Challenges in Hong Kong – Zhuhai – Macao Bridge (HZMB) Hong Kong Link Road Project

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Summary

The Hong Kong Link Road (HKLR) is part of the prominent structure, Hong Kong-Zuhai-Macao Bridge (HZMB), connecting 3 vibrant cities in Southern China. The works which are administered under Highways Department of HKSAR comprises design and construction of approximately 9km of viaducts. About 7km of the viaducts are marine structures with three navigation channels.

The basic structural form of the viaducts is precast segmental prestressed concrete box girder. The span length of the viaducts ranges from 35m to 180m. Balanced cantilever method is selected due to the variability of the span lengths and flexibility in construction. The piers consist of both cast-insitu and precast concrete structures. The viaducts are supported on bored piles with diameters ranging from 2.2m to 2.8m. Foundation in areas with complex geology such as fault zones has posed a major challenge to the job. Some piles are over 100m long due to complex geology.

This paper presents the challenges and solutions employed in the design and construction of the viaducts. It describes the prestressed schemes employed in both the decks and piers with special details used in the formation of monolithic deck-column connections. The three main Challenges on the project were the erection in open sea, the vicinity of the Airport and envirinmental constraints.

Keywords: Precast segment, Durability, Seismic Design and Response, Sustainability.

1. Introduction

The Hong Kong – Zhuhai – Macao Bridge (HZMB) will be one of the longest cross-boundary sea-crossing road infrastructure in the world 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. It is an essential transport construction project included in “National High Speed Road Network Planning”. The Hong Kong Link Road (HKLR) under Highways Department’s Contract No. HY2011/09 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 viaducts in this project consist of 115 spans and can be categorized into different character zones of structures. In the Western Waters, the viaducts are characterized by regular spans of typical 75m intertwined with two 1-way navigation spans of 150m. 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. Towards the east of the headland between San Shek Wan & Sha Lo Wan, viaducts in the Airport Channel are all long-span structures over 100m (max. 180m) meandering in a double S curve in the Channel and merge with the viaducts on land. About 2km of the land viaducts are along the southern side of the Airport Island with variable span lengths to suit for the ground constraints (See Figure 1-1).

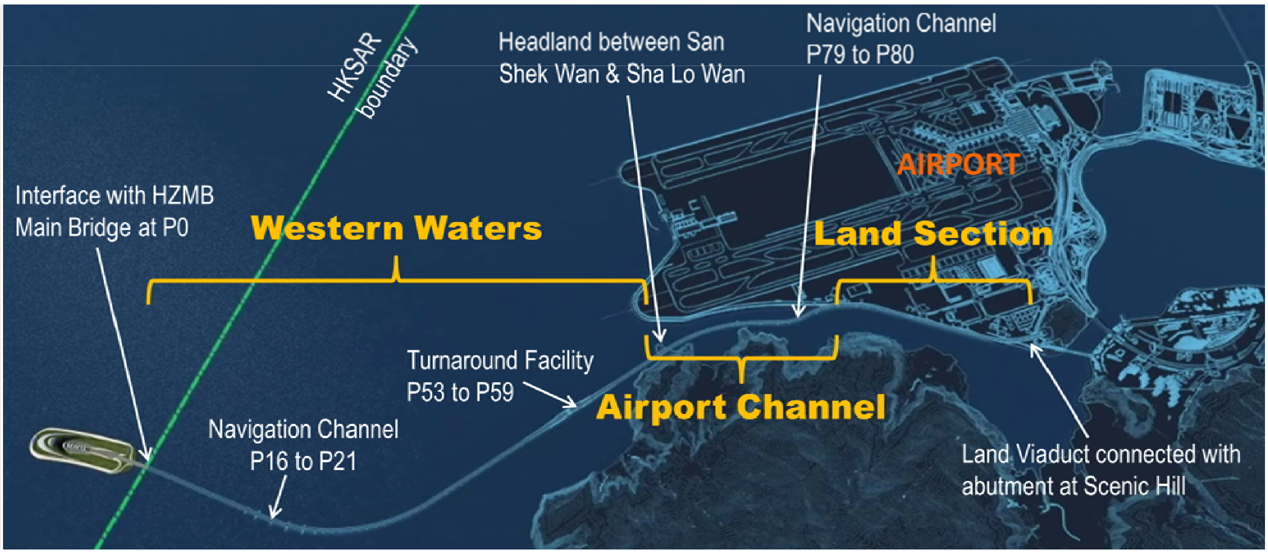

Figure 1-1 – General Layout & Location Plan of HZMB HKLR Project

2. Site Characteristics & 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. Long-span decks are continuously employed in the Airport Channel where a 2-way navigation channel of 46m is provided. All pile caps within the Airport Channel are embedded below existing seabed in order to minimise 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 (AHR) pursuant to the Hong Kong Airport (Control of Obstructions) Ordinance.

3. Design Criteria

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 and the Employer’s Requirements as part of the contract documents. In general, the viaducts are designed for ultimate limit state (ULS) and serviceability limit state (SLS) according to BS5400 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 (SILS). Eurocode 8 – Design of Structures for Earthquake Resistance, Part 1 – General Rules EN1998-1:2004, Part 2 – Bridges EN1998-2:2005 & Part 5 – Foundations EN1998-5:2004 were employed in the seismic design. However the two seismic performances in EN are extended to 3 performance requirements of “no damage”, “repairable damage” and “no collapse” with the corresponding 3 levels of seismic design actions. In the design for ship impact, reference was made to Ship Collision with Bridges by International Association for Bridge and Structural Engineering (IABSE) and Guide Specifications & Commentary for Vessel Collision Design of Highway Bridges by AASHTO.

4. Pile Foundation

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. Generally the piles were designed as end-bearing piles socketed in Category 1(c) or Category 1(b) bedrock with allowable end-bearing capacity equals 5,000kN/m2 or 7,500 kN/m2 respectively. The friction resistance in the CDG and alluvium were generally ignored.

The long piles are located mainly in the marine viaducts in Western Waters 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, CDG and SDG of variable depth. In some location, bedrock exceeds 100m below sea level. Friction bored piles are employed for such deep bedrock locations given the limitation of the piling machine. These piles are both shaft and toe-grouted.

5. 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 with diameter of 2.3m, 2.5m or 2.8m.

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.

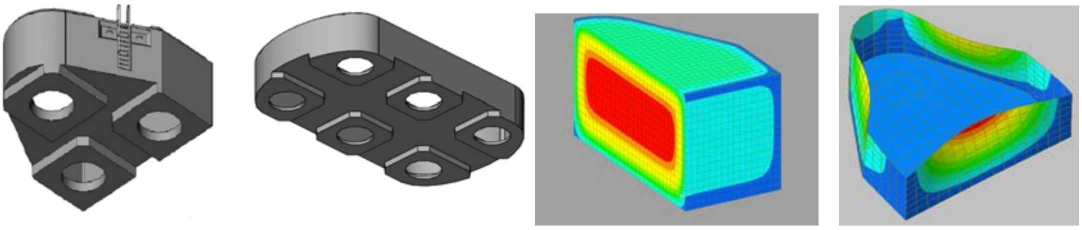

Figure 5-1 – Typical Precast Concrete Shells (3D Views) and Finite Element Model of Pile Cap

There are 7 types of generic concrete shells including that for the dolphin structures. The 3D views of some shell structures are shown in Figure 5-1. In a typical shell (e.g. CP1), 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.

Due to the complex shell geometry, 3-dimensional finite element analyses were conducted to simulate the structural behavior of the system in different stages (See Figure 5-1). 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.

Figure 5-2 – Precast Shell

Driven by the need to release the thermal strain induced in the shell, a novel idea of thermal-structural insolation was conceived in the design. A thin layer of isolating material with specific mechanical & thermal property was introduced and mounted on all inner faces of the shell.

6. Piers

In the Western Waters, tall piers except the twin-blade piers in long-span decks were designed as precast prestressed concrete structures. The typical pier section is hollow with typical external dimension of 5.0mx3.2m and internal dimension of 3.0mx1.5m. A typical precast column unit is 6m and an in-situ stitch of 400mm 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. Some tendons are embedded into the pile cap while some are in the in-situ base due to space limitation and ductility requirement at the column base. The tendons are anchored at the pier head instead of the pier segment so that these two construction activities are delinked. The prestressed piers in this project were designed as Class 1 structure under the service load combinations as stipulated in the SDMHR.

The monolithic connection between the pier segment and the pier was achieved using prestressing instead of reinforcement (see Figure 6-1). All structural components were precast. This method is a new attempt in the practice in Hong Kong and is driven by the need to minimize the in-situ concrete works in the marine environment and to optimize the erection cycle time. After the pier segment was installed with geometry adjusted, its spatial position was fixed on temporary supports. The precast plinths would then be grouted prior to application of the vertical nailing prestressing in the formation of the monolithic joint. The U-shape nailing tendons used in this project were designed to be anchored on top of the pier segment so as to facilitate the stressing operation.

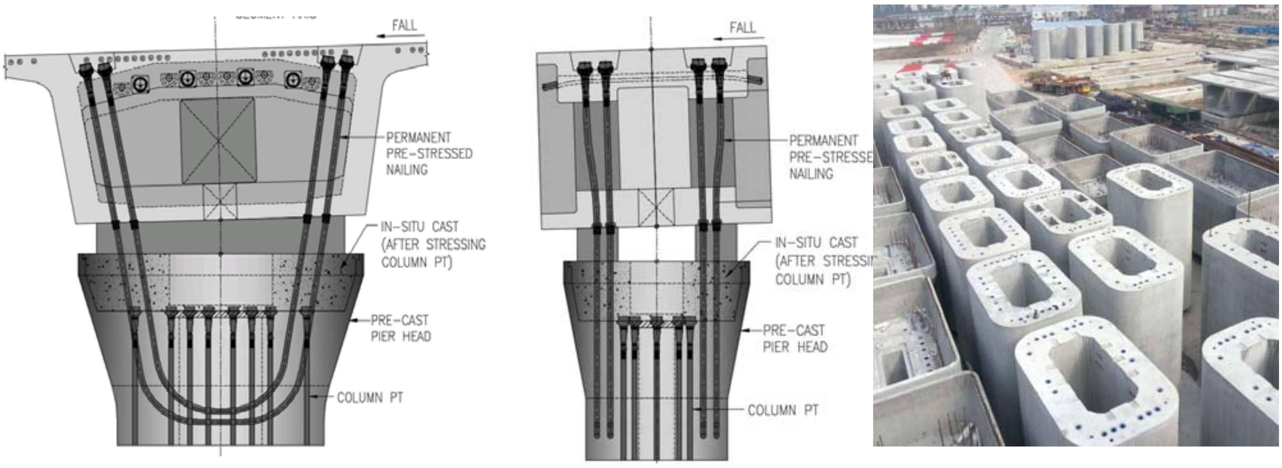

Figure 6-1 – Monolithic Deck-Pier Connection with Prestressing & Precast Pier Units

7. Decks

In the early stage of the project, various structural schemes were investigated in order to satisfy the site constraints and functional requirements of the project. To span over 180m, 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.

7.1 Marine Viaducts with Typical 75m Span

The typical span length of the marine viaducts in Western Waters is 75m with a constant box depth of 4m. In the articulation design, a typical bridge unit of 8-span continuous deck (600m long) was adopted with optimal use of bearings and movement joints so as to reduce future maintenance effort. Other than the first internal piers, all other internal piers were constructed monolithically with the bridge deck.

To improve the aesthetics, the length of the end span was made the same as the internal ones in order to provide a regular rhythm of the spans. (See Figure 7-1).

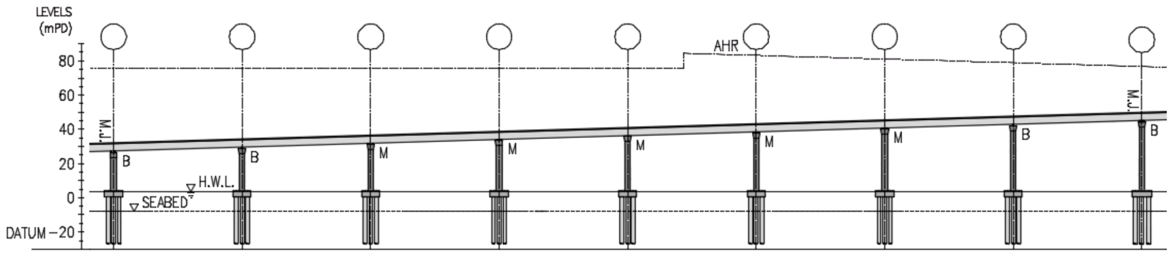

Figure 7-1 -Bridge Unit in Western Waters (8x75m)

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 & internal span 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.

7.2 Long-Span Viaducts with Spans 150m to 180m

Long span viaducts were employed in the navigation channels in the Western Waters (Bridge ML3) and the viaducts near the headland and Airport Channel (Bridge ML10 to ML14). The navigation channels in Western Waters was 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 (see Figure 7-2).

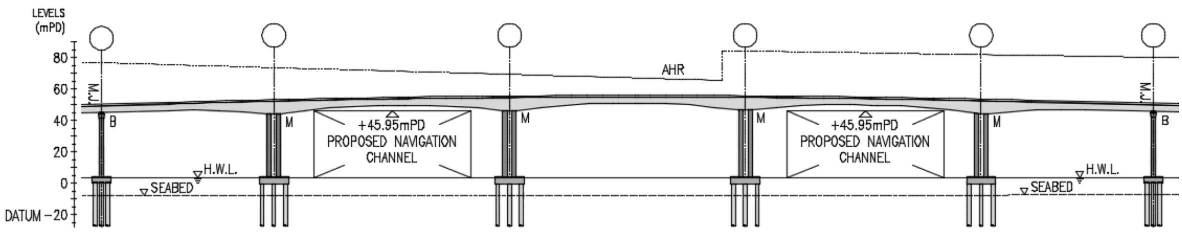

Figure 7-2 - Navigation Channel Unit in Western Waters (109.7+3x150+109.7m)

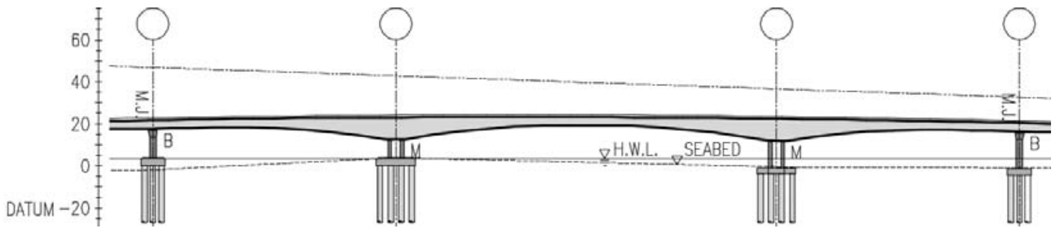

Figure 7-3 - Headland Unit (115+180+115m)

In the headland, a 3-span continuous structure with a 180m long clear span in the centre with two 115m long end spans was employed to span over an archaeological site in the island. (See Figure 7-3). In the Airport Channel, 4 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 SOP. Monolithic internal twin-blade piers provides strong fixity for the long span decks and bearings at two ends allow releases of the large movements due to creep, shrinkage and thermal effects.

The requirements on temporary stabilizing system during cantilever erection will be minimized with deck-pier monolithic connection. However, this articulation 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 e.g. the vaiducts in the headland and Airport Channel. The longitudinal portal frame behavior will result in large tension in the piles due 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.

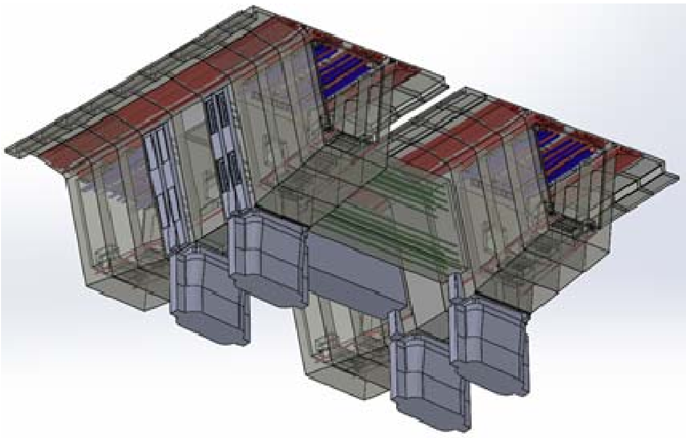

Figure 7-4 – SOP & Cross Beam

In this project, the decks in two carriageways are generally separated with typical box width of 16.82m. 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. (See Figure 7-4). This structural arrangement has resulted in interaction between the two decks and the complicated portal behavior in both the longitudinal and transverse direction.

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

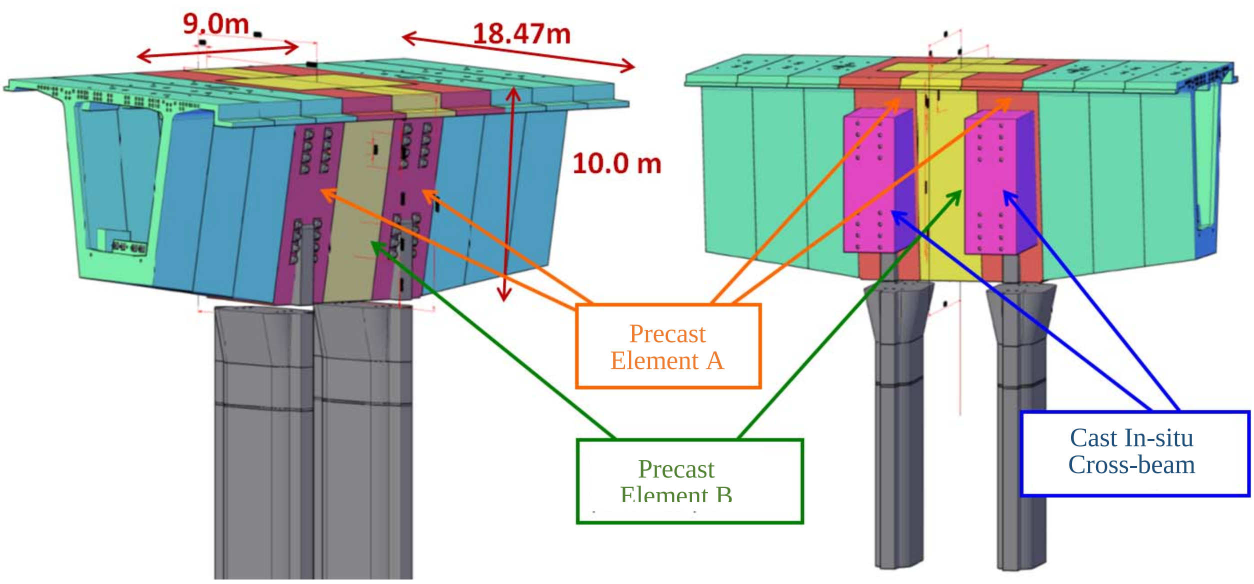

Figure 7-5 - Dimensions of SOP on Bridges ML13/ ML14

7.3 Land section with span lengths from 35 m to 65 m

The deck in this area is sitting on cast in situ portal, each column being supported on a single pile.

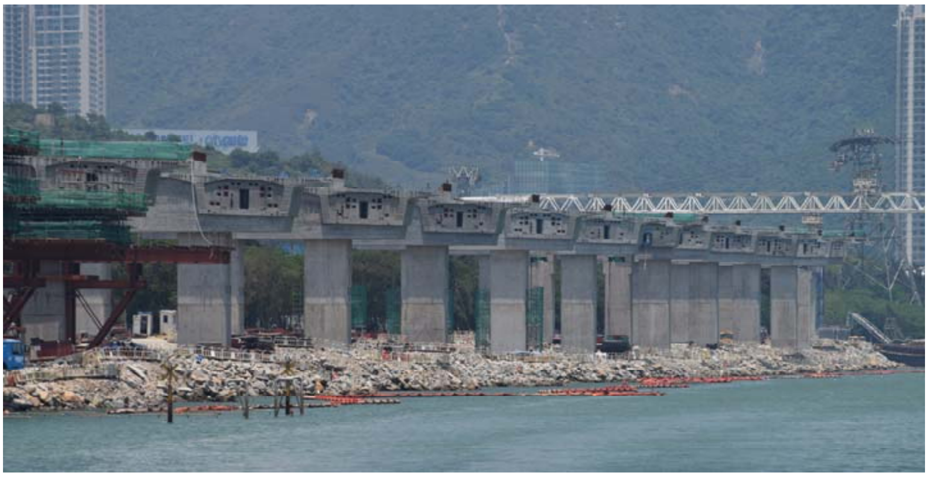

Figure 7-6- Land section Portals

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.

Figure 7-7- Land section Portals

7.4 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 to180m), 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.

8. Casting Yard

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 moulds 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. A liaison & logistic control team was formed to manage the logistic and deployment of barges for the delivery taking into account all factors such as traveling distance (approx. 23NM), numbers of segments per barge, weather condition and actual deck erection cycle time on site.

9. Geometry Control

Used in conjunction with Datums in-house software, a three-dimensional digital model is updated after each segment casting, and countermould is adjusted to get on following segment a geometry as close as possible to the sighted one. Statistical analysis is carried out to confirm the As Cast shape.

On site, first segment is adjusted versus the As Cast geometry in order to minimize any potential step at mid span stitch. Any potential misalignment is identified at very early stage by analysing the erection follow up tables.

Similar approach is adopted for both precast columns and decks. At casting yard, the shape between the column segment to be cast and the countermould one is recorded, and the final geometry calculated superposing the achieved geometry between the two segments.

Figure 9-1- Column Erection

10. Conclusion

The viaducts of the Hong Kong Link Road under Contract No. HY/2011/09 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 environment.

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. Geometric characteristics in the design and on-site geometry control/ erection follow up involve challenging technique adopted in this project particularly for the long-span viaducts of maximum 180m span length using the balanced cantilever erection method.

11. Acknowledgements

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