Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 78 (1998)

Artikel: The design of the Western Immersed Tube Tunnel, Hong Kong

Autor: Morris, Martin W.

DOI: https://doi.org/10.5169/seals-59042

The Design of the Western Immersed Tube Tunnel, Hong Kong

Martin W Morris
Technical Director
Hyder Consulting Limited
Guildford, United Kingdom

Martin Morris is a chartered engineer and a Technical Director of Hyder Consulting Limited. He was resident in South East Asia for nearly 20 years where he was responsible for the company's immersed tube tunnel work in Hong Kong and Australia. He was Project Design Manager for the Sydney Harbour Tunnel in Australia and Project Director for the Western Harbour Crossing road tunnel in Hong Kong as well as for the Western Immersed Tube rail tunnel which is the subject of this Paper.

Summary

The Western Immersed Tube Tunnel carries Hong Kong's new Airport Railway under Victoria Harbour. It comprises a twin track immersed tube tunnel, constructed of ten tunnel units. The tunnel was constructed for the Mass Transit Railway Corporation under a design and build contract strategy and completed in only 30 months. The Paper briefly describes key aspects of the design of the immersed tube structure.

1. Introduction

The Western Immersed Tube (WIT) carries the new Airport Railway under Hong Kong Harbour. The Airport Railway comprises the Airport Express Line (AEL) from the new Hong Kong Airport at Chek Lap Kok and a new mass transit railway, the Lantau Line (LAL) from Tung Chung New Town adjacent to the airport, both to the Central Business District on Hong Kong Island. WIT connects AEL and LAL on common tracks between the West Kowloon Reclamation, via Victoria Harbour to Central Station on Hong Kong Island. At the Hong Kong landfall, turnouts are located so that separate tracks can diverge to the AEL and LAL platforms at different levels.

Contract C502, for the Western Immersed Tube, was awarded to Kumagai - Tarmac Joint Venture (KTJV), a joint venture of Kumagai Gumi of Japan and Tarmac Construction of the United Kingdom. KTJV employed Hyder Consulting Limited to prepare the tender design on their behalf and subsequently awarded a design contract to Hyder Consulting for all permanent works design and for independent checking of KTJV's own temporary works designs. A key feature of the Contract was the need for close cooperation between Employer, Contractor and Designer to achieve the programme.

2. Alignment

The alignment of the tunnel is dictated by the railway alignment on both sides of the Harbour. Airport Railway Feasibility Studies determined that the most appropriate location for the Central Station was on an east-west alignment on the new Central and Wanchai Reclamation (Figure 1). It is conveniently placed for connections to the existing Tsuen Wan and Island Lines as well as to the Central Business District itself.

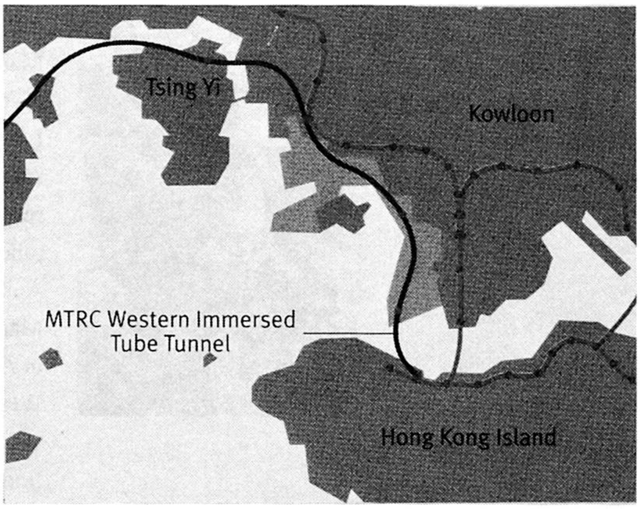

Fig 1 Key Plan

On the Kowloon side, the most convenient access was a north-south route via the new West Kowloon Reclamation rather than attempting to install a further line through the congested Kowloon hinterland. These two landfalls necessitated a variably curved alignment, turning some 60° in total with a minimum radius of 850m (Figure 2). WIT has a total length of 1260m between landfalls and comprises 10 immersed tube tunnel units, each 126m long.

The Hong Kong landfall is at a special tapered unit which accommodates turnouts to enable tracks to diverge to serve separate AEL and LAL platforms. This unit was installed under the Reclamation contract to meet programme constraints but was also designed by Hyder under a direct commission to MTRC. At the Kowloon landfall, the last tunnel unit connects directly to a stub end projecting from the Kowloon Ventilation Building and constructed under Contract C502.

Options for combining the tunnel with the Western Harbour Crossing vehicular tunnel were considered at feasibility stage of both projects but the alignment constraints eventually dictated the need for two separate tunnels. Both immersed tubes were however designed by Hyder and cconstructed by Kumagai so that a common approach to design and construction was adopted.

The vertical alignment is governed by required track levels and gradients at the landfalls and by the fairway width and depth in Hong Kong Harbour set by Marine Department. The resulting alignment takes the track level to about -25m PD and keeps the majority of the units and their backfill at or below existing seabed level. However, the track level constraints at the Hong Kong end were such that Units 1, 2 and part of 3 rise above seabed level, whilst maintaining the necessary depth requirements in the onshore traffic zone between the fairway and the Reclamation limit.

The cross section is a rectangular box 12.42m wide and 7.65m high containing twin ducts for the twin rail tracks. Internal spatial requirements were set primarily by compliance with the structure and kinematic gauges within the MTRC Design Standards Manual (DSM)[1]. The horizontal curvature within the tunnel alignment is not constant, some units being straight, some incorporating transitions and some curved to the minimum 850m radius.

3. Geotechnical Conditions and Settlement

The seabed consists of extremely soft marine muds underlain by sandy/clayey alluvium, underlain by completely decomposed granite (cdg). The vertical alignment resulted in most units (except 1, 2 and 3) being founded in the alluvium.

Low foundation pressures from the units lead to small settlements which are predominantly elastic (i.e. short term). For typical units, predicted total elastic settlements were in the range 10-60mm with 10-40mm occurring within the construction period. Residual non-elastic settlements were of the order of 25-65mm. The Kowloon landfall unit (Unit 10) exhibited higher levels (up to 120mm elastic and 50mm residual) because of the higher loading from the Reclamation. By delaying lock off of the shear keys between tunnel units, long term differential settlements between units could be minimized. Elastic settlement in the construction period was accommodated by setting up the units by that amount when placing them. Post construction settlement was accommodated by oversizing the unit.

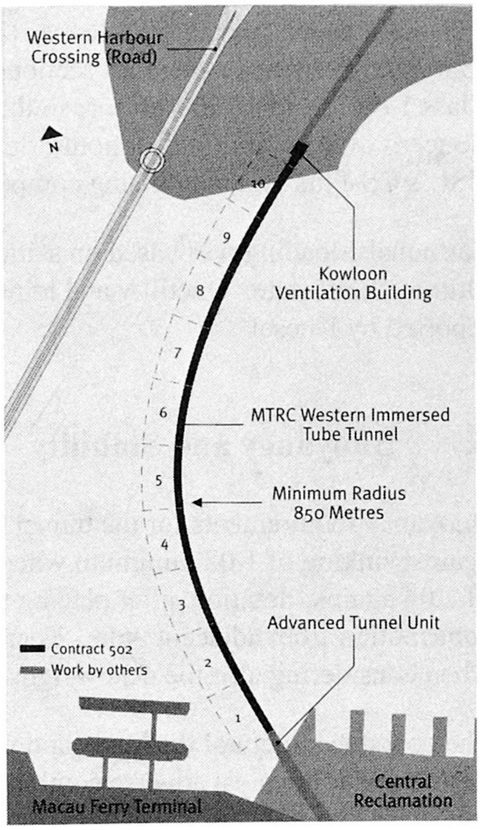

Fig 2 Tunnel Alignment

4. Structural Analysis and Design

Loading cases included self weight, services (including track and trackslab), backfill (and development surcharge allowances on reclamation), hydrostatic pressure, extraordinary loads such as marine hazards, earthquake, flooded tunnel) and temporary loads during construction. Load factors were defined in principle by the MTRC DSM[1] and agreed in detail between the Designer and MTRC following established practice on other IMT's in Hong Kong.

Loadings were applied to a plane frame for transverse analysis, a shear flexible plane grillage to assess load distribution from shear keys and other assymmetric loads and a longitudinal plane frame to assess longitudinal bending and shear in the tunnel units.

Transverse reinforcement was designed in accordance with BS8110[2] to limit flexural and thermal/drying shrinkage crack widths to 0.2mm total based on a notional (rather than actual) cover of 40mm to the outermost bar. Actual cover to both faces of external walls and slabs was 70mm and to the internal walls 40mm. Typical transverse reinforcement was T20 @ 150mm in both faces of base and roof slabs and T25@150mm in outer faces and T20@150mm in inner faces of walls. Longitudinal reinforcement was T16@150mm. Overall reinforcement density excluding prestress was about 160 kg/m^3.

Thermal and drying shrinkage reinforcement was designed in accordance with BS8007[3] and CIRIA Report 91[4].

Longitudinal prestress was provided by 26 no. VSL 31K13 tendons (i.e. 31 strands of 13mm low relaxation strand per tendon) stressed to approximately 75% UTS. These provided a uniform compressive stress in the cross section of about 2.3N/mm². This was sufficient to provide a Class 1 (i.e. no tension) structure in the serviceability limit state, eliminating flexural cracking. Concern over durability and monitoring of the prestress led to the first use in Hong Kong of VSL's CS-Plus system utilising composite material ducting and anchorages.

Earthquake loading was based on static load enhancement utilising an acceleration of 0.07g at ultimate limit state. Ductility and joint opening/closing were checked using the BART criteria reported by Kuesel[5]

5. Buoyancy and Stability

Buoyancy requirements for the tunnel units were conventional and required a factor of safety against sinking of 1.02 minimum when floating fully outfitted for sinking and a factor of safety of 1.04 against flotation after placing to include all permanent ballast but not backfill or any contribution from adjacent units. There was a further requirement of a factor of safety of 1.20 when considering also the deadweight only of backfill on the plan area of the tunnel unit.

The concrete structural thickness and the ballast area was determined to enable these criteria to be met under the most adverse combination of concrete density and seawater density. The range considered was 22.5 to 23.3 kN/m3 for concrete and 9.96 to 10.06 kN/m3 for seawater. Tunnel units of this slenderness and curvature are almost unique and there was concern about floating stability and dynamic effects during towing and mooring. The issue was further exacerbated by the need to use the sinking pontoons from the adjacent Western Harbour Crossing (WHC) Project. These were sized for the much larger WHC units and weighed some 245 tonnes each.

The units were subject to severe wave conditions during towing and when stored on single point moorings (significant wave height up to 3.5m). Analysis of stability and towing/mooring force variations was confirmed by model testing at Kumagai Gumi's Institute of Construction Technology in Tsukuba City , Japan. Peak mooring force was 70t and maximum roll with all temporary fittings was 3°. Figure 3 shows the tunnel units under construction in the casting basin.

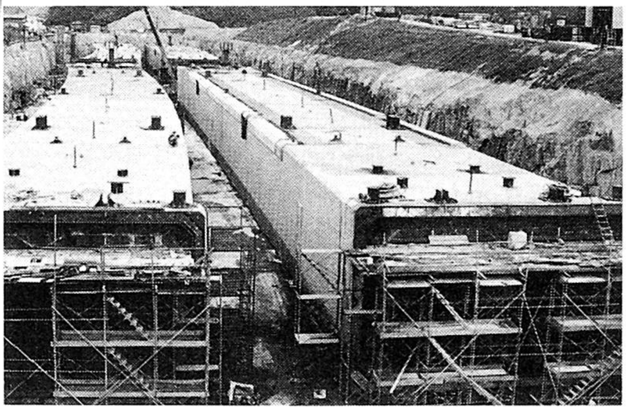

Fig 3 Tunnel Units under Construction

6. Joints

The joints between typical units are conventional hydrostatic joints incorporating two independent seals, the primary gina-profile seal and a secondary omega seal. The detailing was complicated by the need to incorporate the prestress tendon anchorages.

Programming constraints at each landfall dictated that the tunnel units could not be laid in a simple end-to-end sequence. Units 1-8 were laid in sequence from the Hong Kong landfall at the ATU and Unit 10 at the Kowloon (KVB) landfall. Unit 9 was laid last and the final joint formed in-situ between Units 8 and 9.

The final joint was formed by pre -compressing the Unit 8/Unit 9 hydrostatic joint onto the end of Unit 8 during construction in the casting basin, utilising prestressing bars across the joint. This left only a 2.5m section to be constructed in situ between Units 8 and 9. The section was enclosed in steel formwork placed underwater and sealed to the unit, after which the joint was dewatered and concreted in situ.

7. Shear Keys

The combination of extra-ordinary loading conditions with loss of foundation support under the units generates high vertical shear forces at unit/unit joints. These forces need to be carried across the joint to prevent any vertical displacement (particularly important with a rail tunnel) whilst still providing rotational flexibility.

The keys are steel fabrications on heavy steel backplates. Rotational capacity is maintained by laminated rubber bearings. A high stiffness is necessary (1000 kN/m) to limit vertical deflection in the service condition to 0.5mm. Fireproofing of the whole system is achieved with Durasteel (a proprietary steel/fibre sandwich plate) cover plates.

8. Durability

Concrete mix design was optimised to achieve the best balance of high density, low permeability, low water/cement ratio, high cementitious content, low heat of hydration and maximum chemical resistance. Characteristic strength was 40 Mpa using a cementitious content of 425 kg/m^3 (280 kg/m^3 opc and 145 kg/m^3 pulverised fuel ash(pfa)). Pfa was incorporated to reduce permeability and to minimise heat of hydration. The temperature rise (65°C above ambient) and, particularly, thermal gradient criteria (15°C to an adjacent surface within the pour and 20°C between the current pour and th previous adjacent pour) set by the DSM[1] were stringent and could not be achieved without the use of cooling. Cooling pipes were incorporated into critical sections (i.e. in areas of high restraint adjacent to construction joints).

An acrylic resin based waterproof membrane, 2mm thick, was applied to the walls and roof of the tunnel unit. The base was protected by a 9mm thick steel plate attached by headed studs. Neither was taken into account in assessing exposure criteria for concrete durability.

A corrosion monitoring system was installed in selected units to identify corrosion or earth leakage currents from the 1500v DC traction supply system. In the event that corrosion was identified, provision has been made for the retrofitting of a cathodic protection system.

9. Foundation and Backfill

The units were sunk into place, supported from pontoons, onto temporary foundations. The void between the units was then filled a sand layer, nominally 800mm thick, with a tolerance of -10mm/+500mm. The layer is placed after sinking the unit by pumping a sand/water mixture via pipes cast into the centre walls of the unit at 8.7m centres.

The typical backfilling arrangement incorporated locking fill at the lower sides of the units to hold it in place laterally, general fill for the rest of the trench and 1.0m rock armour as protection on top of the unit. The armour extends to a minimum of 25m each side of the tunnel centre line. The armour and general fill was designed to provide protection against scour, falling anchor (design anchor 7.8 tonne) and a falling dredger bucket (design bucket 23 tonnes).

10. Programme

The design and construct contract was awarded in June 1994. Design commenced in July 1994 and was substantially complete by January 1995. Fabrication of units commenced in late 1994. The final joint was completed in October 1996 and the complete tunnel was handed over to MTRC for track laying in December 1996.

References

1. Design Standards Manual, Mass Transit Railway Corporation, Hong Kong.
2. BS 8110, The Structural Use of Concrete, British Standards Institution, London.
3. BS 8007, The Structural Use of Concrete for Retaining Aqueous Liquids, British Standards Institution, London.
4. CIRIA Report 91, Early age thermal crack control in concrete, TA Harrison, Construction Industry Research and Information Association 1992.
5. Kuesel TR, Earthquake Design Criteria for Subways, American Society of Civil Engineers, Journal of the Structural Division, Vol. 95, No. ST6, June 1969.

Acknowledgements

The author gratefully acknowledges the efforts of his colleagues in Hyder Consulting, Kumagai Tarmac Joint Venture and the Mass Transit Railway Corporation in the successful completion of this contract on a fast track programme.