SEISMIC DESIGN OF THE CUT AND COVER TUNNEL OF THE CANADA LINE RAPID TRANSIT

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ABSTRACT :

Construction of the Canada Line Rapid Transit Project is currently underway in Vancouver, BC. The 19 km rapid transit system includes 6.6 km of cut and cover box structure – one of the longest cut and cover rapid transit tunnels in Canada. The design for the cast-in-place reinforced concrete box included standard side-by-side, stacked, special cross-over single box and transitional rollover configurations. The seismic design accounted for both pressure-based and racking displacement-based demands. The racking displacements were based on state-of-the-art research on soil-structure interaction analyses. Four different types of soil conditions were encountered over the 6.6 km length of tunnel. State-of-the-practice seismic design was utilized to produce cost-effective structures for the project.

KEYWORDS: Seismic Analysis; Cut and Cover Tunnel; Racking Displacement; Seismic Design; Canada Line Rapid Transit

1. INTRODUCTION

The Canada Line is a new rapid transit link in Metro Vancouver starting at the emerging transportation hub of Waterfront Centre and terminating at the heart of Richmond's civic precinct and at Vancouver International Airport. With 16 stations located along the 19 km route, the Canada Line will be an important new link in the regional transportation network. The total project cost is approximately CDN$2 billion. The DBFO project was awarded to SNC Lavalin Inc. through a vigorous selection process. An overview of the route is shown in Figure 1.

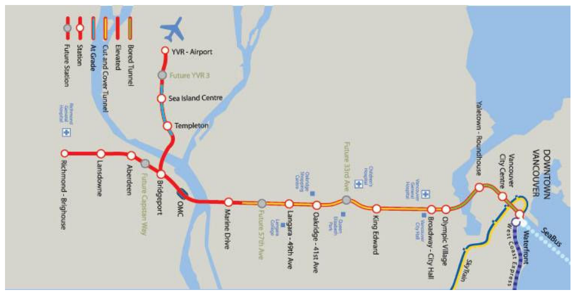

Figure 1 Canada Line Route

The four major types of structures on the Canada Line are bored tunnel, cut and cover tunnel, elevated guideway, and bridge. The cut and cover tunnel is about 6.6 km long along Cambie Street from 2nd Avenue to 64th Avenue. Five stations are placed within this length. Due to limited space available for construction in the commercial portion between King Edward Avenue and 12th Avenue of Cambie Street, the cut and cover tunnel transitions from side-by-side configuration to stacked configuration and back to side-by-side configuration. The design for the cast-in-place reinforced concrete box included the standard side-by-side, standard stacked, and transitional rollover sections. In addition, to maintain continuing operation during an event of train breakdown in the tunnel, two special crossover sections were provided at strategic locations where the centre wall has to be eliminated to allow the track to crossover from one tunnel to the other.

Traditionally low seismic risk is associated with tunnels and buried structures. The main causes of seismic risk for underground structures are liquefaction, active fault crossings, seismically induced landslides and ground shaking intensity. Vancouver is located in one of the most active seismic zones in Canada with a Peak Ground Acceleration (PGA) of 0.23 g for the 1 in 475 year return period earthquake. The Cut and Cover tunnel is not located near any active faults nor in soil with liquefaction or landslide potential. The performance criteria based on the Canada Line Rapid Transit Design Manual (2005) are that the tunnel must withstand the 1 in 100 year seismic event with no damage, and for the 1 in 475 year event with repairable damage. The design life of the project is 100 years.

The ground shaking during earthquakes would induce seismic loadings on underground tunnels in two ways, one relates to the longitudinal propagation of seismic waves and the other relates to the racking/ovaling of the cross section. The longitudinal loads are typically not critical but need to be addressed in reinforcing details. The racking/ovaling of the cross section can be critical and cause plastic hinges or potentially failure of the tunnel box. The racking effect is the focus of the following seismic analysis section.

2. SEISMIC ANALYSIS

The state-of-the-art research by Wang (1993) showed that ground deformation and the interaction between the structure and the surrounding soil control seismic loads in cut and cover tunnels. The racking deformation can be calculated by the flexibility ratio F, which represents the relative stiffness between the rectangular tunnel box and the surrounding soil. It is a better way of defining the seismic loading on a cut and cover box.

In the Canada Line Rapid Transit Project, Cut and Cover Final Geotechnical Report (2005), the lateral seismic soil pressure and the free field displacement were defined for both the 1 in 100 year and the 1 in 475 year events with PGA of 0.10 g and 0.23 g respectively.

Four generalized soil profiles were encountered including rock, till, sand, and silt. The soil cover above the tunnel roof slab varied from less than 1m to a maximum of 7m. The water table also varied from above the roof slab to below the base slab.

The cast-in-place reinforced concrete boxes were modeled in SAP2000 computer program as beam elements with effective moment of inertia (35% gross for slab and 70% gross for wall). Soil support was represented by ground springs calculated using subgrade modulus in the geotechnical report.

To capture the maximum moment and shear demands, both balanced and unbalanced loading conditions were considered. In total, 14 load combinations including permanent loads, transitory loads, exceptional loads, and temporary loads were defined in the analysis.

2.1. Side-by-side Box

The out-to-out dimensions of the side-by-side box are approximately 5.2m in height and 10.6m in width. The roof slab and the exterior wall are typically 450mm thick. The base slab is typically 500mm thick while the intermediate wall 350mm thick. A typical section of the side-by-side box is shown in Figure 2.

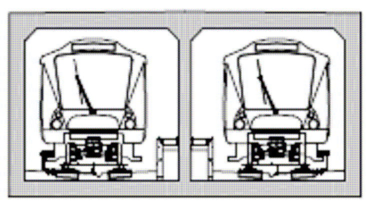

Figure 2 Typical Side-by-side Box

The flexibility ratio for the side-by-side box is typically around 2.0, which indicates an amplification of the free-field ground deformation of about 1.5 (Wang, 1993). As discussed in Hashash et al. (2001), the racking deformation of the structure is amplified because the medium now has a cavity, providing lower shear stiffness than non-perforated ground in the free field.

A typical model for the side-by-side configuration is shown in Figure 3. The vertical soil springs in the model are defined as in Table 2.1.

Table 2.1 Soil Spring in Structral Models

Type of Soil	Modulus of Subgrade Reaction (1m element)	Spring Constant for Model
Rock	9.6 GPa	9600 MN/m
Till	130 MPa	130 MN/m
Sand	75 MPa	70 MN/m
Clay/Silt	75 MPa	70 MN/m

The racking deformation was applied to the model using the equivalent static load method. For shallow rectangular tunnels, the shear force developed at the soil/roof interface decreases with decreasing overburden. The predominant external force that causes structure racking may gradually shift from shear force at the soil/roof interface to normal earth pressures developed along the side walls, so a triangular pressure distribution was applied to the model (Hashash et al., 2001). Generally the triangular pressure distribution model provided a more critical value of the moment capacity of rectangular structures at bottom joints.

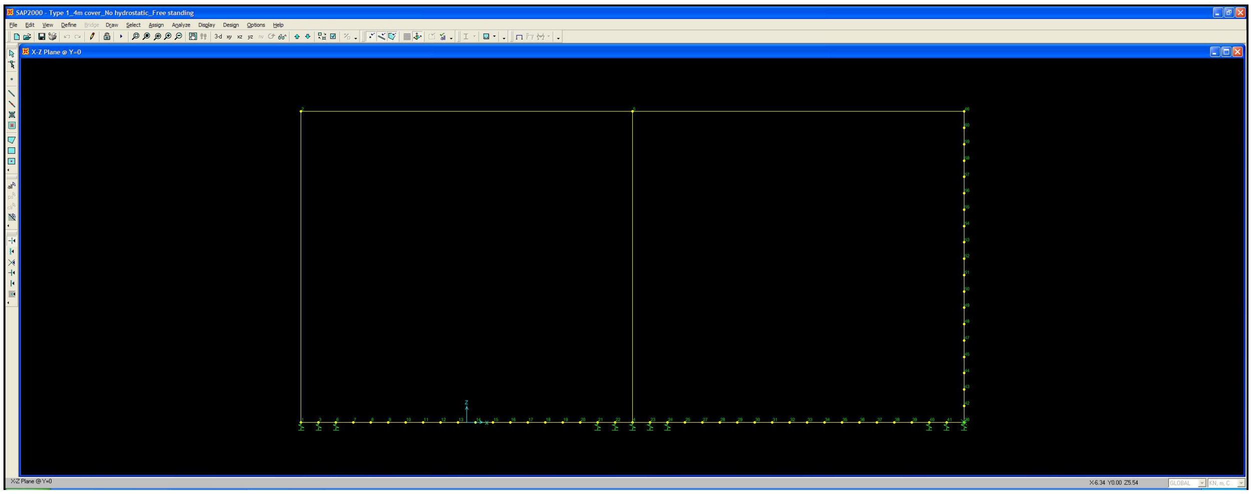

Figure 3 Typical Computer Model

2.2. Stacked Box

The out-to-out dimensions of the stacked box are approximately 10m in height and 5m in width. The advantage of the stacked box is the reduced width during construction in the area where the street is narrow.

The same equivalent static method for the side-by-side box based on amplified free-field racking deformation was used in the computer analysis of the stacked box. Since the depth of the stacked box was greater than that of the side-by-side box, the behavior and the moment and shear distribution diagrams were different.

2.3. Rollover Box

The rollover boxes were used to transition from the standard side-by-side box to the stacked box. To capture the varying structural response due to transitioning, ten different sections were analyzed. The moment and shear demands at T-joints were found to be critical to the reinforcing layout and details.

2.4. Crossover Box

The crossover box is essentially a side-by-side box without centre wall. The elimination of the centre wall effectively increases the roof slab span and reduces the lateral stiffness of the box. The backfill soil loading was found to be governing the demands of the roof slab.

3. DESIGN

The design of the cut and cover tunnel was based on the performance criteria that the structure must withstand the 1 in 100 year seismic event with no damage, and for the 1 in 475 year event with repairable damage. To achieve such performance, the structure was first designed with adequate strength capacity under static pressure and seismic pressure, then checked in terms of ductility when racking displacements are considered.

The essence of good seismic design is to provide sufficient ductility at the critical locations of the structure to accommodate the deformations imposed by the ground during seismic events. The most vulnerable parts of the rectangular frame structure were at its joints. In addition to standard code requirements of hook and tension lap length at or near joints, sufficient ties were provided at critical sections based on racking moment diagrams to ensure sufficient confinement can be achieved.

The reinforcing details for base slab, exterior wall, interior wall, and roof slab are shown in Figure 4. The bottom reinforcement of the roof slab was to consider the worst condition when plastic hinges developed at the wall support changing the roof slab into simply supported condition.

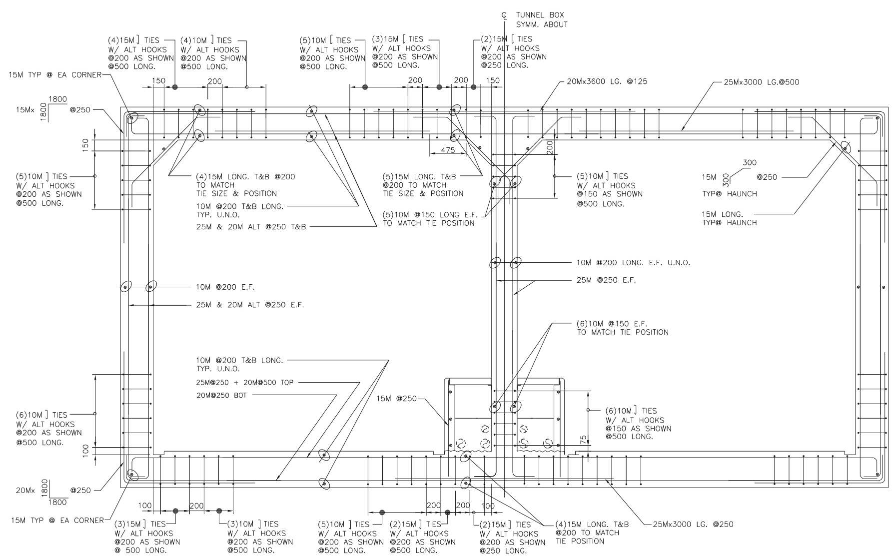

Figure 4 Typical Reinforcing Details of Side-by-Side Box

The special rollover sections would include roof/base slab of the two cells at different elevations which would cause large shear force on centre wall during seismic events. To ensure ductility of the T-joints, sufficient wall ties were provided according to beam-column joint requirements. The backfill material above the lower roof slab required special consideration since it could change the soil-structure interaction behavior.

All reinforcement was continuous at horizontal construction joints located at the base or the top of the walls. All reinforcement was not continuous at all transverse construction joints. Only in the base slab transverse joint were the longitudinal reinforcing bars continuous.

At the interface with stations, the same philosophy was applied as at typical transverse joints. The connection would be continuous at the base slab yet providing sufficient flexibility to allow relative movement/rotations due to the difference of stiffness between the cut and cover tunnel and the bigger station box.

4. CONSTRUCTION

The excavation of a trench from the surface was required for the cut and cover tunnel (Figure 5). The shoring system used was shotcrete with soil anchors. The cast-in-place concrete walls were being poured directly against the shotcrete shoring (Figure 6). No external forming was required.

Figure 5 Excavated Trench near Little Mountain

Figure 6 Side-by-side Box Steel Form and Wall Reinforcing

The presence of a resistant plug of basalt at Little Mountain required blasting during excavation. The transition between the hard rock and other soil material was gradual and did not pose a risk of sudden ground stiffness change. No special reinforcing detail was required near the interface.

The cut and cover tunnel was mainly designed as an undrained tunnel. Only a small portion of the tunnel was designed as a drained tunnel to either avoid floatation or to reduce loading on the walls. In general, bentonite waterproofing strips were provided only at the joints and waterproofing sheets outside wall and roof slab transverse joints. A decision was made based on cost/benefit evaluation to reduce the amount of waterproofing from all exterior surfaces of the walls and the roof slab to only at the joints. The amount of water ingress in the cut and cover tunnel has been observed to be minor. Trenches were provided inside the tunnel to allow water flowing into stations in a controllable manner and finally pumped into the city sewer system.

The typical pour sequence for a side-by-side box was one pour for the base slab, then another pour for the wall and the roof slab using pre-assembled adjustable steel forms. The single pour of roof slab and walls (as shown in Figure 7 and 8) provided good roof joint continuity which would improve the performance during seismic events.

Figure 7 Roof Slab of Side-by-Side Box

To achieve an aggressive construction schedule, high early-strength concrete were used to reduce the formwork stripping time. Although the design compressive strength is 35 MPa, the concrete mix used could easily achieve 40 to 45 MPa at 28 days. The concrete cover where exposed to environment was 60mm to provide protection for 100 year design life.

Figure 8 Roof Slab and Wall Reinforcing

5. CONCLUSION

The seismic design and construction of the cut and cover tunnel of the Canada Line Rapid Transit project have been presented in this paper. The design for the cast-in-place structure included side-by-side, stacked, rollover and crossover configurations. The seismic design accounted for both soil pressure-based and racking displacement-based demands.

The flexibility ratios were greater than 1.0 indicating the racking displacements were greater than the free-field deformations. The displacement demands were found to govern for stacked box design while the soil pressure induced demands would govern for side-by-side configuration.

The wall/slab continuity was considered in reinforcing details to provide the required level of ductility. The shear ties were provided near the wall/slab joints. The special type of rollover configuration required ductile T-joint details and special backfill material. No reinforcement continuation was provided at the transverse construction joints, except in the base slab, to allow certain degree of expansion and rotation.

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