Design of a Steel Fibre Reinforced Precast Concrete Segmental Tunnel Lining For the Evergreen Line Rapid Transit Project

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ABSTRACT
An approximately 2-kilometre-long tunnel will be constructed as part of the Evergreen Line Rapid Transit Project (ELRTP) Project, connecting the SkyTrain network with the Burnaby, Coquitlam, and Port Moody areas. The tunnel will be constructed by the SNC Lavalin – SELI Joint Venture (SSJV). The 8.84-metre inside diameter tunnel will carry both trackways.

A single-pass gasketed precast concrete segmental lining was selected for the tunnel. The tunnel faces challenging geotechnical conditions, and will be subjected to seismic loads during the 100-year design life of the project. For the majority of the alignment, steel fibre reinforced concrete (SFRC) will be used for the segmental lining. Conventionally reinforced concrete will be used for sections of segmental lining adjacent to each portal.

This paper will present the design methodology for the SFRC segmental lining, including the challenges of designing for construction loads, ground and groundwater loads, seismic loads, and long-term durability. Fabrication and installation of the lining is ongoing, and a brief synopsis of progress will also be discussed.

1 INTRODUCTION

1.1 Evergreen Line Overview

The Evergreen Line is an 11-kilometre extension to the existing automated (driverless) Advanced Light Rapid Transit (ALRT), or SkyTrain, system in Metro Vancouver, seamlessly integrating with the Millennium Line at Lougheed Town Centre Station. It will provide a fast, frequent, and convenient rapid transit service connecting Coquitlam to Vancouver via Port Moody and Burnaby, and will integrate with regional bus and West Coast Express commuter rail networks. The Evergreen Line is an integral part of the Provincial Transit Plan and the broader regional planning objectives of Metro Vancouver, which include connecting regional centres with rapid transit to achieve sustainable growth.

The Evergreen Line will provide a travel time of approximately 15 minutes from Coquitlam to Lougheed Town Centre Station, connecting to the Millennium Line at Lougheed Town Centre Station in Burnaby, allowing passengers to travel to Vancouver without changing trains or platforms, with a train frequency of every 3 minutes in peak periods, and an operating speed of up to 80 kph.

The scope of the Project includes:

- Expansion of existing Lougheed Town Centre Station
- Six new stations
- Provisions for two potential future stations
- A vehicle storage and maintenance facility
- 28 new SkyTrain vehicles
- Transit integration facilities, such as bus loops and park and ride lots

Figure 1. Evergreen Line Regional Integration
The total Project budget is $1.431 billion, which includes the base project scope ($1.403 billion) and provision for Lincoln Station ($28 million). Funding for the Project includes contributions of $417 million from the Government of Canada, $400 million from TransLink, and $586 million from the Province of British Columbia. In addition, the City of Coquitlam assembled a unique funding arrangement with a private partner and the federal crown corporation PPP Canada to enable the Lincoln Station to be constructed for opening day of Evergreen Line.

1.2 Project Background and Planning

Metro Vancouver’s Northeast sector—including the municipalities of Coquitlam, Port Moody, Port Coquitlam, Anmore, and Belcarra—has experienced rapid population growth and continues to be one of the fastest growing areas in Metro Vancouver. The most recent estimates indicate that the population in the Northeast sector will grow by approximately 66% (to 376,000) by 2031, which would represent the second highest growth rate in Metro Vancouver.

Planning for the Evergreen Line has been ongoing for more than 10 years to address the growth in this region. Early in the planning process during the construction of the Millennium Line, the as-yet-unnamed line was conceived as an extension of the SkyTrain system, using advanced light rapid transit (ALRT) technology. In 2004, following a review of technology alternatives and in light of the funding envelope of $800 million for the project, TransLink decided to move forward with a Light Rail Transit (LRT) solution. It was during this phase that a naming competition was held by TransLink with the community resulting in the “Evergreen Line” name.

In 2008, work was undertaken by the Province and TransLink to review the choice of technology and route for the Evergreen Line, in light of increasing urgency with respect to providing viable transportation alternatives and maximizing ridership capacity.

In the spring of 2008, the Province announced that ALRT technology would be used for the Evergreen Line, consistent with the technology used for the Expo and Millennium Line components of the existing SkyTrain system. The Province assumed responsibility for the design and construction of the Project, with TransLink having responsibility for the ongoing operation and maintenance of the Evergreen Line as a fully interoperable extension of the existing SkyTrain system.

SkyTrain technology was chosen for the Evergreen Line because it is estimated to have the capacity for two and a half times more ridership than a Light Rail Transit (LRT) system. It will provide a direct connection without transfer onto the Millennium Line; and is almost twice as fast as LRT.

The procurement decision to use a Design Build Finance (DBF) partnership delivery model for the Evergreen Line infrastructure was based on a thorough analysis of procurement options. A Design Build Finance Operate Maintain (DBFO) model (similar to the model used for the Canada Line) was examined but deemed not appropriate for the Project because of the need for full operational integration with the existing SkyTrain system. A Design Build Finance Maintain (DBFM) model was rejected on the grounds that there would be greater economies of scale if the Evergreen Line was maintained as part of the larger SkyTrain system.

A DBF model was chosen because it better met the procurement objectives, providing better risk transfer related to scope and schedule, as well as opportunities for innovation, particularly through construction methodology.

1.3 Project Procurement and Timelines

A two-stage competitive selection process was undertaken for the Project: a Request for Qualifications (RFQ) stage, and a Request for Proposals (RFP) stage. During the RFQ stage, respondents were asked to present their qualifications for the Project. Seven teams responded to the RFQ. Three teams were shortlisted and invited to participate in the RFP stage process.

The timeline of the competitive selection process is outlined below:

- July 2010 – Request for Qualifications
- Nov 2011 to Oct 2012 – Request for Proposals
- October 2012 – Selection of the Preferred Proponent
- December 2012 – Project Agreement Finalization

During the RFP stage, workshops and topic meetings were offered so that each team had the opportunity to discuss issues or concerns related to commercial, legal, design and construction matters. The RFP included a number of specific features that reflected the unique requirements of the Evergreen Line Project including the bored tunnel. The Province provided processes to allow proponents to propose modifications to the Reference Concept tunnel alignment. The RFP also provided the option for two risk scope levels relating to the risk of differing geotechnical site conditions in the tunnel. Proponents could elect to accept all the tunnel geotechnical risks, such as differing site conditions, or to share the risk with the Province based on a Geotechnical Baseline Report, prepared by the Province’s geotechnical consultant. If a proponent elected to share this risk, under the RFP the Province would attribute an additional cost of $30 million to the proponent’s price proposal for evaluation purposes.
Following an extensive evaluation process for the RFP stage, the team led by SNC-Lavalin Inc. was identified as the preferred proponent for the Project in October 2012. The private partner for the Evergreen Line is Evergreen Rapid Transit Holdings Inc., doing business as EGRT Construction, which is owned by SNC-Lavalin Inc.

In December 2012, the Province entered into a performance-based, fixed-price project agreement with EGRT Construction to design, build, and finance the guideway, tunnel, and stations; install the automatic train control and other systems; and test and commission the Evergreen Line. The term of the contract is approximately 3.5 years, and the fixed price of the contract is $889 million.

EGRT Construction will deliver the Project through a series of subcontracts, with key aspects of the project being delivered either by specialist providers or self-performed by SNC-Lavalin. The EGRT Construction structure is illustrated in the figure below.

The Province is responsible for the design and construction of the Project and, following completion, TransLink will operate the new line as part of the SkyTrain network. Construction of the Evergreen Line is well underway, with the completion and opening of the line anticipated for the summer of 2016.

2 TUNNEL ALIGNMENT AND TBM SELECTION

The choice of alignment for the bored tunnel has been greatly influenced by the entire project’s schedule of work. The underground section is positioned halfway between the end of the new alignment and tie-in with existing Millennium Line. Thus, it naturally falls on the construction critical path because of the long lead time for TBM procurement.

The time frame available for the excavation was one year from the start of the delivery of the TBM on site.

The bid team considered three different options: (1) two drives with one 6-metre-diameter TBM; (2) two drives with two 6-metre-diameter TBMs; and (3) a single drive with one 10-metre-diameter TBM. The third option has been selected because it allows the earliest start time for all of the trackworks. The other substantial advantage of the single drive solution is the omitting of cross passage construction, which would have involved challenges due to geological conditions (high overburden and water table).

The chart depicted in Figure 4 presents a comparison of the timing for the three options.

![Figure 4. Timing for Various Drive Options](image)

The single drive alignment fits the inbound and the outbound tracks separated by a partition wall. Doors will allow transfer of passengers from one drive to the other in case of fire.

Despite the ability to better cope with tunnel geology (especially in the case of boulders), the chosen solution has some disadvantages when compared to either of the 6-metre TBM solutions. It requires more space and uses more resources. A smaller boring machine requires less space during the assembly and disassembly phases and less power and water consumption. The Evergreen Line is located in a fairly urbanized district: staging areas for TBM components and tunnel linings are limited, while connection to the power grid or main web can present some difficulties. Quantities related to a 10-meter TBM are greater too: additional extracted material during the excavation, thicker lining, and more consumables.

Nevertheless, their advantages, the 6-metre TBM options would have considerable negative impact on the schedule and a heavier construction risk than would the 10-metre TBM option.

3 DESIGN-BUILD PROCESS

The fundamental difference between the Design-Bid-Build process and the Design-Build process is that certain key design decisions need to be made early on in the Design-Build process that set specific parameters or geometry for the project. This is different from Design-Bid-Build where Contractors have a chance to evaluate different approaches during the bidding phase in an attempt to come up with the most economical construction approach.

For the engineering team, the design process essentially began in May 2011 with pre-tender phase meetings between Jacobs Associates, SNC-Lavalin and SELI. The primary design deliverable during this phase was a report
that provided an evaluation of geotechnical and tunnel design issues for the original twin-bore concept. Based on this report and cost estimates performed by SELI, the Design Team elected to pursue the single-bore option thus avoiding having to construct Cross Passages in difficult ground.

The tender phase report was finalized in March 2012 whereupon schematic tunnel lining design commenced to determine the construction cost of the tunnel. The financial submittal was delivered to the Province in late summer of 2012 and the SNC-Lavalin team was officially notified of winning the project in late 2012.

Final design began almost immediately after news of the project win and by summer of 2013, final design was complete. The design process consisted of four submissions (in order of increasing completeness) of drawings and specs accompanied by a selection of technical memos that addressed various specific project issues. One of these was the Seismic Design Summary Memorandum (SDSM). This document covered the seismic design demands on the tunnel and paved the way for the use of steel fibre reinforcement in the segmental lining for the majority of the tunnel alignment.

An effort was made to keep the same individuals that were involved during the design phase engaged on the project throughout construction. This has proven to be valuable since these individuals are familiar with the challenges that surfaced during the design phase and are better prepared to deal with related issues as they come up during the construction phase. Additionally, the teaming relationships that developed during the design phase have also been beneficial heading into the construction phase. Things can happen very suddenly on a design-build project. When a team is prepared to react quickly to surprises, it can help to manage risks associated with safety, cost overruns and schedule delays.

4 DETAILED DESIGN

As discussed in the previous section, the order of design was generally reversed from the typical design-bid-build in that geometry had to be set early in the process to allow both the TBM and segment moulds to be ordered. Thickness was set early in the process as well, and the design then followed an accelerated path to check construction, static, and seismic loading conditions. Based on previous project experience in similar ground and seismic conditions, it was felt that steel fiber reinforced concrete (SFRC) segments could be feasible for at least some portions of the alignment. The structural design focused on whether the use of SFRC was acceptable.

4.1 General Requirements

Requirements for the tunnel lining design were set in the Project Agreement (PA) document, which also referenced various design codes and design guidelines. The tunnel lining was designed as a one-pass system for a 100-year design life. The lining also had to withstand seismic loading, as discussed in more detail below.

4.2 Geometry

During tender design, a segment thickness of 350-mm was set based upon preliminary analyses that indicated that this thickness would be sufficient to handle anticipated construction and static loading on the tunnel. Adjustments to required concrete strengths and reinforcement could allow some control of capacity if needed for the given thickness.

Layout and segmentation of the lining were coordinated with the TBM manufacturer to match thrust ram locations, stroke lengths, and overall tail shield length. The geometry was developed in 3-D to account for the complexity of the geometry, and to verify mould drawings. See Figure 5 for a view of the 3-D model for the lining. A tapered universal ring with seven equal segments and a smaller key was selected for the 8.84m ID tunnel. The ring taper is 58-mm, segment width is 1.5-m and typical length of segment is 3.7-m.

Figure 5. 3-D Model of Segmental Lining

4.3 Static Structural Design

Load conditions for the tunnel were developed at a few key locations along the alignment, including lowest cover, highest cover, and highest groundwater location. In general, ground conditions were favorable throughout the alignment, consisting of glacially overconsolidated soils. The groundwater regime is complex along the alignment, but detailed studies of available information allowed for estimates of groundwater pressures to be made. Construction loading transportation and handling, TBM thrust rams, and grout loads were also considered. The Project Agreement (PA), which provided design criteria for the design, required other loading conditions to be analyzed as well. A 0.5% eccentricity in ring build was also accounted for.

For analysis of static loading, a beam-spring model developed with the computer program STAAD was used.
Spring parameters were developed based upon anticipated soil conditions. The Muir-Wood and Curtis (1975, 1976) closed-form elastic method was also used as a verification of the STAAD results. Load factors and strength reduction factors were based upon requirements of the PA, and generally followed CSA 23.3, with additional guidance from ACI 318 and the FHWA Road Tunnel Manual (2010). Moment-thrust interaction diagrams were developed for both conventional rebar reinforcement, and SFRC, using various codes. The SFRC capacity curve was based upon design parameters given by King (2005), which draws from various standards used worldwide.

Figure 6 presents the critical results of the static analysis for the lining. Figure 7 presents the critical results accounting for tail void and proof grouting loads. It can be seen that all loads fall within the various capacity curves, including the SFRC curve. All curves assumed a compressive strength of concrete of 50 MPa, and the SFRC curve was developed for a residual flexural strength of 3.3 MPa.
4.4 Seismic Structural Design

Seismic design criteria and parameters were set for the project, including the tunnel. These inputs to the seismic design followed the PA and various codes. The tunnel lining was designed for two levels of earthquakes: a 100-year return period in which the tunnel must be ready for immediate use (Operating Design Earthquake [ODE]); and a 975-year return period in which repairs may be required (Maximum Design Earthquake [MDE]). A larger subduction event was also required to be considered, but was determined to be less critical than the 975-year return period earthquake because of a larger distance from the source.

Earthquake ground motions were developed for the nearest station site, and applied to the tunnel, accounting for depth of the tunnel and other factors. Soil parameters were determined based upon available information, and a range of parameters were used to account for uncertainty. Two locations along the tunnel were selected for analysis—one for the shallowest portion of the alignment and one for the deeper portions. See Table 1 for a general summary of parameters used in the analysis.

Table 1. Seismic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ODE Value(s)</th>
<th>MDE Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGA (g)</td>
<td>0.12</td>
<td>0.34</td>
</tr>
<tr>
<td>PGV (m/s)</td>
<td>0.11</td>
<td>0.32</td>
</tr>
<tr>
<td>$V_{se}$, Lower Bound (m/s)</td>
<td>310</td>
<td>274</td>
</tr>
<tr>
<td>$V_{se}$, Best Estimate (m/s)</td>
<td>361 to 492</td>
<td>319 to 434</td>
</tr>
</tbody>
</table>

The tunnel lining was analyzed for seismic racking using the finite difference program FLAC, and verified using the closed form elastic solutions presented in Hashash et al. (2001 and 2005) and Wang (1993). Longitudinal strains were analyzed using Hashash et al. (2001). The presence of a stiff invert was accounted for in the FLAC analysis, and a number of sensitivity runs were performed to determine design requirements for the invert. Vertical accelerations were also investigated, as required by the PA, but did not control design.

For results of the analyses performed, see Figures 8 and 9 for typical plots of moments and thrusts induced on the lining from seismic loading for the MDE event. As can be seen, moments were higher for a few points in proximity to the invert slab, but these were mitigated to some extent by requiring a “soft” invert, consisting of lower strength backfill, and a flexible joint between the invert slab and the segmental lining. These seismic loads were then combined with static loads, and plotted on moment-thrust interaction diagrams. See Figure 10 for static plus ODE loads, which all fall well within the capacity curves, indicating that the lining can withstand the seismic event without damage. See Figure 11 for static plus MDE loads, which also fall within the capacity curves, indicating that significant repairs are unlikely to be required even after the larger seismic event.

Figure 8. Moments and Thrusts for MDE Loads, Shallow Case
Figure 9. Moments and Thrusts for MDE Loads, Deep Case

418+300 MDE Loads, Low K,0, Best Estimate Modulus, Soft Invert

Figure 10. ODE Seismic Loads Moment-Thrust Interaction Diagram

Evergreen Project, Moment-Thrust Interaction, ODE Loads

- RC-20MA
- RC @2 MA
- SRFD (King, 2002)
- Triflex
- 43#-MDE, no invert
- 43#-MDE, no invert
- 43#-MDE, no invert
- 43#-MDE, invert
- 43#-MDE, invert
- 43#-MDE, invert
- Compression Line
Despite the results of the analysis, it was decided that conventionally reinforced segments would be provided in proximity to the portal locations. The rationale used to justify these segments was uncertainty about TBM thrust loads during the early and late portions of the drive, uncertainty about ground parameters, and the desire to provide a more robust design in these sensitive areas.

4.5 Joint Design

The longitudinal and circumferential joints were designed for anticipated bursting stresses. Longitudinal joint loading was derived from hoop thrusts from ground and groundwater loading. Circumferential joint loading was derived from TBM thrust loads. The thrust ram configuration was taken into account when determining design requirements. The design confirmed that SFRC had sufficient capacity to resist bursting stresses, provided that the SFRC had a minimum tensile strength of 3.9 MPa.

4.6 Construction Loading Design

TBM thrust loads were discussed above. The segment design was also checked for required stripping strengths during demoulding and early handling, stacking, and transportation load scenarios. Requirements for each condition were passed on to SSJV and the segment manufacturer Architectural Precast Structures (APS).

4.7 Other Design Considerations

Gaskets and connectors were designed to resist anticipated grout and hydrostatic pressures, and maintain compression of the gaskets. Connectors were also designed to provide support to incomplete rings if a power failure were to occur. Spear bolts were selected for the longitudinal joints, and dowels were selected for the circumferential joints.

For fire design, the segmental lining incorporated approximately 1 kg/m$^3$ of polypropylene fibers. No specific testing was performed, but previous experience and testing from other projects were considered in the selection of the fiber dosage.

A packer was allowed for the circumferential joints, although not required.

5 FABRICATION

The segments were fabricated off-site by APS in Langley, B.C. The plant layout was based on 24 static moulds that are firmly fixed to the floor. The moulds are equipped with vibration dampers and adjustable bearings for an optimum concreting result. The moulds were subdivided into six zones. Each zone was connected to the steam supply system for moist curing under tents (see Figure 12).

The typical production sequence of the fibre reinforced segments involved casting of concrete, vibrating, initial set, trowelling of the extrados of the segments, installation of steam tents over the moulds, steam curing, demoulding using a vacuum seal erector, turning of the segments for storage position using hydraulic lifting and turning device, and transport to storage yard.

The casting plant typically operated in two shifts with six working days in a week. The maximum number of segments produced in a day was 48 segments and weekly average was 176 segments at the time of writing. In comparison, the TBM advance target speed was 10 rings per day, i.e. 80 segments per day. Hence, the timing of the production head start to avoid critical path delays was crucial and segment production commenced in the middle of October 2013, more than 20 weeks ahead of the TBM boring.
As part of the physical verification of the physical segment design geometry, a mock-up ring was built in the casting yard, as shown in Figure 13.

Figure 12. Static Moulds under Steam Curing Tents

Figure 13. Mock-up Ring

6 CONCLUSIONS

Following the typical design-build process, the segmental lining thickness was set early in the process, followed by key geometry parameters to allow for TBM and segment mould procurement. Design then focused on the use of SFRC for all anticipated loading conditions. It was found that SFRC could be used for both static and seismic loading conditions, although the seismic design required that the invert of the tunnel has a reduced stiffness and flexible connections to the lining to reduce interactions. To provide a more robust design at lower-cover areas, a conventionally reinforced lining was used for short sections near the portals. The segmental lining production and TBM excavation are ongoing, and are anticipated to be completed by late 2014.

REFERENCES

American Concrete Institute. ACI-318 – Building Code Requirements for Structural Concrete.
CAN/CSA A23.3. 2010. Design of Concrete Structures, Update No. 3.