ANALYSIS AND DESIGN OF PATCO TUNNEL CROSSING #2 BRIDGE, CAMDEN, NEW JERSEY

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ABSTRACT

PATCO CROSSING #2 (PATCO #2) is a new bridge located in a very populated commercial area, crossing over a subway tunnel, carrying two light rail Transit (LRT) tracks diagonally across the bridge. A new LRT station with two side platforms, canopies and part of the station building structure were constructed integrally with the bridge. In this paper, the major design concerns, assumptions, and problems are discussed for this complex structure. The focus of this paper is the bridge type selection, live load distribution, component design, and special issues such as the station roof column that is supported by the bridge abutment, and relative thermal movements between the bridge and the platforms. Although concrete bridges are not common in the railroad industry, distinct benefits of using concrete for this particular structure can be demonstrated.

Keywords: Light Rail, Embedded Concrete Bridge, Live Load Distribution, Platform.

INTRODUCTION

PATCO Crossing #2 is a new bridge crossing over the Delaware River Port Authority (DRPA) Broadway Tunnel at Port Authority Transit Corporation's (PATCO) Broadway Station in Camden, New Jersey. It is one of several bridges included in the Southern New Jersey Light Rail Transit (SNJLRT) project to provide a new light rail transit system connection from Trenton to Camden by utilizing and rehabilitating an existing rail corridor including replacement of several bridges. A new SNJLRT Station with two side platforms, canopies and a part of the station building structure has been included as an integral part of PATCO #2 Bridge. This unique three-layer structure is in the final stage of construction and located in a very populated commercial area in the center of Camden City, where city streets, a subway tunnel, a subway station and a bus station are all linked together. In order to minimize its impact on the existing tunnel, PATCO #2 is designed as an independent structure straddling the tunnel. Loadings on this crossing include dead loads from the bridge, the platforms and canopies, the station building and live loads from an AASHTO HS25 truck, LRT vehicles, and wind and snow loads from the building.

This single span bridge carries two LRT tracks, the driveway of a CVS store, parts of the LRT platforms and the LRT station-building floor over the tunnel, and spans 60 feet between abutments. The abutments utilize drilled shafts to straddle the PATCO Tunnel preventing any of the loads due to proposed LRT tracks and the station being imposed on the existing PATCO tunnel structure. The drilled shafts were constructed as close as possible to both sides of the tunnel in order to minimize the span length. A minimum 4-foot lateral distance between the centerline of support and the outside face of the tunnel (at the north abutment) and the south face of the existing retaining wall located along the south fascia of the tunnel (at south abutment) was used. The bridge carries the LRT tracks on a 52.85-degree skew span over the PATCO Tunnel (see Fig. 1). The LRT tracks are placed diagonally across the bridge surface. The two 200-foot long side platforms are supported partially on the bridge and partially on drilled shafts for the portion beyond the bridge. The platforms are all cast-in-place concrete with 8-inch thick slab on top of two continuous edge beams along the length of the platforms.

Due to lack of sufficient cover over the tunnel (explored by soft-dig) and in view of the sharp skew angle between the tunnel and the LRT alignment it was proposed to span the tunnel with hollow prestressed concrete box beams placed perpendicular to the tunnel alignment. The superstructure consisted of twenty-two 27-inch deep AASHTO Prestressed Concrete Box Beams on the west side and eight 21-inch deep Voided Slab Beams on the east side. A minimum vertical clearance of 4 inches is provided between the bottom of the beams and the top of existing tunnel. In order to control differential deflections between beam units, all the beam units are transversely tied together by tie rods at four diaphragm locations (end diaphragms and two intermediate diaphragms).

Directly on top of the prestressed beams is a 6-inch thick (minimum) concrete deck slab-topping with reinforcement normal to the beams. On top of the deck slab is an 8 ½-inch thick by 58'-6" wide track slab with reinforcement normal to the LRT tracks. The LRT tracks are embedded in this track slab. All three layers of concrete were assumed to act compositely to resist the applied loads.

The superstructure is supported by reinforced concrete pier type abutment caps integral with the superstructure founded on 36" diameter drilled shafts spaced at 12'-8" on center. Elastomeric bearings are used under each beam slab unit. The integral abutment cap is rigidly connected to the bridge deck and the approach slab at the northwest corner and southeast corners of the bridge along the track alignment. In the remainder of the abutments, where there is no approach slab, the integral abutment cap is rigidly connected with the bridge deck only to create a rigid frame structure for live loads.

The southbound platform is 22’-0” wide and 200’-0” long, with a 20’-0 wide by 22’-10 ½” long extension at the west end to accommodate the door way of the adjacent station building. The northbound platform is 12’-0” wide and 200’-0” long. The platform beams are doweled into the bridge deck within one bay for each platform. The rest of the platform beams are seated on ½” elastomeric pads to allow differential thermal movements in different directions the between bridge and platforms.

A triangle shaped (Fig. 1) roof of the connection building for the LRT Station Stop was proposed to be carried by three 3-foot diameter columns supported by drilled shafts located at its three corners. Two of these columns are outside of the limits of the bridge and one is in line with the drilled shafts supporting the north abutment of PATCO Crossing #2 Bridge. The triangular floor of the building for the Station will be partially on the bridge, partially on the existing tunnel roof and partially at grade.

Due to the complexity of the structure described above, this paper explains how the bridge has been designed and analyzed based on the assumptions established for this special case, the issues that came up during the design and the solutions found for the problems. The design of this structure features the following main concerns:

- Bridge Type Selection – Considering the features and site constrains of this bridge, a structure composed of prestressed box beams integral with the abutment cap, supported on drilled shafts, was selected.

- Live Load Distribution – Since the Light Rail Vehicle (LRV) runs diagonally across the bridge surface, the live load could not be distributed in accordance with any design code. We had to develop a reasonable method to treat this problem.

- Design of Bridge Components– For superstructure and substructure designs, several analysis models were created for different types of load distribution. Each component was designed based on its individual considerations and assumptions.

- Special design issues, including relative thermal movement between the bridge and the platform; the integral abutments; and the drilled shafts supporting both the station column and the bridge.

BRIDGE TYPE AND COMPONENT SELECTION

EXISTING CONDITION

According to the plans of existing utilities from the as-built plans for the existing tunnel, this bridge site is heavily congested with utilities. For the new bridge construction, all utilities within the limits of the site had to be relocated to clear the substructure and at-grade superstructure.

The ground water level was found at elevation +11 feet in the test borings conducted before final design phase. The bottom of the superstructure had to be located approximately 4.5 feet above the ground water. In order to have more accurate information at this site, a trench dig exploration, a new field survey, an inside the tunnel survey and an inspection of the tunnel roof were also preformed. Observations from this field work revealed the following additional information:

- The existing tunnel roof steps down at 75'-0" +/- from the front face of the existing West Head-house.
- A 4" diameter metal utility pipe must be relocated because it interferes with the fascia box beam of the new bridge.
- A 4-foot (±) soil cover exists over the existing tunnel in most places.
- A 4-foot wide existing retaining wall was found along the south wall of the existing tunnel.
- A 4-inch concrete cover exists over the area of exiting tunnel truss roof. The area was defined by the exploratory trench dig.
- The width between the outside faces of the existing tunnel was measured during the trench dig exploration.
- The existing columns that support the roof truss under the area of the proposed LRT station building were removed 15 years ago. The roof trusses are no longer functioning as structural members for the tunnel. A 3-foot thick reinforced concrete slab was cast to span over the tunnel walls. This slab encases the remaining steel trusses partially and holds them in place.
- One corner of the CVS Store building is 6'-0" +/- from the centerline of the proposed drilled shaft foundation of the south abutment of the bridge.

BRIDGE ALIGNMENT

Based on a previous PATCO tunnel analysis, the steel members of the existing tunnel frame would be significantly over-stressed if the additional LRV loads were to be applied directly on top of the tunnel. There is also a considerable risk of future service disruptions and liability for repair costs if the tunnel were to be used to support the LRT tracks. Therefore, a bridge straddling the tunnel was selected to eliminate the above problems.

A 22-foot wide non-standard platform was required at this station because New Jersey Transit prefers to operate LRT trains from the southbound track based on passenger projections. Due to limited space available between the original track alignment and the existing Head-house building, and limited cover over the existing tunnel, the LRT alignment was shifted to the northeast to provide enough clearance for the bridge and the platform. As a result, the alignment was set with a skew angle of 52.85 degrees to the tunnel.

SUPERSTRUCTURE SELECTION

The PATCO #2 bridge is buried under ground, which makes the maintenance of the bridge very difficult. Based on the site restrictions, maintenance access to the superstructure is impossible. Any bridge type or detail that needs regular maintenance would therefore not be suitable for this bridge. Expansion joints, for example, always require maintenance. By elimination of the bridge deck expansion joint, not only a maintenance item is eliminated, but also the construction costs are reduced. Therefore an integral abutment option was a more reasonable approach.

The other major site constraint is inadequate vertical clearance from the bottom of PC box beam to the top of the existing PATCO tunnel. The location of the bridge is very close to the Broadway Station (Fig. 1). The tunnel profile rises quickly to the east as it approaches the Broadway Station. This gives a very limited depth of soil cover above the existing tunnel, especially at the east end of the bridge, and it limits the beam depth that can be used to span over it. A feasibility study using rolled steel beams was conducted and found that it was not economical because of height restriction. The maintenance for steel beams was also a big concern; therefore the option of using steel beams was eliminated.

A prestressed concrete adjacent box superstructure was selected because it is easier and more economical to fabricate, and build with better quality control compared to the cast-in-place slab-bridge option suggested in the original Request for Proposal. In addition, it would not impose any loads on the existing tunnel, and spans over the tunnel with the minimum structure depth possible.

The final proposed bridge superstructure consists of twenty-two 27-inch deep AASHTO Prestressed Concrete Box Beams on the west side and eight 21-inch deep Voided Slab Beams on the east side due to vertical clearance restrictions. This configuration gives a minimum of 4 inches vertical clearance over the tunnel. All beam units are transversely tied together with tie rods at four diaphragm locations to prevent potential differential deflections between beam units. To eliminate any need for future inspections and to protect the prestressing strands and the reinforcing steel from corrosion, all exposed surfaces of the prestressed beams were coated with epoxy waterproofing. In addition, a corrosion inhibitor admixture was used in the deck slab concrete over the tunnel.

SUBSTRUCTURE SELECTION

The superstructure is supported by reinforced concrete integral abutment caps on 36" diameter drilled shafts spaced at 12'-8" on center. Elastomeric bearings were used under each slab unit. The integral abutment caps are rigidly connected to the bridge deck and the approach slabs at the northwest and southeast corners. In the remaining sections of the abutments, where there is no approach slab, the integral abutment cap is rigidly connected with the bridge deck only to create a rigid frame structure for live loads. Waterproofing membrane is provided on top of the existing tunnel in the area within the limits of the construction.

In order to minimize soil disturbance around the existing tunnel, permanent steel casings were utilized for the drilled shaft construction from the top of the drilled shaft to 5 feet below the bottom of the tunnel. The concrete drilled shaft was reinforced from top to 15 feet below the bottom of the tunnel, and below that it was unreinforced.

PLATFORM SELECTION

Cast-in-place platforms, rather than precast platforms, were recommended at this site because of the complicated shapes of the platforms at grade, on the bridge and over the existing tunnel roof. With appropriately selected deck joints and reinforcement provided in the different locations of the platforms and the building floors, cracks in the concrete surfaces could be avoided or minimized.

The proposed northbound platform is 22'-0" wide and 200'-0" long, with a 20'-0 wide by 22'-10 ½" long extension at the west end to accommodate the door way of the adjacent station building. The southbound platform is 12'-0" wide and 200'-0" long. The platforms will all be cast-in-place with an 8-inch thick slab on top of two continuous edge beams along the length of the platforms. The platforms will be supported by pedestals on top of the superstructure for the portion over the bridge and by drilled shafts for the portion over the ground. The 22-foot wide platform was also designed to carry a full-length canopy supported on double columns (1'-6" apart) spaced at 16'-0" along the platform. The 12-foot wide platform carries only a partial-length canopy at the east end.

STATION BUILDING

The roof of the connection building for the LRT Walter Rand Station Stop is triangular in shape and it will be carried by three 48-inch diameter columns supported by drilled shafts located at three corners. Two of these columns will be parallel to the front face of the existing West Head-house and one will be in the line with the drilled shafts supporting the north abutment of PATCO Crossing #2. The triangle floor of the building for the Station will be partially on the bridge, partially on the existing tunnel roof and partially at grade. The building floor over the bridge and over the existing tunnel roof will consist of an 8-inch thick cast-in-place concrete slab supported by cast-in-place reinforced concrete grid beams.

DESIGN CRITERIA AND GENERAL ASSUMPTIONS

DESIGN CRITERIA

All of the bridge components were designed in accordance with the mandatory document, Book V[1] of South New Jersey Light Rail Transit System. The design criteria used for this bridge are from AREMA[2], ACI[3] and AISC[4] and AASHTO[5] specifications. For instance, the loadings transferred from station building to the bridge are based on the ACI. The truckload HS-25 on bridge along the CVS driveway is from AASHTO.

The new bridge is designed for the LRT cars moving diagonally across the tunnel. The Light Rail Vehicle (LRV) and Light Rail Maintenance Vehicle (LRMV) load configurations were provided by the car manufacturer.

GENERAL ASSUMPTIONS

The superstructure was designed as simply supported for all non-composite dead loads and as a continuous frame for composite dead loads, loads from station building, live loads and other forces, such as longitudinal, temperature and continuous welded rail (CWR) forces. The applied loads from the canopy were also considered in the design.

Since the rail trough cross-section was relatively small compared to the entire slab cross-section, the part of the track slab (top slab) area, which is poured together with the 6” deck slab, was considered to act compositely with the deck slab and prestressed concrete box beam units.

The rigid frame straddling the tunnel was analyzed by assuming that the drilled shafts at each abutment are not laterally supported by the soil above the point of fixity (10 feet below the bottom of the existing tunnel). They were, however, assumed to be rigidly connected to the superstructure for all applied loads except for the dead weight of the superstructure. The frame analysis approach was necessary to make the 27-inch box beams work, thereby allowing them to clear the top of the tunnel.

The deck thickness varies (6” minimum and 9” maximum) to accommodate the track profile since all the box units were placed level. Due to the complex geometry of the finished grade and uncertain depths of fill over the tunnel, it was proposed to make no attempt to vary the seat elevations, but a 6-inch minimum deck thickness had to be provided over the entire bridge.

LIVE LOAD DISTRIBUTION

Unlike highway live load distributions where a truck can be positioned at any location on the superstructure, which would generate a critical loading, the positioning of the LRV is limited by the track locations. In addition, the LRT track alignment has a big skew angle to the bridge. Although AASHTO provides a design guide for distribution of live loads on prestressed concrete adjacent beams (AASHTO 3.23.4), it can not be applied directly to the railroad bridges. Therefore the AASHTO method needed to be modified for the LRV load distribution.

In order to accomplish this, first the critical location on the bridge was graphically determined and then the LRV wheel loads were positioned onto several beams in the critical area. From the site geometry, the critical situation was also analyzed by assuming that two trains will be on the bridge at the critical spot simultaneously. For the transverse live load distribution, the provisions of the AASHTO Standard Specification for Highway Bridges were still applicable. Since the interaction among the adjacent beams is developed by continuous longitudinal shear keys, transverse tie rods and the deck slab cast on top of them, the maximum bending moment due to live load for each critical section can be computed by multiplying the load fraction calculated from the following equation to the wheel loads on the critical beam and on the adjacent beams.

$$LoadFraction = \frac{S}{D}$$

where,

S	=	width of prestressed member, (in this case, 4 feet);
D	=	$(5.75\text{-}0.5N_L) + 0.7N_L(1\text{-}0.2C)$;
NL	=	number of traffic lanes;
C	=	K(W/L);
W	=	width of bridge measured perpendicular to the longitudinal beams in feet;
L	=	Span length measured parallel to longitudinal beams in feet;
K	=	$\{(1+\mu)I/J\}^{1/2}$;
I	=	moment of inertia;
J	=	Saint-Venant torsion constant;
μ	=	Poisson’s ratio for beams;

The overall width of the bridge measured perpendicular to the longitudinal beams is 120 ft. It is conservative to assume that the live load is distributed to the adjacent seven beams, e.g. with a distribution width W = 28 ft.

Once the Load Fraction is calculated, the actual wheel load effects on the critical beam can be quantified. Two cases were found to govern in this design. Case 1: When the live load is acting on the critical beam, the distributed load equals the wheel load times the load fraction; Case 2: When the live load is acting on the adjacent beams, the distributed load on the critical beam equals the remaining portion of the load fraction (1-Load Fraction) times the wheel load divided by the width of four adjacent beams. The locations of these wheel loads were assumed as normally projected to the critical beam.

SUPERSTRUCTURE DESIGN

BEAM DESIGN

Twenty-two 27” P/S box beams were installed on west side and eight 21” P/S void slab beams were installed on the east side of the bridge due to the varying vertical clearance over the tunnel (See Section B in Fig. 2). Each type of beam was designed for dead load and live load as a simply supported beam, even though the beam was rigidly connected to the abutment. The live load distribution was based on the method explained above and the bridge deck was considered acting compositely with the beams.

The deck slab within the limits of the track slab and platforms has a minimum thickness of 14½ inches. Beyond these limits, it has a constant thickness of 6½ inches. The 14½-inch deck thickness includes an 8½-inch thick track slab and a 6-inch minimum thickness deck slab underneath. The deck slab thickness varies to accommodate the vertical profile of bridge alignment. The reinforcing mat in the 8½-inch thick track slab is in the direction of the centerline of tracks and the reinforcing mat in the 6-inch minimum deck slab underneath is in the direction of the centerline of prestressed box beams.

CAMBER ANALYSIS

Due to the bridge configuration, the applied dead loads on the prestressed beams along the transverse direction are different. On west part of the bridge, dead loads are mainly from the beam slab, 12-foot wide platform and portion of track slab on northwest corner of the bridge. In the middle of the bridge, dead loads include the beam slab, track slab, 22-foot wide platform and canopy weight on top of the platform. On east part of the bridge, the dead loads include beam slab, track slab and 22-foot wide platform and building floor. All the effects of the dead loads were treated carefully in the design. The camber calculations were divided into four groups and for each group the averaged superimposed dead load camber effects were calculated separately. Since the beams were designed for the governing load case, and the dead loads vary across the width of the bridge, the resulting cambers were different from beam to beam. To minimize the effects of camber on deck slab thickness, a thorough check for the minimum deck slab thickness and the beam capacity based on survey information obtained during construction were conducted.

SUBSTRUCTURE DESIGN

Substructure analysis of the PATCO #2 Bridge was based on the integral framing system, including the cap beam and drilled shafts. The analysis involved different kinds of loads, such as LRV, HS25 truck, wind load from station building, thermal loads, rail forces, platform dead loads and live load, bridge and approach slab self weight, etc. In general, the design loads for the substructure components due to all lateral loads, such as wind load on building, thermal load on building, platform and bridge superstructure and LRT hunting force, were obtained by applying these loads to the 3D model of the bridge developed using LARSA structural analysis program. (Hunting force is the force caused by the interaction of the vehicle and the guideway.) Live load distribution on the critical location of the abutment cap beam was also calculated through the computer model.

CAP BEAM DESIGN

One two-dimensional model of the abutment cap and drilled shafts was created for LRV live load distribution analysis. Another two-dimensional model of superstructure beams and drilled shafts was created for HS25 truck loading analysis. Moment connections at beam-cap connection were assumed for live loads only. The dead load on the prestressed box beams and deck slab were assumed to be uniformly distributed along cap beams. Loads from canopy were considered to transfer through a moment couple at the corresponding location on top of the bridge.

The longitudinal loads along tracks are from:

- LRV braking load, acting at eight feet above the rails;
- Thermal loads from continuous welded rail (CWR);
- Thermal load differentiation between the platform and bridge deck;
- Hunting force.

Since the cap beam and the tracks are not perpendicular, the components of longitudinal forces parallel to the axis of the abutment cap beam create horizontal forces and moments. The components perpendicular to the axis of the cap can be transferred as vertical forces on the cap beam. The CWR force is assumed as 0.4 kip per foot (Ref. # 6) acting in one direction, since the rails are embedded in the track slab. Like longitudinal forcer, the CWR force also creates a horizontal force, a vertical force and a moment in the abutment cap beam and drilled shafts. Similar load distributions can be obtained for the hunting force as well.

Because of the skew of the platform to the bridge, the live loads and dead loads from the platforms are distributed on abutment cap beams assuming a triangular distribution.

DRILLED SHAFT DESIGN

For the drilled shaft design, a 3D computer model for the entire bridge was created by assuming that the fixity points of drilled shafts were 10 feet below the bottom of the tunnel and the building column was rigidly connected to the bridge. Since the superstructure was modeled integral with the abutments in the program, all the drilled shafts would be subjected to the design loads not only from the bridge but also from the station building. Based on the variations of loading due to the skew of the bridge, the following four cases were considered for the design of the drilled shafts:

1. Maximum Load Plus Maximum Shear Due To Live Load - These shafts are located directly underneath the LRT line, and therefore will resist most of the live load. Two cases are considered: Case 1, the LRV wheel loads are placed in the middle of the span to create maximum moment in the shafts; Case 2, LRV wheel loads are placed directly at the abutment for maximum axial loading on the shafts.

2. Under-loaded Shafts – These shafts are located at the southwest and northeast corners of the bridge. These shafts are away from the LRT line and subject to very little live loading.

3. The Column Supporting Bridge and the Roof Structure - This four-foot diameter drilled shaft is located at the northeast end of the bridge. It carries all design loads from the bridge, the LRV live load and the majority loads from the station roof column.

In addition, the active earth pressure from backfills against cap beam was also included for the drilled shaft design.

OTHER DESIGN ISSUES

The other design concerns related to this bridge are listed below:

- Building Loads on Bridge through the attached Station Roof Column: - The triangle shaped station building is supported by three 48-inch diameter columns. One of the columns is lined up with one of the bridge drilled shafts at the north abutment. Portions of the dead load, live load and wind load from building will be transferred to bridge through this column. In order to analyze this distribution, a three-dimensional model of the bridge framing structure was created and building loads were applied to this model.

- Integral Abutment Analysis - A positive connection at the ends of the beam was provided by extending the strands from the PC beams and encasing them along with the ends of the beams in the abutment cap and the backwall. This provided full load transfer through the displacements due to thermal expansion, contraction and all other applied loads from the superstructure to the drilled shafts. But in the design of the superstructure, this connection was assumed as a pin connection for a conservative approach. The same 3D model developed for the entire bridge for column load distribution was also used here for thermal analysis.

- Relative Thermal Movements Between Bridge And Platform - Cast-in-place station platforms were chosen at this site because of the complicated shapes of the platforms at grade, on the bridge and over the existing tunnel roof. Temperature changes will cause movement in different directions due to the difference in the longitudinal axes of bridge beams and the platform beams. To allow for movement in different directions, platforms are doweled only in one bay in the middle. For the rest of the platform, a ½” thick elastomeric bearing pad was provided between the platform beams and the bridge deck.

CONCLUSIONS

Due to site restrictions and features of this embedded bridge, the selected bridge type, prestressed box beams integral with the abutments supported by the drilled shaft foundations, was found to be the most economical and durable choice. Since the live load could not be distributed in accordance with any design code for this unique structure, a live load distribution method was developed during the design. Complex computer models were developed to handle the different types of load distributions. The selected design provided a structure to address several major special design issues, including relative thermal movements between bridge and platform, the use of integral abutments, and the use of drilled shafts for the both bridge and the station roof support.

REFERENCES

1. *BOOK V*, 1998 Edition, South New Jersey Light Rail Transit System.
2. *ACI*, 1998 Edition, American Concrete Institute.
3. *AREMA*, 1999 Edition, the American Railway Engineering and Maintenance-of-Way Association.
4. *AISC*, Ninth Edition, American Institute of Steel Construction, Inc.
5. *AASHTO Specifications for Highway Bridge*, 16th Edition with interims through 2000, American Association of State Highway and Transportation Officials.
6. *Railroad Engineering,* Second Edition by William W. Hay. Mgt E. MS, PhD.

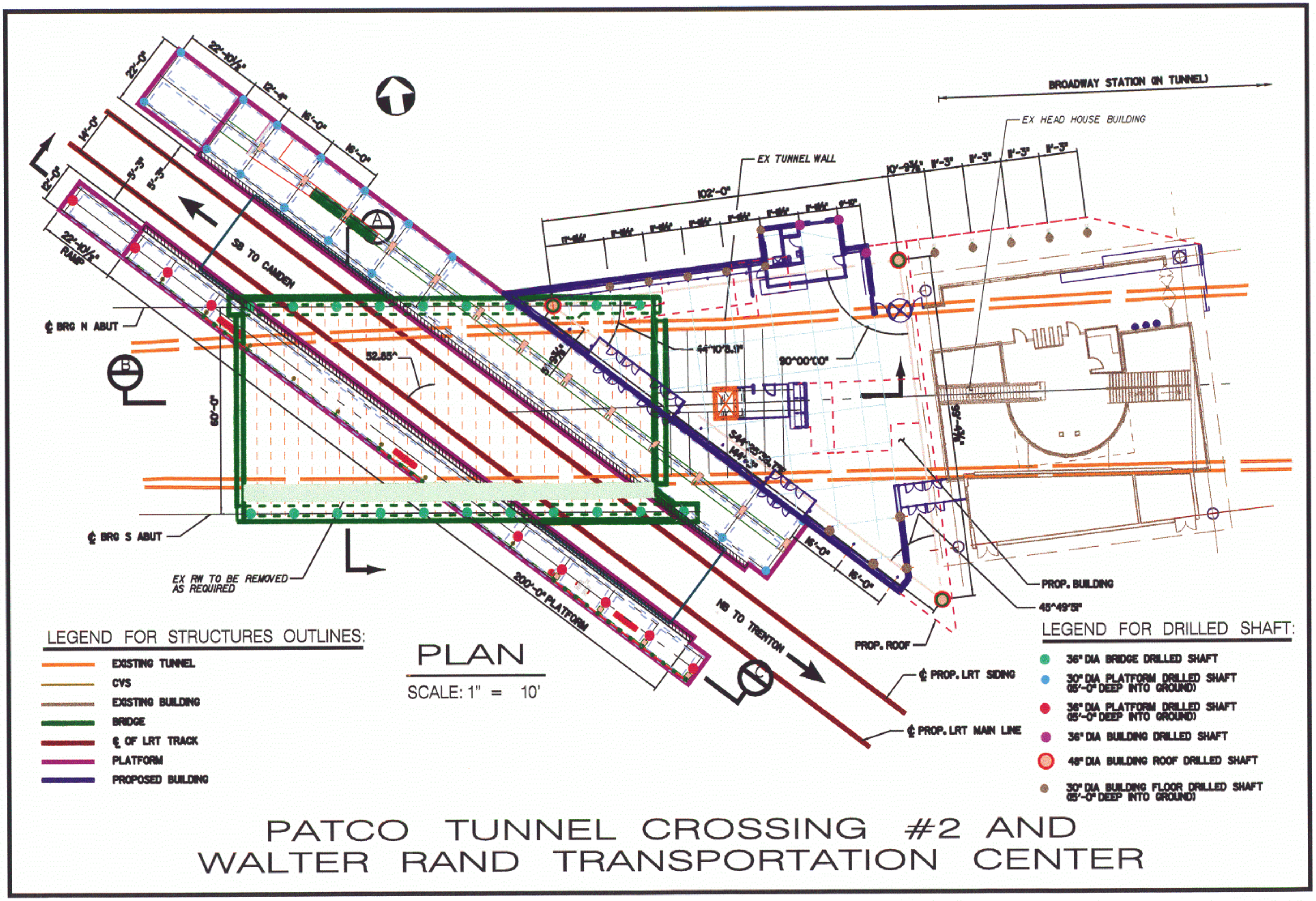

Fig. 1 – PATCO Crossing #2 Layout

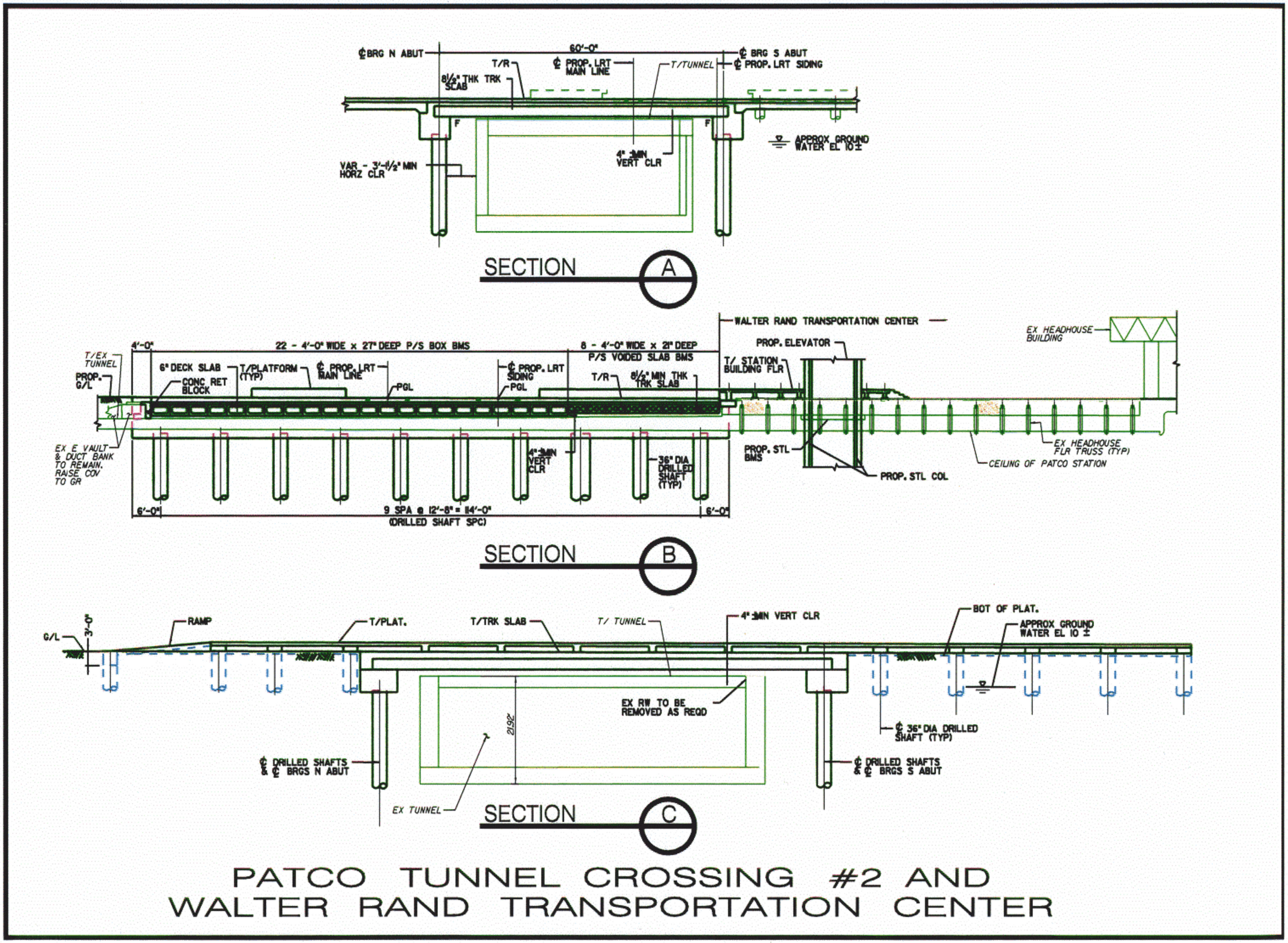

Fig. 2 – PATCO Crossing #2 Sections

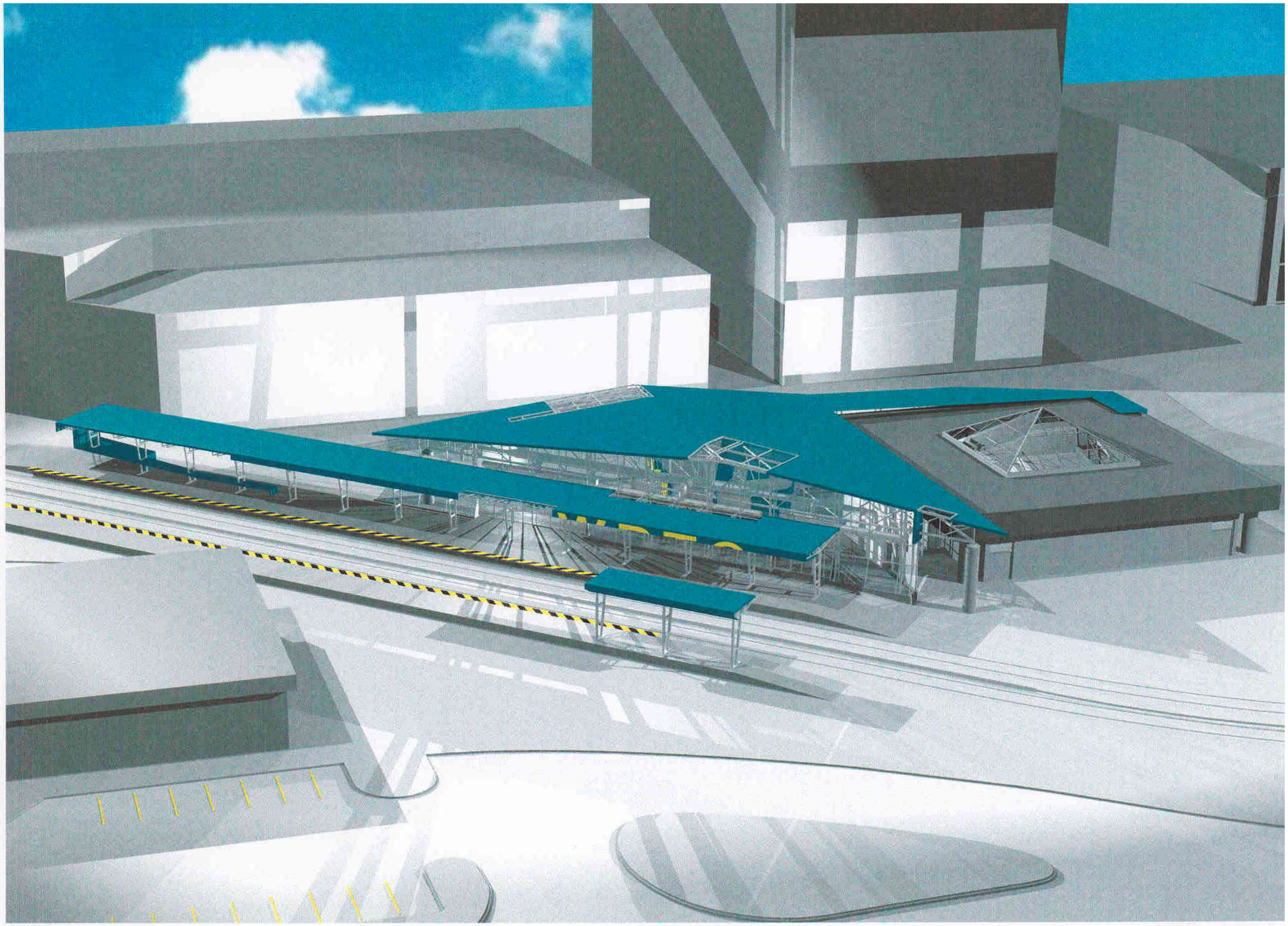

Fig. 3 – PATCO Crossing 3D Rendering