PRECAST SEGMENTAL AERIAL GUIDEWAY FOR HONOLULU RAIL TRANSIT CORRIDOR PROJECT

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ABSTRACT

The Honolulu Rail Transit Project (HRTP) includes the design, construction and operation of a 20-mile grade-separated fixed guideway transit system in Honolulu, Hawaii. The alignment of the project traverses densely developed urban areas, over Interstate highways, streams, or existing streets, etc. The majority of the guideway is elevated to avoid any potential conflicts with the existing facilities and utilities.

AECOM was retained by Honolulu Authority Regional Transit (HART) to perform the design of the 5.2-mile Airport Segment and 4.2-mile the City Center Segment of HRTP. Precast concrete segmental box girders, erected span-by-span with an overhead launching gantry, were proposed to accommodate a 30.6-ft-wide dual track cross-section. The maximum precast guideway span length is 165-ft for continuous spans and 150-ft for simply-supported spans. The structure was designed to handle a very tight horizontal curve of 400 feet.

The paper describes the background and current status of the project and provides insight for the innovative design approach, cost-effective structural arrangement, and key design considerations for the precast concrete segmental elevated guideway.

Keywords: Precast, Span-by-Span, Segmental, Transit, Aerial Guideway

INTRODUCTION

The Honolulu Rail Transit Project (HRTP) includes the design, construction and operation of an approximately 20-mile grade-separated fixed guideway transit system in Honolulu, Hawaii. Figure 1 displays the guideway alignment of the entire HRTP project. The project consists of four major sections: West Oahu/Farrington Highway, Kamehameha, Airport, and City Center Sections. The West Oahu/ Farrington and Kamehameha Sections have already been awarded as design-build contracts and are currently under construction. Under contract to the City and County of Honolulu, AECOM is providing design review on behalf of the Hawaii Department of Transportation (HDOT) for these two design-build sections that utilize mainly precast concrete segmental guideways. The article will focus on the aerial guideway structures for the Airport and City Center Sections. AECOM was retained by Honolulu Authority Regional Transit (HART) to perform final design for both of these guideway sections. The guideway alignment of the project traverses densely developed urban areas, over Interstate highways, streams, or existing streets, etc. The majority of the guideway is elevated to avoid any potential conflicts with the existing facilities and utilities.

The Airport Section consists of approximately 5-1/2 miles of aerial guideway between the vicinities of Aloha Stadium and the Middle Street Transit Center. The Airport Section follows Kamehameha Highway, H-1 Freeway, Aolele Street through Honolulu International Airport, Ualena Street, and crosses Ke'ehi Lagoon Drive and terminates at the Middle Street

Transit Center. The guideway is generally situated within existing public roadways and public properties to minimize impacts to private properties.

The City Center Section is comprised of approximately 4.2 miles of aerial guideway transit structure through the urban core of Honolulu. The City Center Section begins just past the Middle Street Transit Center follows Dillingham Boulevard in the vicinity of Ka'aahi Street and then turns east to connect to Nimitz Highway near Iwilei Road. The alignment follows Nimitz Highway to the Central Business District where it turns down Halekauwila Street passes the Federal Building, the redevelopment of Kakaàko and splits into two single track segmental boxes at its terminus at Ala Moana Mall.

PRECAST SEGMENTAL SPAN-BY-SPAN SOLUTION

Given the large size of the project and the desire to minimize impacts on surrounding urban areas, match cast, precast concrete span-by-span segmental box girders are proposed for the Airport and the City Center Sections. Precast segmental span-by-span construction has successfully been used for large light rail transit projects in urban congested environment, such as a 24.3 km of elevated light-rail viaduct in downtown Bangkok for Bangkok Mass Transit System, and a 16.5 km elevated guideway for Vancouver Skytrain Millennium Line. Figure 2 shows an example of a typical precast concrete segmental elevated guideway erected by the span-by-span method with an overhead gantry.

Figure 2. Example of Span-by-Span Construction for Precast Segmental Guideway

One of the advantages is that the precast segments can be cast at the same time that the substructure elements are being built. This has a great impact on shortening the construction schedule. Another advantage is that the segments for the superstructure guideway are manufactured in the factory-like setting of a precast yard where high degrees of quality control are possible resulting in a finished product of highest quality. Much of the economy of the precast segmental bridge construction results from the standardization and industrialization of the segment manufacturing process. Precast segments made individually in casting cells can readily be cast curved and adjusted to change the cant of the track if necessary. The repetitive nature of the casting operations allows for the maximum labor efficiency and the minimum of errors. Figure 3 shows a number of precast box segments in storage at the casting yard. When design details permit repetition of daily activities, one segment per day can be achieved from each casting cell with a relatively small production crew.

Figure 3 Precast Concrete Segments in Storage Area (from HART)

Precast segmental construction using a short-line match casting method also offers very accurate geometry control. Tolerances are in the order of fractions of an inch and any deviation in excess of this will result in misalignment of the bridge that becomes more critical when there are horizontal and vertical curves in the guideway alignment.

AERIAL SUPERSTRUCTURE GUIDEWAY OVERVIEW

Simply supported precast concrete segmental spans are used for the vast majority of tangent and curved guideway superstructure. Span lengths vary from 55 feet to 150 feet with a typical span of 140 feet. The precast superstructure guideways are to be constructed span-by-span with an overhead gantry. Approximately 195 simply-supported spans at the Airport Section and 180 simply-supported spans at the City Center Section would be erected in this method. At three locations, for a longer span exceeding 150-foot span, two-span continuous precast segmental spans are proposed, with lengths up to 165'-3". Also, there is one location with a tightly curved alignment that required three-span continuous precast segmental spans to handle the uplift arising from the alignment curvature. The precast segmental span-by-span erection method is also used to construct these continuous spans with additional temporary supports being used at the intermediate piers.

GUIDEWAY CROSS-SECTIONS

Two types of precast concrete segmental box segments are designed, a double track box girder and a single track box girder segment. The double track box girder accounts for the vast majority of the project and it is designed to handle two tracks. The box girder is a single cell trapezoidal box girder with a depth of 8'-6" at centerline of the box. Figure 4 shows a typical section for a double-track guideway. The 8'-6" segment depth was developed to provide an optimum section for a typical 140-foot span. To provide sufficient space for maintenance and inspection of the box girders, the minimum interior clear height is typically set at 6'-0". The box depth was established considering both the minimum first-mode natural frequency criteria (not less than 2.5 Hz) and the AASHTO LRFD SERVICE limit state longitudinal stresses (no tension stresses allowed after all losses). The top slab of the cross-section was developed to accommodate the safety of walkway and facilitate drainage between the tracks.

The double-track box girder is designed to handle widths varying from a typical 30.5' to 34' at the track crossover sections. The structure was designed to handle a very tight horizontal curve of 400 feet for shorter spans. The top slab is transversely post-tensioned. The track is supported on longitudinal plinths cast on top of each box girder. Spans consist of individual typical segments varying in length from 6'-7" to 10'-3". Located at either end of the span is 6'-7" long diaphragm segment for simply supported spans. The segment length was developed to account for the maximum weight allowed for the lifting segment and the casting module. Segments will be match-cast to include variations in plan and elevation of alignment. The superelevation will be addressed through the cant of up 6" that can be introduced in cast-in-place plinths on top of box for each track after the completed spans.

The single track box girder is used at the Ala Moana terminus of City Center Section. There are 11 spans, comprising 1,127 feet: the cross-section splits into two 17'-9" wide single-cell trapezoidal box girders each supporting a single track (see Figure 5). The single track box cross-section was dimensioned similarly to the dual track section to allow the dual track casting formwork to be modified for casting the smaller segments.

The constant depth and web inclination also allow for a seemingly seamless visual transition at the merge areas within the alignment. The single track box girder has a constant depth of 8'-6" at center line of girder as well. External post-tensioning is located within the box girder. The post-tensioning is anchored at each of the two diaphragm segments and is typical deviated within the box girder at ¼ points.

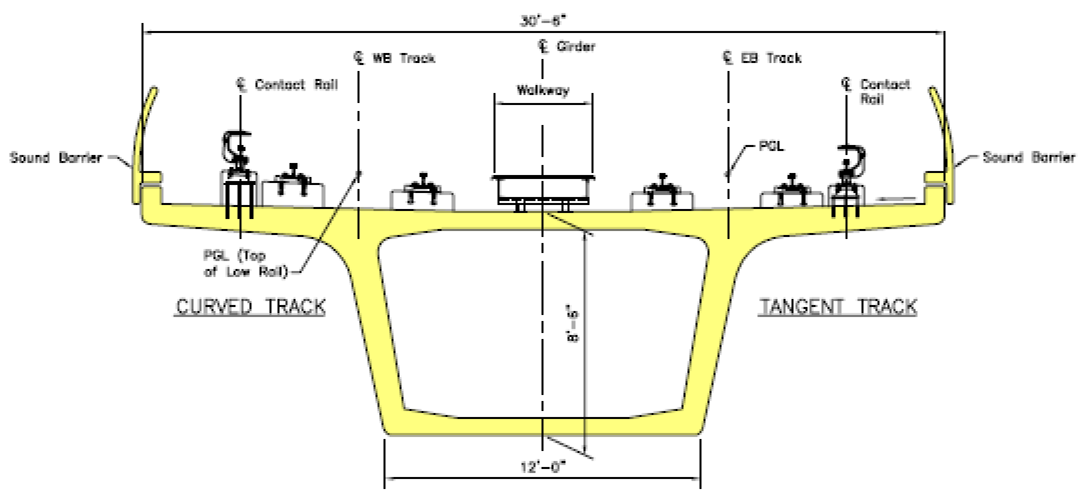

Figure 4 Typical Dual Track Cross-sections

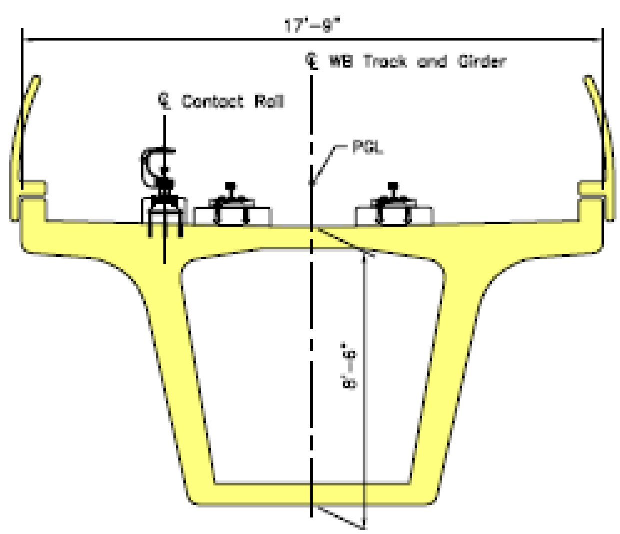

Figure 5 Typical Single Track Cross-Section

ANALYSIS OF PRECAST GUIDEWAY SUPERSTRUCTURE

The design of the aerial guideway is in accordance with HART's Compendium of Design Criteria, AASHTO LRFD 5th Edition, and Design Criteria for Bridges and Structures (HDOT). The precast concrete segmental guideway is designed for Serviceability

limit states (1) full prestressing with minimum compressive stress (2) shear transfer in the joints (3) no uplift at bearings, Strength limit states- opening of the joints and load transfer in the joints, and Extreme limit states- derailment and seismic events. A three-dimensional frame model was developed for the spans using the program CSI Bridge to determine the longitudinal bending moment, shear & torsion, reactions for bearings and diaphragms, and camber growth and live load displacement. Various loads were considered in the model, such as self-weight (DC), superimposed dead load (DW), longitudinal post-tensioning; live load-light metro vehicle (LMV), rail-structure interaction force (TTR & TLR), creep & shrinkage, thermal effects, centrifugal force, derailment loads (DR), longitudinal forces (LF) due to accelerating and decelerating trains, and restraint of continuous welded rail (CWR), rail facture (RF), wind loads, and seismic loads.

The superstructure was subdivided into elements in the model in accordance with the segment layout for the spans. Span curvature was explicitly modeled to determine torsional effects. Staged construction sequences as per the contract drawings were incorporated in the model. Post-tensioning tendons were explicitly modeled in three-dimensions to properly include all relevant prestress losses.

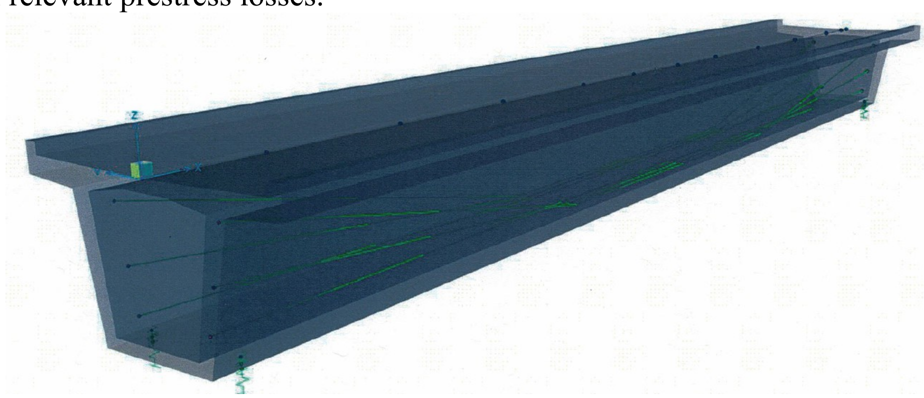

Figure 6 CSI - 3D Model

GUIDEWAY VIBRATION

It is essential to limit potential dynamic interaction between aerial guideway and light rail transit vehicles; therefore, the superstructure was designed so that the natural frequency of the first mode of vibration of the precast guideway is not less than 2.5 Hz. In addition to estimate the first natural frequency using a simply supported beam formula, the full three-dimensional the superstructure guideway for a typical span was created in ANSYS

Workbench by generating the various parts of the geometry. The resulting of the modal analysis of the precast box girder was presented by the first 10 natural frequencies and mode shapes, see Figure 7.

For a few longer spans exceeding 140 feet, a rolling stock analysis using actual LRV's configuration would be needed to verify for those spans with a first mode natural frequency less than 2.5 Hz.

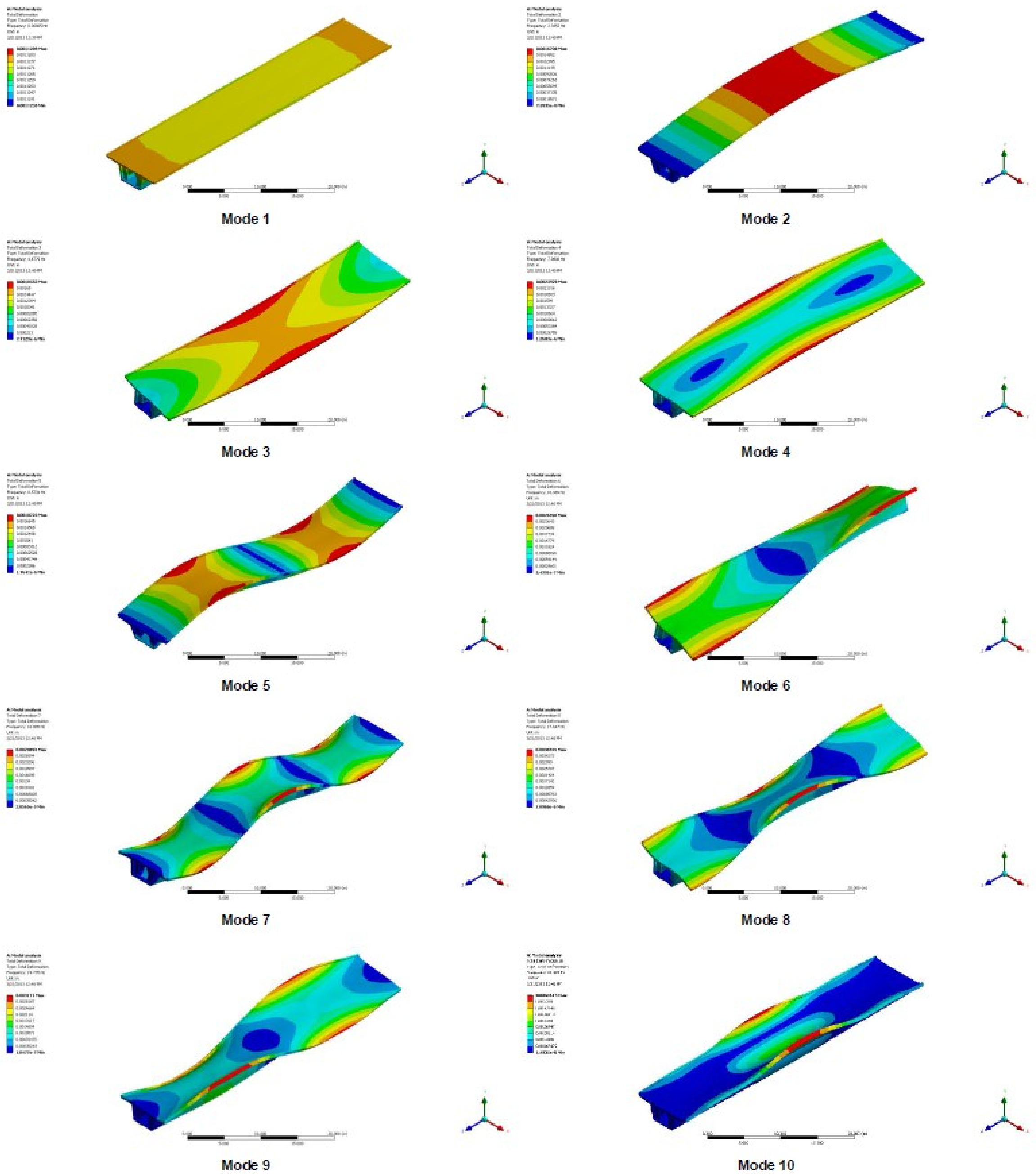

Figure 7 Partial Mode Shapes and Frequencies

SIMPLY-SUPPORTED BOX GIRDER DESIGN

A typical span, shown in Figure 8, has a length of 140 ft that is divided into 15 concrete segments varying length from 6’-7” at diaphragm segments to 9’-10” at typical segments. A nominal gap of 1” is provided between the centerline of each pier to each end of the span, allowing for full movement due to thermal effects at the expansion joints. Diaphragm segments are used at each end of the span in order to receive and anchor longitudinal post-tensioning tendons and distribute bearing reactions. The external post tensioning tendons- 4x19 tendons per web are placed longitudinally inside the trapezoidal box girder, but external to the concrete cross-section. They are draped and deviated at each deviator segment. For external tendons, steel pipe ducts with a minimum of 9 feet tendon radius are used for the curved portions of tendon profile in the deviator segment. Additional closed stirrups are provided around each individual steel tendon ducts to resist tendon deviations forces at each deviator ribs, see Fig 10 for the deviator rib reinforcing details.

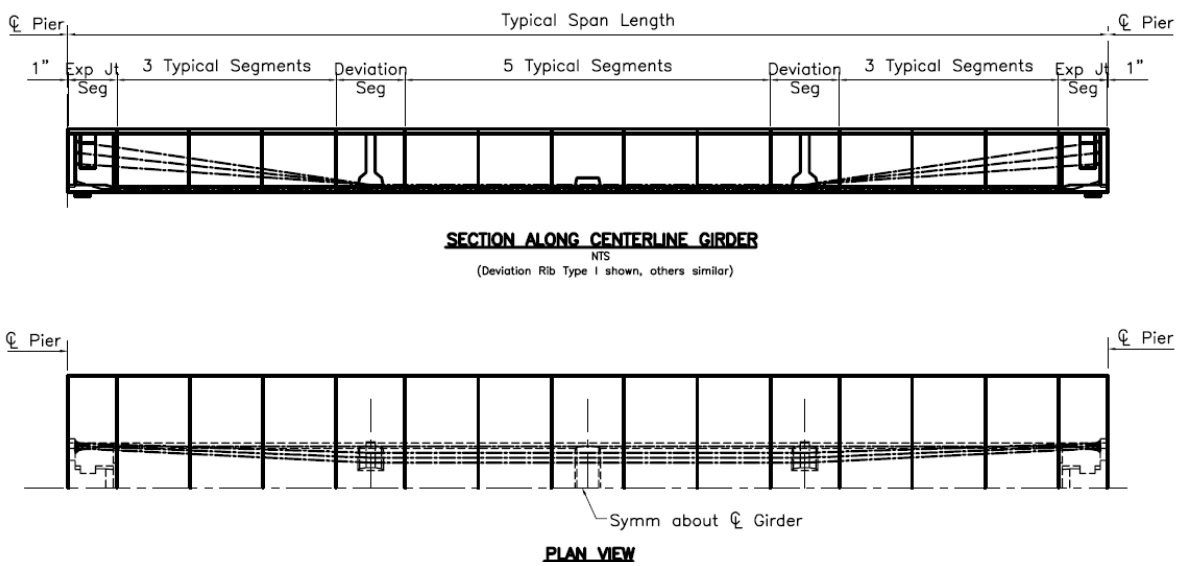

Figure 8 Typical 140-ft Simple Span Layout

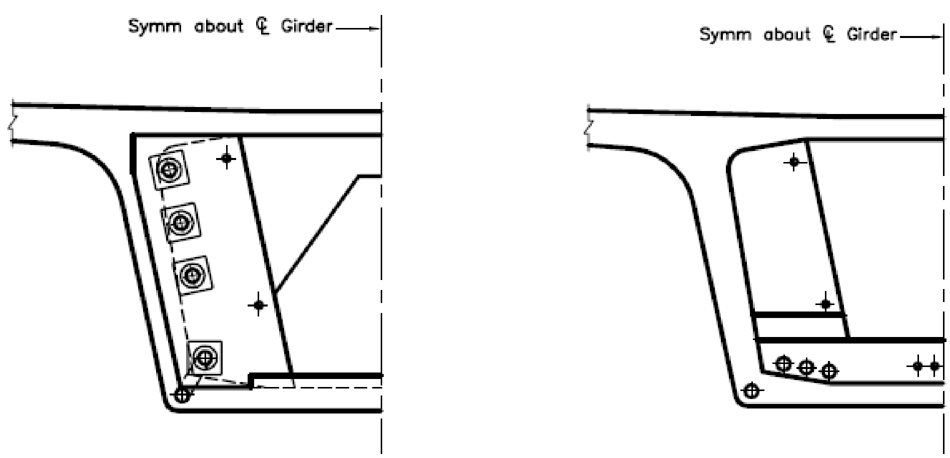

Figure 9 Diaphragm & Deviator Segments for a Typical Simple Span

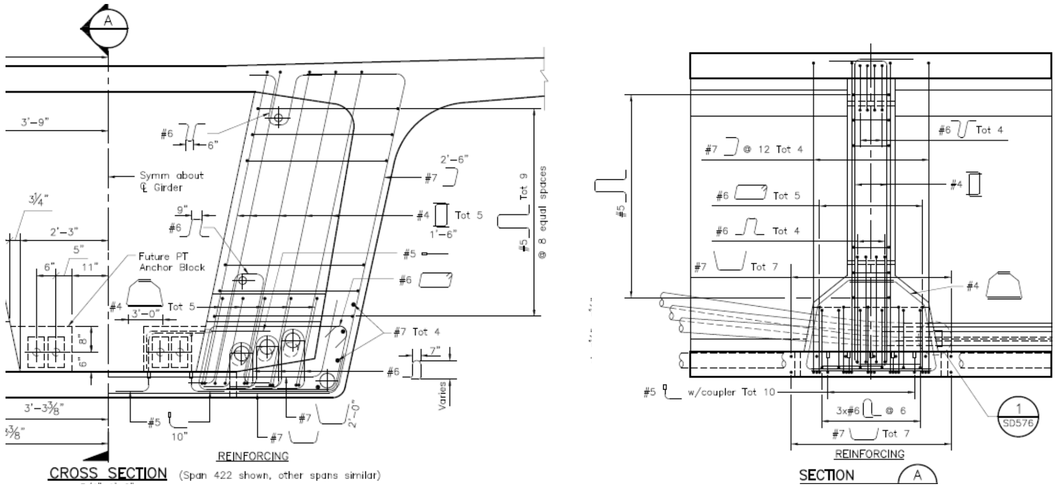

Figure 10 Typical Deviator Rib Reinforcing Details

As shown in Figure 11, the jointing face of the segments has a number of shear keys that are designed to transmit the shear force. Shear keys in each web of the segments extend for as much as of the web depth and shear keys are placed in the top and bottom slab for the horizontal alignment to prevent the shifting of the slabs between segments.

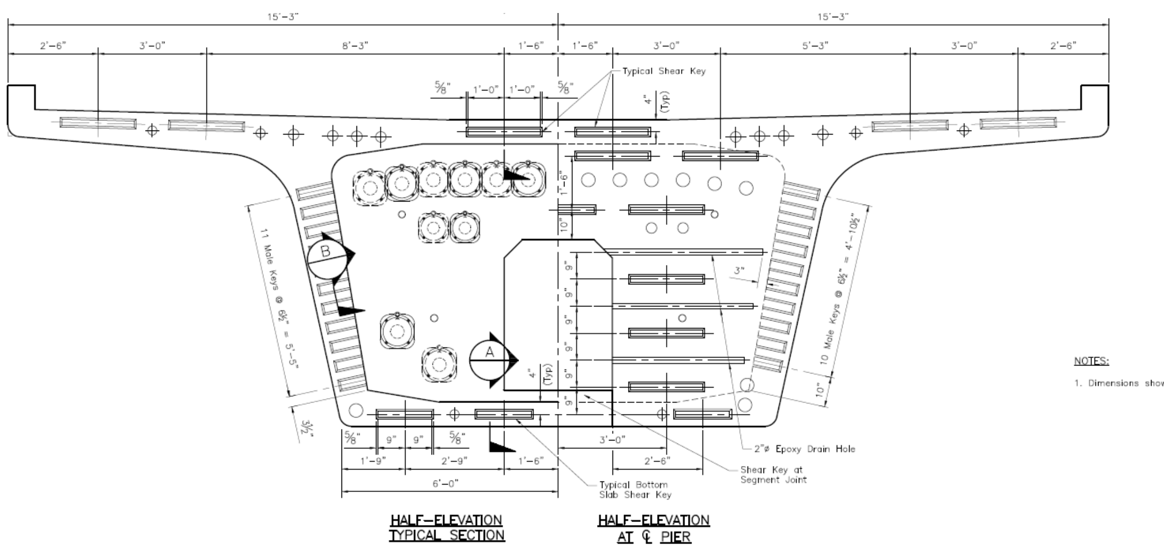

Figure 11 Typical DT Segment Bulkhead Details

TWO-SPAN CONTINUOUS BOX GIRDER DESIGN

The two-span continuous span, shown in Figure 12, has a length of 165’-3” + 165’-3”, that is divided into 17 concrete segments plus ½ pier segment per span varying length from 6’-7” at end diaphragm segment to 9’-10” at typical segments. Diaphragm segments are used at each end of the span to receive and anchor longitudinal post-tensioning tendons and distribute bearing reactions. Pier segment is used at the middle pier to allow longitudinal post-tensioning tendons to be overlapped and anchored at each face of the pier segments. See Figure 13 for the associated details.

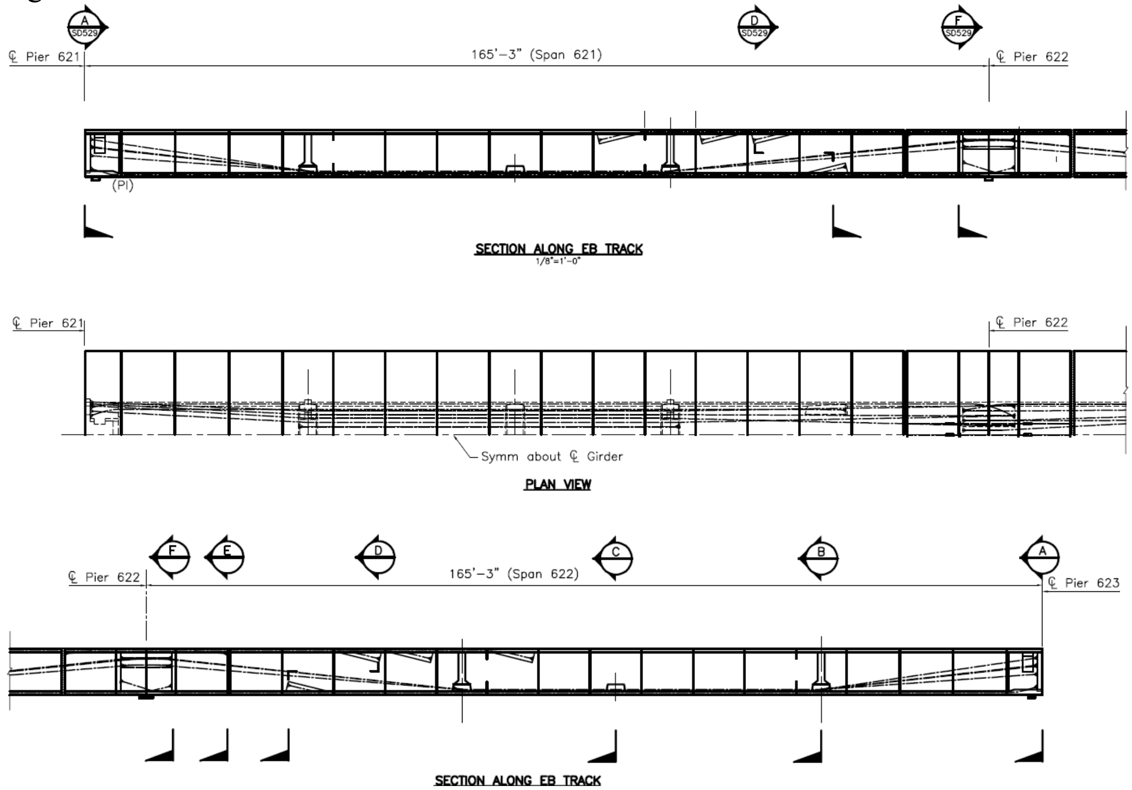

Figure 12 Two-Span Continuous Segment Layouts

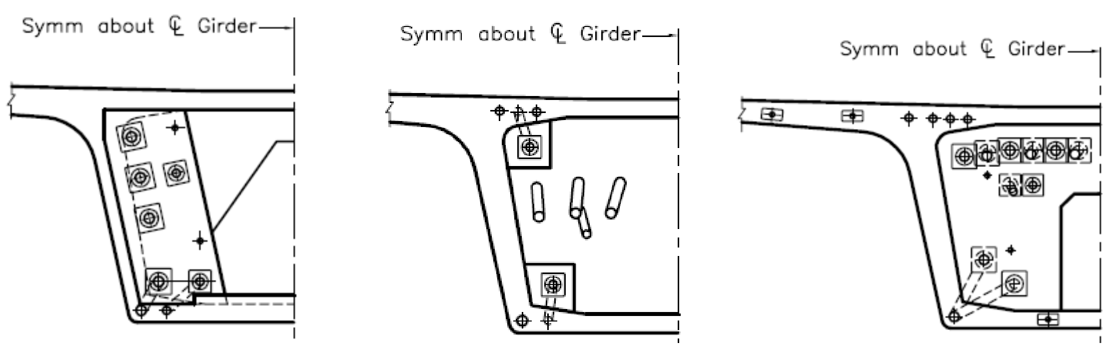

Figure 13 End Diaphragm, Anchor Blocks, & Pier Segments for a Two-Span Continuous

SPECIAL TRACKWORK GUIDEWAY DESIGN

The crossover spans are in the tangent portions of the guideway in order for crossover tracks to utilize standard turnout geometry. Switch machines use rods below the tracks to move the rails at the point of switch in the frogs. To accommodate the stitch and special trackwork, the tracks are supported on a 6" thick overlay instead of directly on the deck. Longitudinal analysis of the spans has increased forces from rail/structure interaction, as well as additional dead load. The special trackwork has fixed fasteners as well as different spacing of the typical rail fasteners. The transverse PT and reinforcement is designed for the extra weight of overlay and for wheel loads that can be in the middle of deck.

Track crossovers require a length longer than a simple span. To keep the special trackwork aligned, a link slab, see Figure 14, is used to prevent longitudinal displacement between the spans. The link slab must resist the longitudinal force generated by rail/structure interaction. Shear friction reinforcement is provided between the girder and link slab. Bending of the link slabs occurs from wheel loads and deflections of the adjacent spans. A portion of the link slab is designed to flex independently from the spans to reduce the induced bending from rotations and vertical deflections of the adjacent spans. The cracked section stiffness of the link slab shall be used to determine bending from adjacent span rotations and deflections.

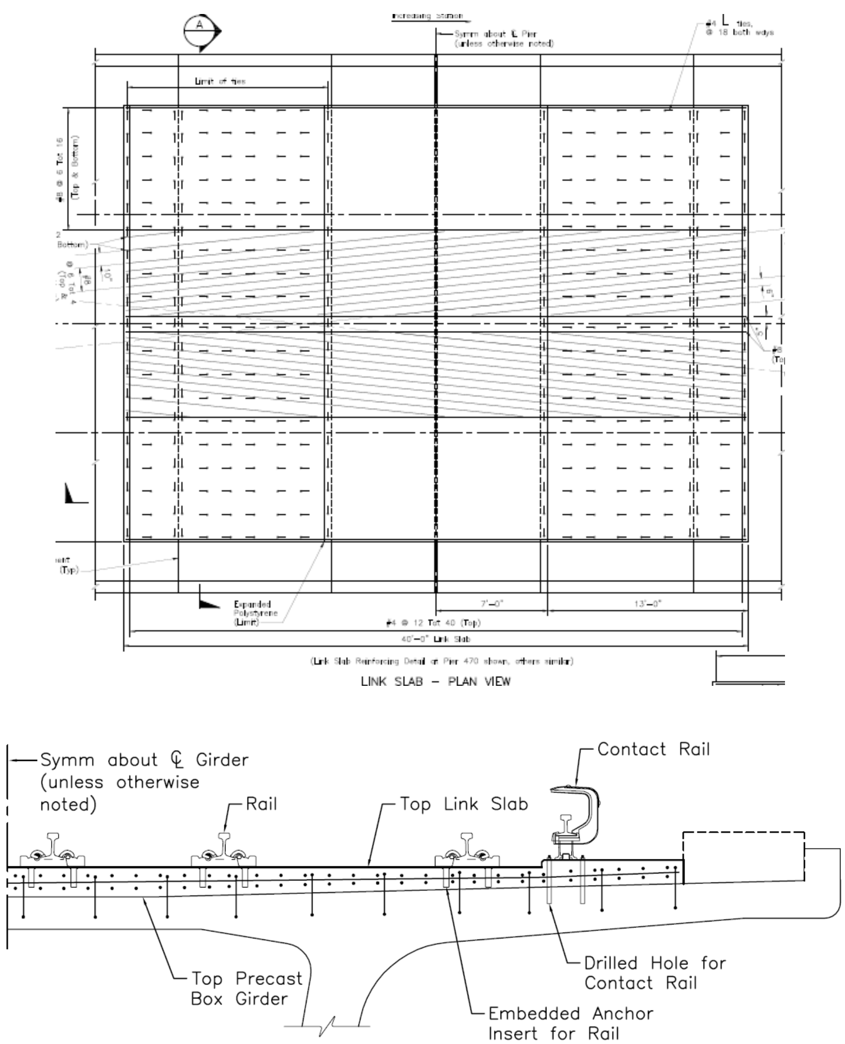

Figure 14 Link Slab Plan View and Detail at Special Track Guideway

PROPSED SPAN-BY-SPAN ERECTION METHOD

All of precast segmental spans, including simply- supported spans and continuous spans, are designed to be erected using span-by-span method with overhead gantry. For simply supported spans, erection of precast segments is limited to a maximum of span length of 150 feet. For a longer span exceeding 150-foot span, a temporary falsework would also be needed to support pier segment and the first pair of segments near the middle pier. Additional PT bars and cantilever tendons are provided to resist a much large bending member due to the continuity of the spans. The overlapping longitudinal tendons over the pier segments would be required to anchor tendons at each face of the pier segments.

<u>Suggested Construction Sequence Schematic for Typical Simply Span Unit (see Figure 15</u>):

Stage 1- Gantry Advancement:
Previous span complete, advance overhead forward to the position shown

Stage 2- Segment Placement:
-Deliver segment underneath the span to overhead gantry.
-After all segments are hung from overhead gantry; adjust grade & alignment of each segment. Leave a gap between segments for application of epoxy

Stage 3- Epoxy and Stress Tendons:
-Apply epoxy in joints between segments and stress together with temporary PT bars.
-Install and stress permanent longitudinal post-tensioning tendons
- Remove temporary PT bars. Release segments from gantry on to bearings

Stage 4- Gantry Advancement:
-Advance overhead gantry forward to next span

Stage 5- Segment Placement:
-Repeat Stages 3 and 4.

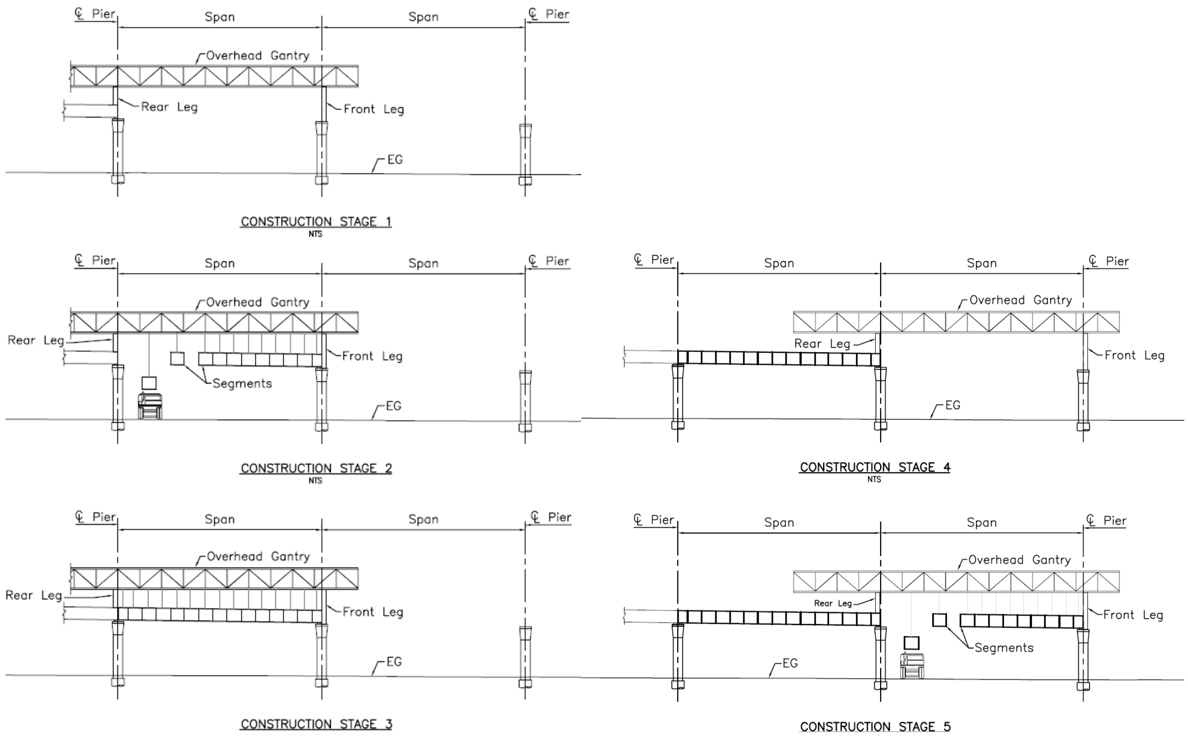

Figure 15 Suggested Construction Sequence Schematic for a Typical Simply Span

Suggested Sequence Schematic for a Two-Span Continuous Unit (See Figures 16-18):

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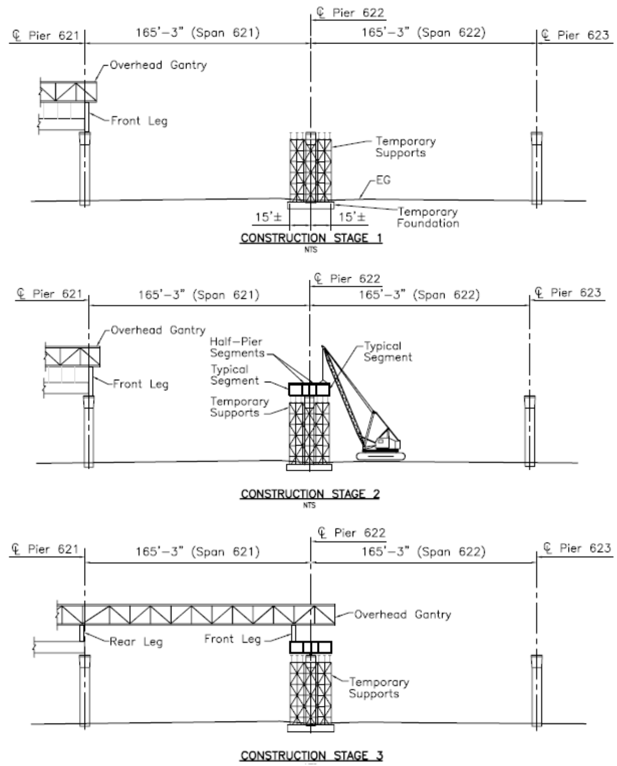


Figure 16 Two-Span Suggested Sequences 1-3

Stage 1- Install Temporary Supports:

-Construct temporary foundation and install temporary supports at middle pier.

-Place jacks at pier segments and first pair of typical segments.

Stage 2- Install Initial Segments:

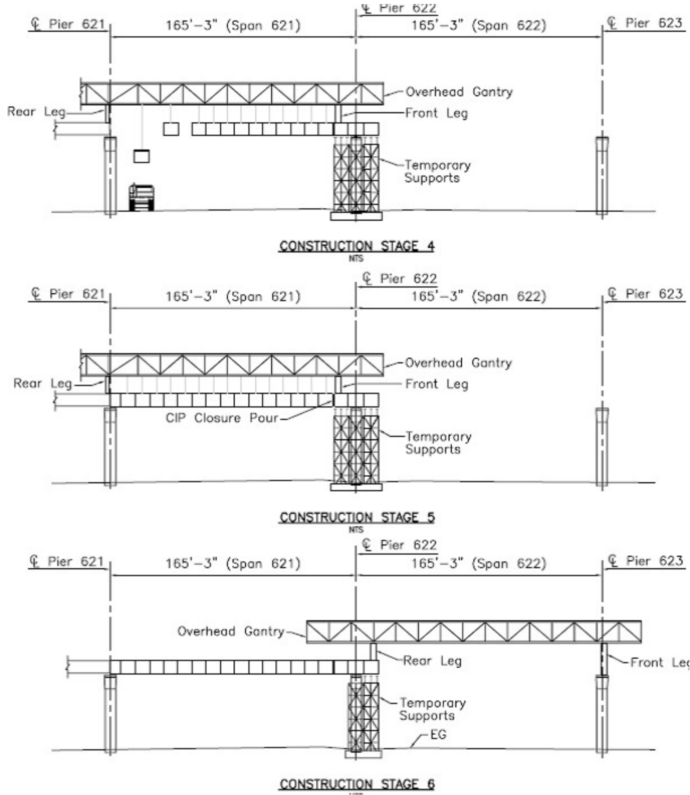
- Erect both halves of pier segment
- Apply epoxy to match cast face of pier segment and stress PT bars
- Erect first typical segment, apply epoxy and stress PT bars
- Erect second typical segment on the other side, apply epoxy, and stress PT bars and cantilever tendons.

Stage 3- Gantry Advancement:

- Advance overhead gantry to the position shown.

Stage 4- Segment Placement:

-Deliver segment underneath the span to overhead gantry.



-After all segments are hung from overhead gantry, adjust grade & alignment of each segment. Leave a gap between segments for application of epoxy

Stage 5- Epoxy & Stressing Tendons:
-Place concrete blocks in closure joint. Apply epoxy between segments and stress together temporary PT bars
-Stress some tendons and cast CIP closure pour.
-After concrete of CIP closure has reached the specified minimum compressive strength and stress tendons sequentially and simultaneously by pairs to final force.
-Remove temporary PT bars and temporary support in Span 621.
-Release segments to bearings

Stage 6- Gantry Advancement:
-Advance overhead gantry forward

Figure 17 Two-Span Suggested Sequences 4-6

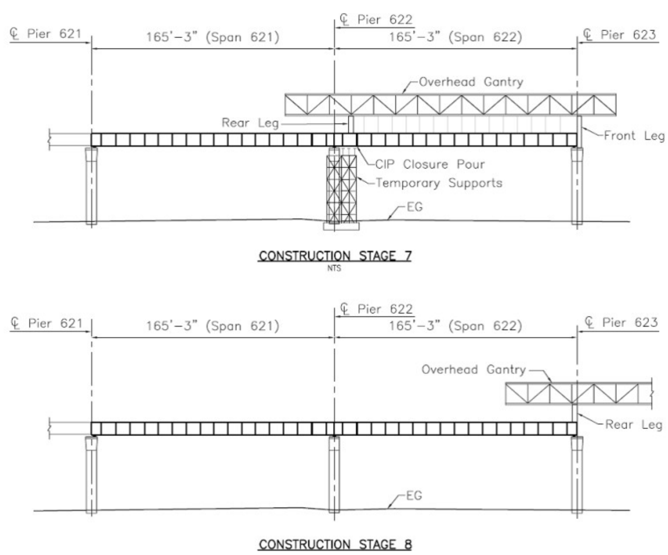


Figure 18 Two-Span Suggested Sequences 7-8

Stage 7- Segment Placement, Epoxy Joining and Stress Long. Tendons
-Repeat Stage 4 for segment placement
-Repeat Stage 5 for epoxy joining and stress longitudinal tendons.
-Remove temporary PT bars and temporary support in span 622.
-Release segments from gantry on to bearings
-Install and stress continuous tendons sequentially to the final force.

Stage 8- Gantry Advancement
Advance overhead gantry forward to the next pier.

CONCLUSION

The precast concrete span-by-span segmental box girders have proven to be very successful for large light rail transit projects in urban congested environment. It offers many benefits resulting from the use of the precast concrete segmental guideway, which include the following:

- Speed of bridge construction arising from the efficient and fast erection of the precast concrete span-by-span segmental guideway
- Avoidance of potential conflicts in urban environment from the construction equipment of overhead gantry by erecting superstructure segments from above existing roadways or streets.
- Assurance of concrete product quality due to factory conditions for concreting in the precasting yard.
- Inherent long-term durability of precast concrete segmental construction.
- Cost-effective solution through the acceleration of erection

CREDITS

Owner:	Honolulu Authority Regional Transit
Precast Concrete Bridge Design Engineer:	AECOM, Honolulu, Hawaii