solution has typically been achieved through the use of concrete.

The versatility of concrete enabled the NAT to be constructed using a variety of different techniques. These include:

- The use of top down construction methods using tremie pipes and bentonite to cast concrete directly against the ground. This method of placement, not only enabled the trench's side walls & CFA piles to be installed within the confines of a narrow site, but also helped to minimise the amount of disruption to local traffic.

- The use of cast in formwork to create a circular soft eye within the trench's facing wall. This method of placing different strengths of concrete within the same structural element assisted in the retrieval of the TBM.

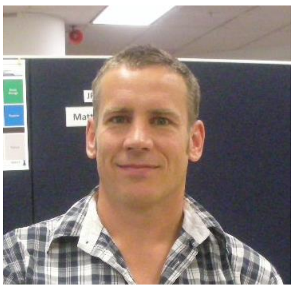
- Placing concrete in situ using conventional construction methods. This provided the flexibility needed to coordinate construction around on going tunnelling operations, in particular enabling the trench's road level to be built in stages.

- The use of precast concrete elements within the trench's internal structure. This has typically facilitated the quick installation of beams and floor units within the trench.

Furthermore, the ability to vary concrete constituents, to achieve mixes of different strengths and characteristics, also enabled concrete to satisfy a wide variety of project requirements: A fluid concrete mix lent itself well to being placed via tremie pipes. The use of low strength mixes in both the CFA piles and the portal's facing wall enabled the TBM to enter and exit the trench with relative ease. The use of high strength concrete also enabled pre-cast elements to reach high early age strengths, assisting in their rapid production.

At the time of writing this paper, the NAT's internal structure is being constructed around on-going tunnelling operations, and is scheduled to be completed in time for the projects opening in 2017.

AUTHOR BIOGRAPHIES

Photograph	Short Biography
	Stuart Paterson is a Senior Structural Engineer with Beca Ltd, based in Auckland. He joined Beca's Civil Structural group after graduating in the UK and now has over seven years experience in the design of cut and cover structures. Stuart is the Senior Design Engineer on the Waterview Connection project responsible for the Northern Approach Trench.
	Richard Gardiner is an Associate Structural Engineer with Beca Ltd, based in Auckland. He has a broad range of structural design experience in both New Zealand and the UK. With significant involvement in large scale retail projects, and more recently leading the structural design on major civil infrastructure projects. Richard was the Discipline Lead for the Portal Structures on the Waterview Connection project.
 .	Andrew Dickson is a Senior Technical Director with Beca Ltd, based in Auckland. He has 29 years of structural design experience, the last 18 of which have been spent as a bridge engineer with Beca's Civil Structural group. Andrew is the Surface Work Structures Design Verifier on the Waterview Connection project, responsible for the overview and verification of the surface structures design.
	Matthew Wansbone is a Senior Geotechnical Engineer with Tonkin & Taylor Ltd, based in Auckland. He has over 11 years experience in the field of geotechnical engineering, covering a broad range of areas, including commercial and industrial developments, water resources engineering and major transport infrastructure projects. Matthew is the geotechnical discipline lead for the Portal Structures on the Waterview Connection Project.
	Matt Sinclair is a Project Engineer with Fletcher Construction. He has over 16 years of experience working in the construction industry. He has worked on a number of large scale motorway projects involving earthworks, drainage, pavements, retaining walls, foundations and bridge structures. On the Waterview Connection project, Matt is the Project Engineer responsible for the planning, programming and execution of the construction works at the Northern Approach Trench.