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The Design of the Western Harbour Crossing, Hong Kong

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Summary

The Western Harbour Crossing is the fifth Hong Kong harbour crossing, the third road tunnel and the first dual 3-lane tunnel, all constructed by the immersed tube technique. It was implemented using a build-operate-transfer strategy and constructed under a fast-track design and build contract in just 44 months. This Paper reports on key areas of the immersed tube tunnel design.

1. Introduction

A tunnel crossing of the western end of Hong Kong Harbour was identified in 1981 in a report prepared internally by Hong Kong Government[1]. In 1983, the Study of Harbour Reclamations and Urban Growth (SHRUG)[2] identified a suitable Kowloon landfall on the proposed Western Reclamation. In 1989, the Second Comprehensive Transport Study (CTS2)[3] formally proposed a third harbour crossing as a means of meeting increased cross harbour traffic demand.

In 1989, Hyder Consulting as leader of a joint venture, Western Harbour Crossing Consultants, was appointed to undertake a feasibility study of the Crossing. Their report, presented in early 1991, determined that a dual 3-lane tunnel would meet traffic needs into the 21st Century, and would provide a satisfactory return as a BOT project.

The franchise was subsequently offered to competitive bidding and was won by the Western Harbour Tunnel Company Ltd (WHTC) in 1993. WHTC awarded a construction contract to Nishimatsu Kumagai Joint Venture (NKJV), who in turn appointed Hyder Consulting, as part of a joint venture, to undertake the design of all tunnel works, including the immersed tube, approach tunnels and ramps, and traffic surveillance and toll systems. Within the confines of this Paper it is only possible to concentrate on the immersed tube tunnel section.

2. Alignment

The tunnel alignment (Figure 1) was defined by exhaustive studies at the feasibility stage and constrained by existing and committed development. The alignment extends from an interface with the West Kowloon Expressway (WKE) on the West Kowloon Reclamation (WKR) to a major interchange and connection to Route 7 at Sai Ying Pun on Hong Kong Island.

The West Kowloon Approach and the immersed tube tunnel were maintained on a straight alignment to simplify construction and maintain, as far as possible, a constant cross section. The need to connect the north-south tunnel with the east-west Route 7 within a limited coastal fringe at Sai Ying Pun necessitated curving the Sai Ying Pun approach to a horizontal radius of approximately 400m.

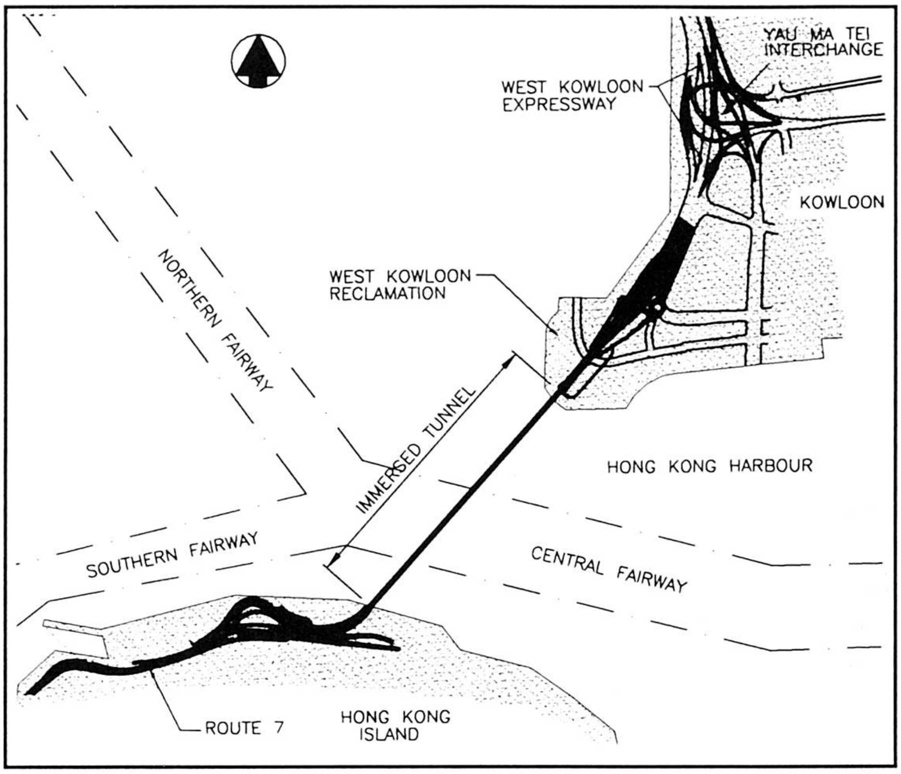

Fig 1 Tunnel Alignment

This enabled the interchange to be fitted between the existing seawall cope line and the existing and planned building developments immediately to the south of Connaught Road West, whilst maintaining a design speed of 70km/h.

The tunnel is 2.2km long from portal to portal. The immersed tube section is 1360m long and was constructed as 12 units, each 113.5m long, 33.4m wide and 10m high. They were constructed in three batches of four in a casting basin at a quarry site at Shek O on the southeast coast of Hong Kong Island. The quarry floor was excavated to a sufficient depth to enable the units to float when the basin was flooded to sea level. The rock working platform relieved the necessity for any consideration of settlement effects during construction.

The vertical alignment of the tunnel was governed by the required navigational clearance of 14m in the Central Fairway over a width of 700m. The vertical alignment was otherwise maintained as shallow as possible to limit gradients to 5%, to minimise the length of the approach tunnels and to minimise the depth of excavation at the Ventilation Buildings. On the Sai Ying Pun side, this means that the tunnel units project above existing seabed level, necessitating additional marine protection.

3. Cross Section

The two primary factors in determining the immersed tube cross section were the traffic gauge and the ventilation duct requirements. The traffic gauge for a dual 3-lane tunnel was defined within the Project Brief. Walkways were provided adjacent to the centre wall, connected by fire doors at 50m intervals. The ventilation duct area was designed to meet the airflow requirements for an acceptable user environment and for emergency ventilation and smoke extraction requirements.

The desire to minimise the depth of the cross section and to minimise dredging and the necessary depth of the casting basin, led to the decision to locate the ventilation ducts outboard of the traffic ducts to achieve the cross section shown in Figure 2.

4. Design

4.1 Buoyancy

The structural cross section was determined from buoyancy considerations such that the unit would float with a factor of safety against sinking of at least 1.02, representing a freeboard of approximately 200mm. Provided that water plane area is maintained, metacentric height and therefore stability, is not a problem with rectangular units of this width. After sinking, the units were required to have factors of safety against flotation of 1.04 without backfill and 1.20 with 1.5m of backfill.

Within the limitations set by the buoyancy criteria, top and bottom slab and outer wall thicknesses (and local haunching) were determined by bending capacity of reinforced concrete sections. Internal wall thicknesses were determined on the basis of vertical shear capacity. Despite the long spans of the dual 3-lane traffic ducts, transverse prestressing proved not to be required. Longitudinal prestress was considered but rejected on cost grounds.

4.2 Analysis and Design

Transverse structural analysis was based on a standard pc-based plane frame software. Plane grid models were used to determine local load concentrations and distribution in the vicinity of joints. Longitudinal analysis was based on line elements on an elastic foundation, using spring constants or moduli of subgrade reaction derived from settlement analysis.

Design loads were identified in four groups.

- Dead load, the long term loads on the structure including water pressure from the mean sea level case.
- Live loads, traffic, earth pressure including that from the surrounding backfill as well as variable hydrostatic loads (tidal variation, storm surge etc) and siltation of the harbour bed.
- Exceptional and extreme loads, including the effects of variation in foundation stiffness, loss of foundation support through erosion or other causes, effects of applied load from a sunken ship, anchor impact, flooding of the tunnel, explosion, fire, design earthquake and the resulting soil displacements.

- Construction stage loads, including wind and wave forces on the unit during towing and sinking.

These load groups were considered in a number of combinations at the serviceability and ultimate limit states using load factors defined in the Project Brief and developed as part of the Feasibility Study.

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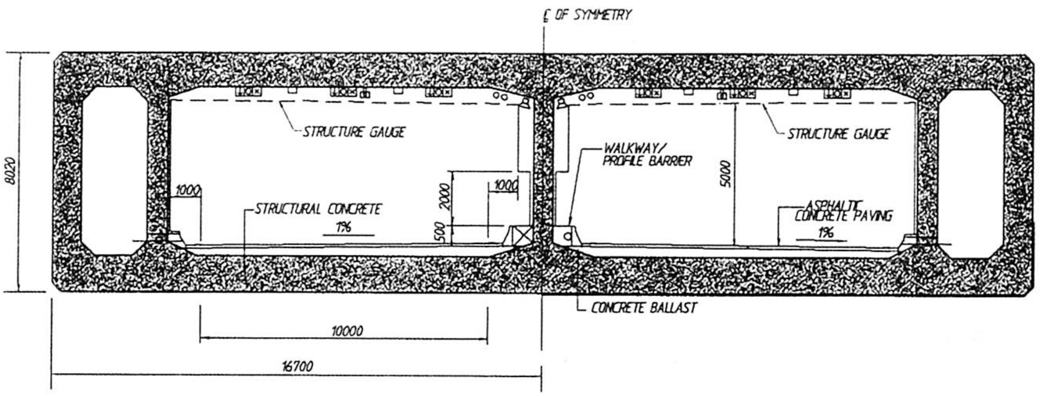

Fig 2 Typical Cross Section

Design of the concrete structure was based on BS8110[4] and BS8007[5] with flexural crack widths limited to 0.2mm. Thermal reinforcement was designed to BS8007[5] and CIRIA Report 91[6]. Each unit was cast in separate base, wall and roof pours with a bay length of 15m. Thermal restraint was modelled using finite element analysis based on a defined sequence of construction. Thermal crack widths were limited to 0.1mm with an overall limitation on combined thermal and flexural crack width of 0.2mm. Leading quantities were: concrete (characteristic strength 40N/mm^2 at 28 days) 149,000m^3 and reinforcement (Grade 460) 30,000 tonnes, representing a reinforcement provision of approximately 200kg/m^3.

4.3 Durability Analysis

The tunnel structure was subject to a special durability analyis. The two major components were the structural concrete and the waterproof membrane.

Experience gained from the Sydney Harbour Tunnel, Australia was used to develop a mix which simulated low heat cement whilst maintaining high resistance to chloride ion penetration. Pulverised fuel ash (pfa), which is readily available in Hong Kong to high quality, was used in preference to ground granulated blast furnace slag (ggbfs) which would have had to be imported. The final mix used 450kg/m^3 cementitious content (300kg/m^3 opc, 150kg/m^3 pfa) with a water cement ratio of 0.4. Superplasticiser was used to add workability. Laboratory chloride penetration tests were used to demonstrate a 120 year design life.

The waterproof membrane on the roof and walls of the tunnel was a 2-part methylacrylic membrane, spray-applied in 2 layers, and originally developed for use in waterproofing bridge decks. The roof membrane was protected from abrasion by a 75mm thick (minimum) mesh reinforced concrete layer. This layer was also used to provide trimming ballast to ensure that the correct freeboard was obtained. Precast cover units cast into the edge of the external protection concrete provided a measure of protection to the side walls.

For the base of the unit, following the precedent of the Sydney Harbour Tunnel, the usual steel bottom plate was replaced by a high density polyethylene (HDPE) sheet 1.5mm thick. This was anchored to the concrete by extruded ribs.

5. Foundations and Joints

The units were sunk, supported from pontoons, onto temporary foundations (Figure 3). The void below the foundation was filled with a sand/water mixture placed via pipes cast into the units. Typical unit to unit joints must provide rotational capacity, whilst maintaining vertical shear capacity and preventing significant vertical displacement.

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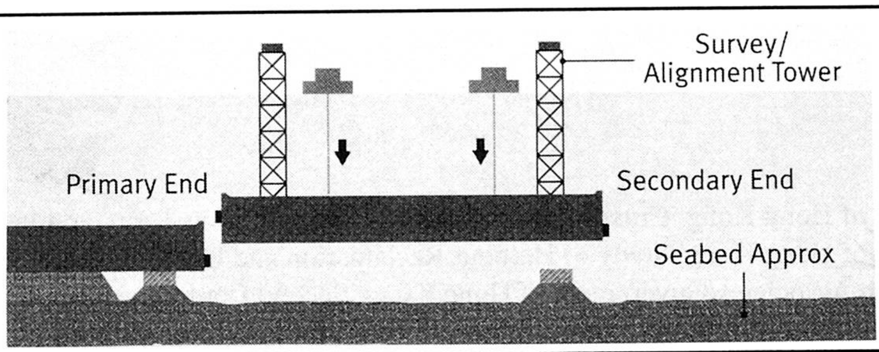

Fig 3 Sinking Arrangement

The units are jointed with conventional gina profile primary seals and omega section secondary seals. Vertical shear is transmitted by large interlocking steel shear keys, attached to the concrete section using stressbars. Laminated rubber bearings between the keys allow slight rotational movement and enable the very high peak shear forces which would be generated by a rigid vertical connection to be reduced. The bearings are inserted as late as possible after sinking and backfilling and shimmed to fit, thereby minimising the initial 'locked-in' load in the key system. At the landfalls, the potential for long term differential settlement between the landfall units (1 and 12) and the Ventilation Buildings had to be addressed. The units are supported on a sill beam and barrettes. No shear key is fitted and the gap between the underside of the unit and the sill beam has been grouted as late as possible after primary settlement has been completed.

6. Backfill and Armour Protection

The tunnel units are generally set below existing seabed level and are backfilled using suitable granular material. Protection against marine hazards is provided by 0.6m backfill, overlain by 0.9m of rockfill with particle size 25-250mm. Further protection against dragging anchors is provided by bands of rock armour (100-500kg), 5m wide, set either side of the tunnel. This material is designed to cause anchors to release from the backfill before penetrating deeply enough to damage the tunnel structure.

In the area of the Sai Ying Pun landfall, where the units project above seabed level, the backfill and armour is extended laterally to a minimum of 15m from the tunnel structure. This is intended to provide sufficient space and resistance for a grounding ship, having left the fairway for whatever reason, to be arrested before impinging on the tunnel structure.

7. Programme

The franchise was awarded in August 1993. Design commenced immediately and was substantially completed in the following 12 months, some 1400 working drawings having been provided by the design consortium. The tunnel was opened to traffic in April 1997, some 3 months ahead of schedule.

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Acknowledgements

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