



THE HONG-KONG-ZHUHAI MACAO BRIDGE THE HONG-KONG LINK ROAD

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Introduction

The Hong Kong – Zhuhai – Macao Bridge (HZMB) will be one of the longest cross-boundary seacrossing road infrastructure in the world (42 km) providing a direct land transport connection between two shores of the Pearl River Delta, linking Hong Kong in the east to Macao and Zhuhai in the west. The Hong Kong Link Road (HKLR) is a prominent structure that serves to connect the Main Bridge of HZMB from the HKSAR Boundary to the Scenic Hill on the Airport Island in Hong Kong. The works comprises mainly design and construction of approximately 9.4km of viaducts supporting dual 3-lane carriageways. This 12.9 billion Hong Kong dollar contract was awarded to Dragages-China Harbour-VSL Joint Venture (DCVJV) in May 2012. YWL Engineering Pte Ltd was appointed as the Designer and construction engineering consultant for the marine viaducts under the Contract and Bouygues Travaux Publics was appointed as design in-charge for long-span viaducts. The architect of DCVJV is Alain Spielmann office.

The viaducts in this project consist of 115 spans and can be categorized into three categories: marine viaducts, land viaducts and large viaducts [1]. A particular care has been brought to the coherence and optimization of formworks, and therefore to the architectural unity of the viaducts. A grade-separated turnaround facility is proposed with slip roads in the form of single-lane viaducts diverging from the HKLR mainline carriageways on both sides forming an elevated junction in the middle of the viaducts.

This paper presents the challenges and solutions employed in the design and construction of the viaducts. It synthesizes different papers published by the authors [1, 7, 9].

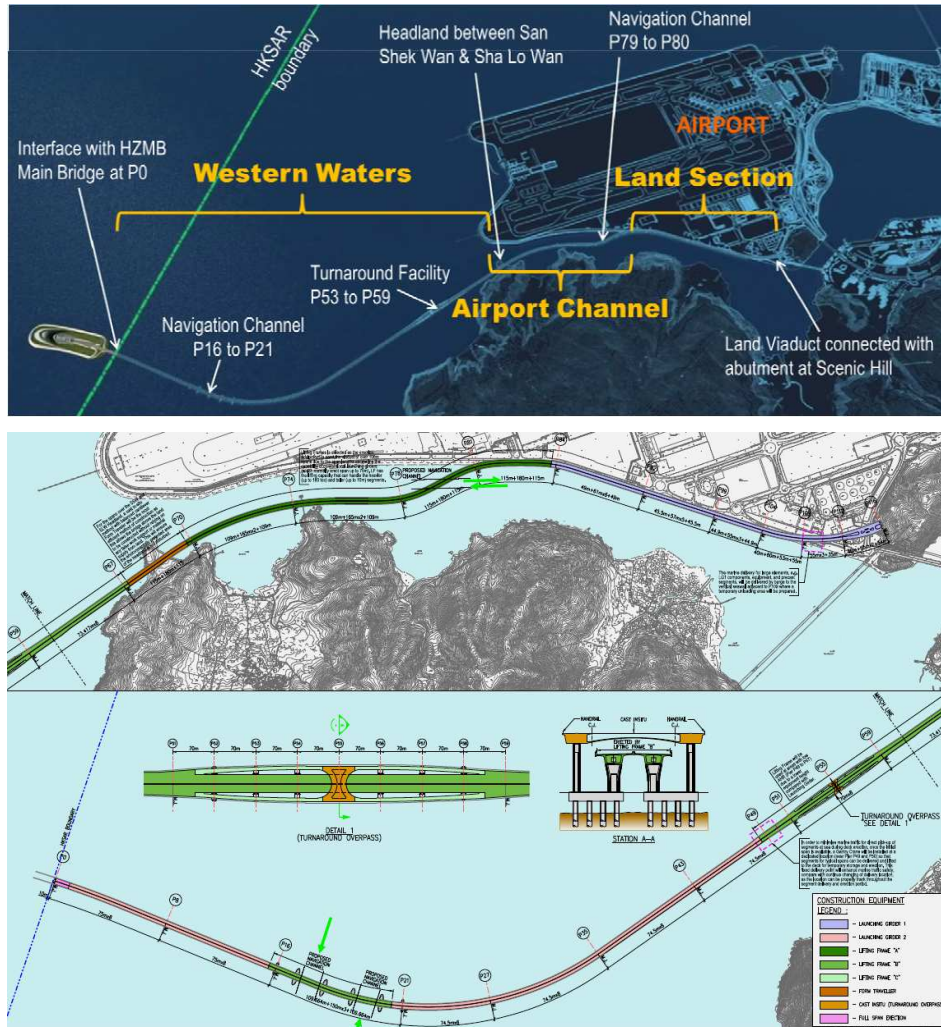


Fig.1. Location of the HZMB-HKLR link ©photothèque BYTP

Project constraints

In the west, it is open water with a vast horizon where the HKLR connects to the HZMB Main Bridge in the mainland. Existing seabed in this area is generally underlain by 30m-40m of soft marine clay. Due to the presence of fault zones, the bedrock in some locations exceeds 100m deep. As the viaducts approach the headland, the geology changes drastically where bedrock becomes shallow. Since an archaeological site is located in the vicinity, no structures (either permanent or temporary) are allowed to be built in this sensitive zone and therefore, long-span decks (180m) have been adopted in this area. All pile caps within the Airport Channel are embedded below existing seabed in order to minimize any hydrodynamic impact to the Channel, except those for the navigation span which are emerged with the pile cap top above the sea at +3.95mPD. The viaducts on land are mainly along the sloping seawall running towards the tunnel portal at Scenic Hill.

Despite working in marine environment, other critical site constraints for constructing the viaducts include: ecological impact to Chinese White Dolphins, material logistic for concrete supply, construction noise, and the requirement on Airport Height Restriction.

Because of spans up to 150 m, various structural schemes were investigated in order to satisfy the site constraints and functional requirements of the project. The cable stayed bridge solution was studied but rejected due to the height restriction in the vicinity of the airport.

Another solution with composite steel and concrete deck was also studied based on the use of a wide steel box. However, this concept was found commercially unattractive and considered against the sustainability principle as it would require significant long-term maintenance effort. Therefore the precast concrete segmental option was finally selected. This posed a major technical challenge as building a precast segmental bridge of 180m would be a world record.

The design criteria of the viaduct structures are in accordance with the Structures Design Manual for Highways & Railways (SDMHR) published by Highways Department of HKSAR Government. The viaducts are designed for ultimate and serviceability limit states according to BS5400 [8] with a design life of 120 year except two special load scenarios (i.e. seismic & ship impact designs) which are considered as extreme events and designed under structural integrity limit state.



Eurocode 8 (Parts 1, 2 and 5) has been employed in the seismic design [2-4]. The two seismic performances in EN are extended to 3 performance requirements of “no damage”, “repairable damage” and “no collapse” with the corresponding three levels of seismic design actions. In the design for ship impact, reference was made to the IABSE guidelines [5] and AASHTO specifications [6].

The viaducts

The **marine viaducts** are composed of 8 equal spans of 75 m, starting at P00 in the Hong Kong Special Administrative Region (HKSAR), 10 m away from the ROC frontier (Fig.2). A junction area is made in order to connect the HKLR section on the larger and thinner chinese deck cross-section. ML01 and ML02 are the first viaducts between piers P00 and P16. Between P16 and P21, in order to enlarge the two navigation channels, ML03 is the first large viaduct with 5 spans (109 m+3x150 m+109 m) and variable depth. In the headland, ML04 and ML09 are identical to ML01 and ML02.

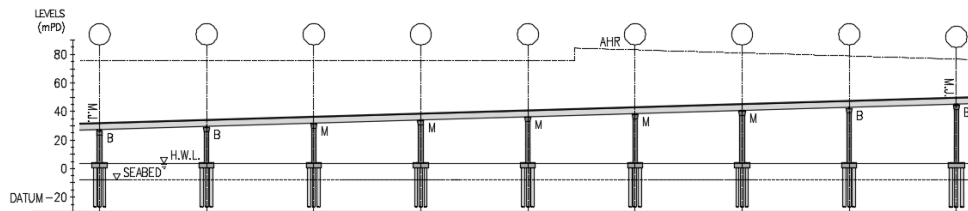


Fig.2. Marine viaducts ©photothèque BYTP

The **large viaducts** start with ML3 and continue with the ones close to the airport island (ML10 to ML14). The viaduct ML3 (Fig.3) is formed by a 5-span bridge unit with a configuration of 109m+3x150m+109m. Movement joints and bearings were provided only at the 2 ends of this 668m long bridge. The internal twin-blade piers were monolithically connected to the deck. The form of these piers was selected with the objective to minimize the longitudinal stiffness of the bridge and reduce the lock-in effects due to creep, shrinkage and thermal deformations.

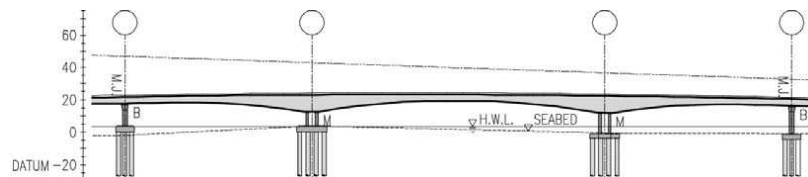


Fig.3. Large viaducts ©photothèque BYTP

In the headland, a 3-span continuous structure with a 180m long clear span in the center with two 115m long end spans was employed to span over an archaeological site in the island (Fig.5). In the Airport Channel, 2x2 bridge units with two generic configurations of 109m+2x165m+109m and 115m+2x180m+115m and similar articulation were proposed. Spans of 180m are in the upper limit of precast segmental concrete bridges built thus far. With a variable box depth of 4m to 10m, the span-depth ratio is 1/45 at mid span and 1/18 at pier.

The **land viaducts** are along the artificial airport island between P84 and P115. The vicinity of the airport requires low bridges but the presence of several infrastructure networks (such as kerosene pipelines and embankment foundations) are the principal constraints. The bridge is made of 5 viaducts (ML15 to ML19) with a total length of 1.7 km. The number of spans vary from 4 to 8 (spans ranging from 55 to 65 m).

A **turnaround facility** completes these three families of viaducts. The slip roads contribute to make this project complex from ML07 to ML09 (Fig.4).



Fig.4. Turnaround facility ©photothèque BYTP

Foundations

There are a total of 725 numbers of bored piles in this project; out of which 65 piles are in the land viaducts with 2.8m diameter and 660 piles are in the marine viaducts with diameters 2.3m, 2.5m and 2.8m. Due to significant variation in geology, the pile length varies from 7m to 107m.

The marine piles (P00 to P68) are bored by means of the Kelly method or by the Reverse Circulation Drilling method. The Kelly method is used from P16 to 049, as well as for P00. Pile unit have volumes ranging from 80 to 400 m³. The work platforms are moving steel structures lying on bored steel shafts (1.2 m diameter).

The long piles are located mainly in the marine viaducts where the geology is characterized by a thick layer (maximum 40m) of weak marine deposits immediately below seabed. It is underlain by alluvial clay/sand. In some location, bedrock exceeds 100m below sea level. Friction bored piles are employed for such deep bedrock locations. These piles are both shaft and toe-grouted [7].

Pile caps

Pile caps are conventional reinforced concrete structures. Except for the viaducts inside the Airport Channel, top level of the pile caps in the marine viaducts is at +3.95mPD, so that they are observable by the vessels even at high tide level. The bored pile group in this project ranges from 3 to 6. The objective was to provide a safe & dry environment to enable the work to be carried out in marine tidal zone. Therefore, it led to the development of the use of concrete shell as loss formwork, but integrated with the permanent cap as additional protection against corrosive marine environment.

There are 7 types of generic concrete shells: two are presented Fig.5 [9]. The wall thickness is 300mm and the bottom slab is 450mm. Two aspects of the shell design were considered, namely, strength requirement and durability performance. In strength design, the shell is to resist the concrete pressure from the permanent core, buoyancy force & wave load, construction load and thermal effects due to expansion of the core from heat of hydration. Although the shell is not part of the permanent structure for resisting the service loads, it serves as a protection for the cap against the corrosive marine environment during its design life of 120 years in the durability assessment (Fig.6).

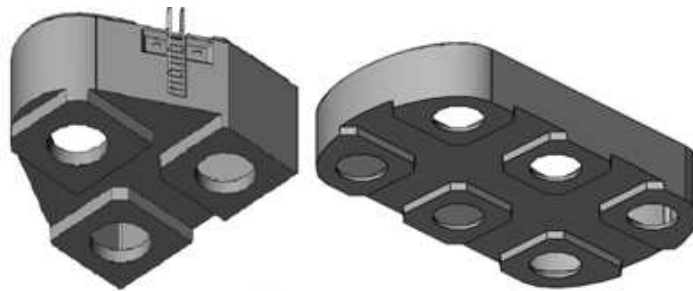


Fig.5. Examples of precast concrete shells ©photothèque BYTP

Due to the complex shell geometry, 3-dimensional finite element analyses were conducted to simulate the structural behavior of the system in different stages. It was found that the thermal stresses induced due to concrete hydration in the permanent cap would be the governing load scenario. The tensile stresses could be in the order of 6-7MPa. Without controlling the early thermal effects (e.g. using cooling pipe), a significant amount of the tensile reinforcement would be needed in order to avoid cracks on the surface. A novel idea of thermal-structural insulation was conceived in the design. A thin layer of isolating material with specific mechanical and thermal property was introduced and mounted on all inner faces of the shell.



Fig.6. Precast shell for pile cap ©photothèque BYTP



Piers

Except short piers from P45 to P67 that are cast in-situ, the piers of the marine viaducts are precast and hollow (Figs.7-8). The external and internal dimensions are 5.0m x 3.2m and 3.0m x 1.5m.



Fig.7. Precast piers of marine viaducts ©photothèque BYTP

A vertical nailing is used to connect the in-situ pier base and the first precast unit. U-shape internally prestressed tendons were used to connect the precast units. The tendons are anchored at the pier head, anchorages being embedded into the pile cap (Fig.8).

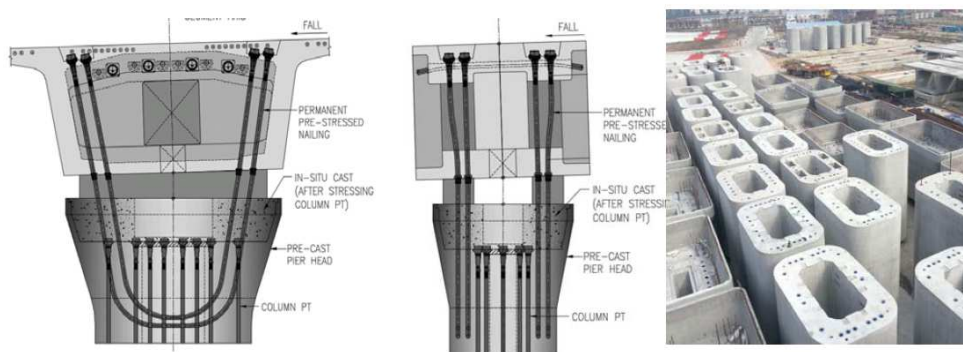


Fig.8. Deck-pier connection of the maritime viaducts ©photothèque BYTP

There are two types of columns: the monolithic ones with a full connection between the pier and the deck or the sliding ones with special bearings (MAGEBA). The pile caps are widened for allowing the transfer of deck loads. Regarding the seismic scenario, the special bearings are equipped by a fuse device in such a way that, under extreme loading, stopping devices will support transverse load effects.



Fig.9. Piers of the large viaducts ©photothèque BYTP

The piers of large viaducts are cast in-situ. The deck is fully connected to the twin-blade piers and is simply supported on sliding bearings at the extreme piers providing longitudinal displacement with transverse locking (Fig.9). This monolithic connection is an appropriate design for tall piers, as in ML03: it provides a longitudinal flexibility regarding linear deformations and longitudinal seismic loading.

The piers of land viaducts have 3.20x3.20 m sections, connected to a single concrete pile cast in a steel shaft (3 m diameter and 32 mm width) driven to bedrock. The usable cross-section in this bedrock has a diameter of 2.78 m (Fig.10).



Fig.10. Piers of the land viaducts ©photothèque BYTP

Decks

The typical cross-section of marine viaducts is a double deck of 4m. The carriageway is 14.80 m wide for each traffic lane with a traffic separator of 1.30 m (Fig. 11).



Fig.11. Deck of the marine viaducts ©photothèque BYTP

The deck is supported by two columns sitting on two triangular pile caps connected to three piles of 2.30 m diameter. The service galleries are precast with the segments.

The cantilever deck sections of marine viaducts are made of 2x10 segments, completed by two half-segments on piers. The construction is performed by the balanced cantilever method, with lifting equipment or launching gantries. The segments on piers are erected by cranes.

To reduce future maintenance effort, except the first internal piers, all other internal piers were constructed monolithically with the bridge deck. Although the span balance is not optimal, this regular spacing is necessary to fulfil the aesthetics required by the contract. A mixed prestressing scheme of using both internal and external tendons was employed in order to minimize the self-weight of the deck and reduce the erection cycle time. Internal cantilever tendons were provided to support the self-weight of the cantilever decks while external continuity tendons were used to resist the other loads. All external tendons were designed to be replaceable. Spare ducts were provided for the tendon replacement operation. In order to enhance the performance and constructability of these deflectors at deviator segments, a double curvature diabolo surface was adopted in the design instead of the conventional single curvature steel tubes that are commonly used in other projects in Hong Kong.

For large viaducts, the twin-blade piers were monolithically connected to the deck. This gives stiffness to the viaducts while movement joints and bearings (with transversal blocking) at the two ends provides freedom to creep, shrinkage and thermal movements. This structural scheme has resulted in strong interactions among decks, piers and foundations. The longitudinal behavior of the bridge is very sensitive to foundation stiffness especially for bridges with low piers, and therefore to seismic load cases or longitudinal movement effects. In order to reduce these effects, some of the bridge cantilever were jacked against each other prior to the stitch formation.

The deck is 16.82m wide. However, due to requirement on sight distance in tight horizontal alignment of 513m, the box in Bridge ML13 and ML14 together with a portion of Bridge ML12, has to be widened to 18.47m. In these areas, the two decks are connected transversely by a cross beam at the SOP. This structural arrangement has resulted in interaction between the two decks and the complicated portal behavior in both the longitudinal and transverse direction (Fig. 12).



Fig.12. SOP of large viaducts ©photothèque BYTP

The segment on piers (SOP) is one of the most complex structural elements in the deck design. It serves mainly two functions: firstly, transferring the longitudinal loads from the span to the blade piers and secondly, connecting the adjacent decks via the cross beam (Fig.13).

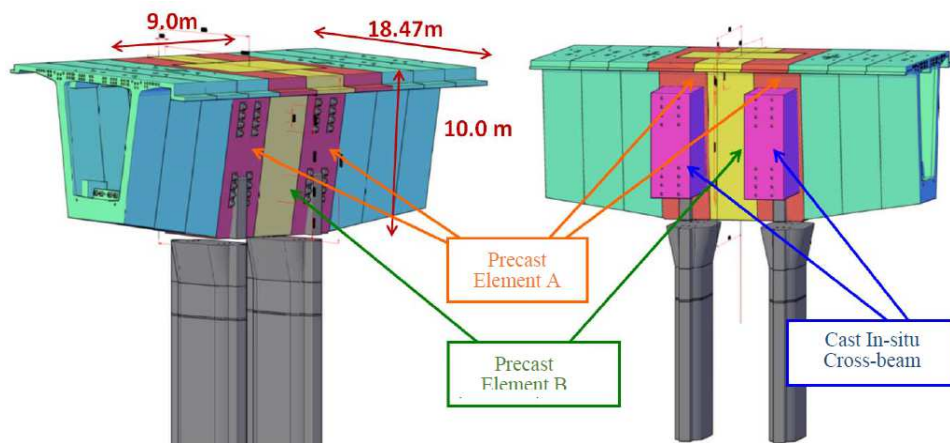


Fig.13. SOP on ML13/ ML14 viaducts ©photothèque BYTP

The SOP consisted of three numbers of 3m long segments which were formed by precast shell segment with subsequent infilled concrete cast together with the cross beam (Fig.13). Shear keys were provided at connection between precast and cast in-situ works. Transverse prestressing was employed to mitigate effects due to differential shrinkage and to enhance the beam's shear capacity.

The deck of land viaducts is sitting on cast in situ portal, each column being supported on a single pile. The five bridge units along the sea wall are twin decks, and the sixth one have 3 decks integrated into the portal structure. The viaducts are designed as precast segmental erected by the balanced cantilever method with overhead launching gantry. To enable adequate structural behaviour, side spans are on sliding bearings and intermediate ones, fully embedded into the portals.



Fig.13. Land viaducts ©photothèque BYTP



Standardization of segment design

The key to the success of a segmental bridge project is good standardization so that works can be executed in a controlled and repetitive manner. In this project, the segment geometry was carefully designed so that variation in construction method/ equipment (e.g. segment formwork) was minimized. For the typical 75m spans, constant segment box of 4m deep was used. For the long span decks (150m to 180m), the segment depth varied from 10m (max.) at pier to 4m at mid-span.

The segment design in the shorter spans was re-used in the long ones. For example, segments in typical 165m span would be re-employed in the 180m long deck; the 15m extra deck length was made up by additional segment types.

An off-site segment casting yard has been set up in Zhongshan of Mainland China since July 2013 with total 6 operation lines for casting over 5,694 numbers of precast deck segments. The yard is about 20 ha in size and equipped with all facilities such as concrete batching plant and lifting gantries for casting and handling of the segments. Three operation lines and 33 sets of formwork molds are dedicated for day-to-day segment production. The remaining lines are reserved for necessary repair and storage use. About 1,000 segments can be stored in the yard to cope with the actual deck erection cycle on-site. Two segment unloading jetties were set up with heavy duty cranes for unloading the segments directly onto the barges of different capacities (normally 2,500t or 5,000t) subject to the type of the segments.

Geometry control

Used in conjunction with Datums in-house software, a three-dimensional digital model is updated after each segment casting, and counter-mold is adjusted to get on following segment a geometry as close as possible to the sighted one. On site, first segment is adjusted versus the As Cast geometry in order to minimize any potential step at mid span stitch. Similar approach is adopted for both precast columns and decks.

Conclusions

The viaducts of the HKZM-HKLR are precast prestressed concrete structures constructed using segmental balanced cantilever method with span length ranging from 35m to 180m. About 7km of the viaducts are marine structures and some special techniques have been employed to tackle the challenges encountered in this project.

Prestressed method in the formation of monolithic deck-column connection and pier works is a new attempt in this project driven by the need to minimize the in-situ concrete works and to optimize the erection cycle time. Special design and construction considerations for the use of precast concrete shells in the marine pile caps and pier segments of the long-span viaducts are also novel ideas motivated by the construction requirements. On-site geometry control helps to analyze deviations and the SOP adjustment in order to reduce step at mid-span.

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