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NELSON AND CYPRESS CREEK BRIDGES: SEISMIC SAFETY RETROFIT OF TWO SIMILAR BRIDGES WITH DIFFERENT SOLUTIONS

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ABSTRACT: Nelson Creek Bridge and Cypress Creek Bridge were built circa 1974 and carry the Trans-Canada Highway 1 over two major valleys in West Vancouver. Both bridges were designed by the same engineering firm with many apparent structural similarities. Cypress Creek Bridge is 130 m long, comprising three suspended girder spans and two intermediate cast-in-place multi-cell concrete piers. Nelson Creek Bridge is a 214 m long, horizontally-curved structure with five suspended girder spans and three intermediate piers. All suspended spans are simply-supported prestressed concrete I-girders, which are supported by table-top piers, through concrete half-joints. While the original design of both bridges was based on a same concept, and they thus contain similar gravity load paths, their seismic responses differed significantly. In addition, Half-joints are a deterioration-sensitive detail, and the capacity of the existing configuration was deficient for current highway loading. Also, the longitudinal and transverse restraint provided at the girder bearing locations was insufficient to prevent loss-of-span in a design earthquake. Both bridges have poor reinforcing details for ductility with lap splices at potential plastic hinge locations. Two different retrofit strategies to improve the seismic performance of the bridges were implemented. At Cypress Creek Bridge, the retrofit strategy was based on reducing the longitudinal and transverse displacements such that limited ductility demands are seen at potential plastic hinge locations, eliminating the need for strengthening. The deck was made continuous at the half-joint locations with link-slabs, preserving the simply-supported behaviour of the suspended span girders under gravity loads. To strengthen the pier half-joints, high-strength bars were drilled and grouted through the corbels, and cast into a new reinforced concrete diaphragm between the existing girder end diaphragm and pier table wall. For Nelson Creek Bridge, the seismic displacement demand was reduced and a strengthening strategy to increase the ductility level of the structure elements was adopted. At Nelson Creek Bridge, the half-joints were made fully monolithic, creating a fully continuous deck system to increase the redundancy of the superstructure.

1. Introduction

Nelson Creek and Cypress Creek Bridges, located in West Vancouver, are multi-span prestressed I-girder bridges constructed during the 1970s. Both bridges contain concrete half-joint bearing seats and other suspect, deterioration-sensitive details. Associated Engineering was retaining by the Ministry of Transportation and Infrastructure (the Ministry) to carry out the design of rehabilitation works for the bridge.

A major focus of the rehabilitation project was to provide a seismic safety retrofit. The bridges were constructed prior to modern ‘capacity design’ principles, and as such, contained deficient load paths and detailing for adequate seismic response.

2. Description of Structures

2.1. Nelson Creek Bridge

Nelson Creek Bridge was built circa 1970 and carries the Trans-Canada Highway over Nelson Creek in West Vancouver, approximately 2 km west of Cypress Creek Bridge. The 214 m- long horizontally-curved structure comprises four tangent prestressed concrete girder spans and three cast-in-place multi-cell concrete pier tables. Each of the intermediate piers is supported by four tall, slender columns, which are in-turn supported on individual spread footings upon bedrock.

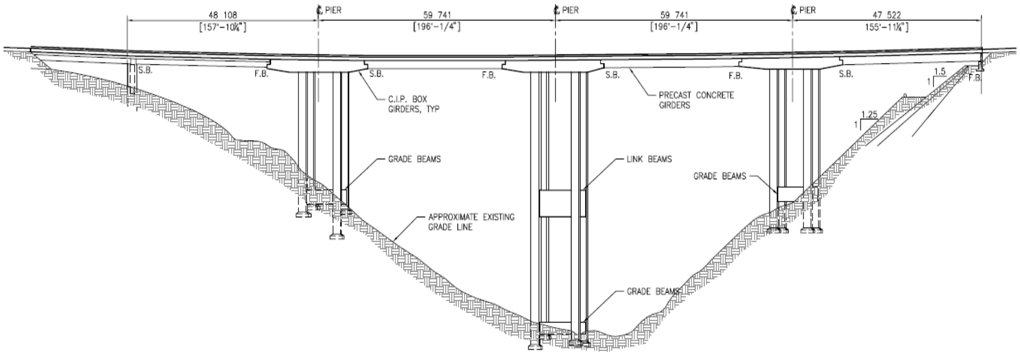
The east and west columns each have a height of approximately 30 m, and have reinforced concrete grade beams connecting the four columns just above the footings, thus providing frame action. The centre pier has a similar configuration to the east and west piers, although it is nearly twice as tall with a height of approximately 57 m. It also has deep link beams connecting the columns at mid-height, acting to provide frame action and increased column stability under the original design loading. Both the columns and connecting beams contain poor detailing with deficient confinement, rebar curtailment and lap-splices all within expected plastic hinge zones.

The west abutment comprises a short, highly-skewed cast-in-place reinforced concrete approach span, supported at the east approach by a monolithic grade beam and at the west by a small cast-in-place pier on bedrock. This pier also contains poor seismic details, and was significantly corrosion damage. The east abutment comprises a bank-seat abutment with spread footing, sitting on approximately 12 m of fill above bedrock.

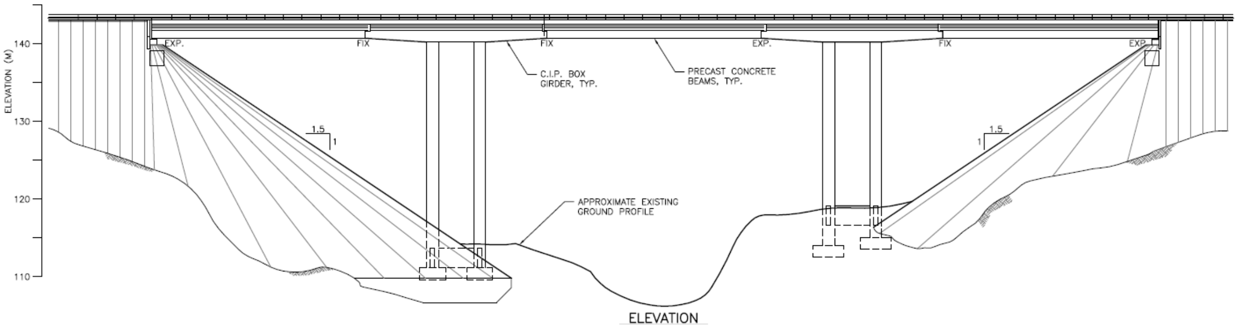
2.2. Cypress Creek Bridge

Cypress Creek Bridge was built circa 1974 and carries the Trans-Canada Highway over Cypress Creek in West Vancouver, Southeast of Horseshoe Bay. The 130 m-long structure comprises three prestressed concrete girder spans and two cast-in-place multi-cell concrete pier tables, each cast integrally with a four-column reinforced concrete pier.

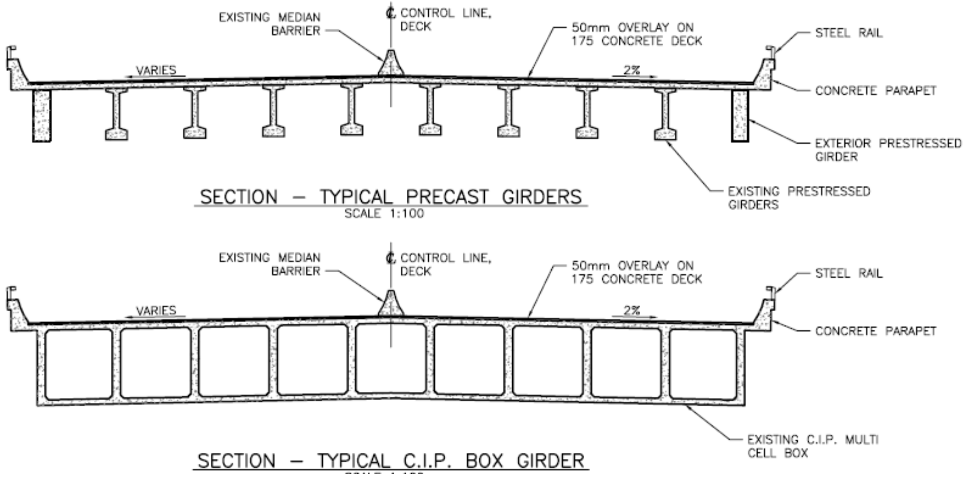
The prestressed girder spans are supported on half-joints at the pier tables, and on perched abutments at the bridge extents. A concrete bin wall retains the toe of the west approach fill adjacent to the creek, immediately downstream of the bridge. Figure 1 below shows the general configuration of each bridge.



a- Nelson Creek Bridge Elevation



b- Cypress Creek Bridge Elevation



c- Typical Cross Sections

Fig. 1 - Bridge elevation and typical cross section

3. Seismic Assessment and Retrofit Design Criteria

The seismic assessment and retrofit design criteria for both bridges are similar. The seismic parameters were derived based on the applicable guidelines and standards. Material properties, including strengths and densities are based on the information that was available from the Record Drawings, as well as limited in-situ material sampling. Seismic performance criteria was based on British Columbia Ministry of Transportation and Infrastructure's (MoTI) 'Bridge Seismic Retrofit Criteria' guideline (2005).

3.1. Seismic Parameters

The assessment and design is based on a design earthquake with a uniform hazard spectrum 10% probability of exceedance in 50 years (475-year return period). The bridges are classified by the Ministry as "Disaster Response Route" (DRR) bridges. For DRR bridges, significant damage is acceptable, provided that limited use by emergency traffic is possible following an earthquake. The acceptable damage level is "Significant Damage (No Collapse)" Both bridges are located in a highly seismicity zone with a 0.234 g Peak Ground Acceleration. Load combinations are based on the 'Canadian Highway Bridge Design Code CAN/CSA-S6-06 (CHBDC). However, we considered load factors of 1.0 for dead and live loads as recommended by the MoTI seismic retrofit criteria.

3.2. Design Response Spectra

The Uniform Hazard Spectrum was obtained from Natural Resources Canada on the latitude and longitude position of the Cypress and Nelson Creek Bridges. The PGA is 0.234 g, however, due to the sensitivity of the spectral acceleration (and therefore seismic response coefficient) of structures with periods less than 0.2 seconds, the acceleration associated with a period of 0.2 seconds is maintained for shorter periods (Figure 2).

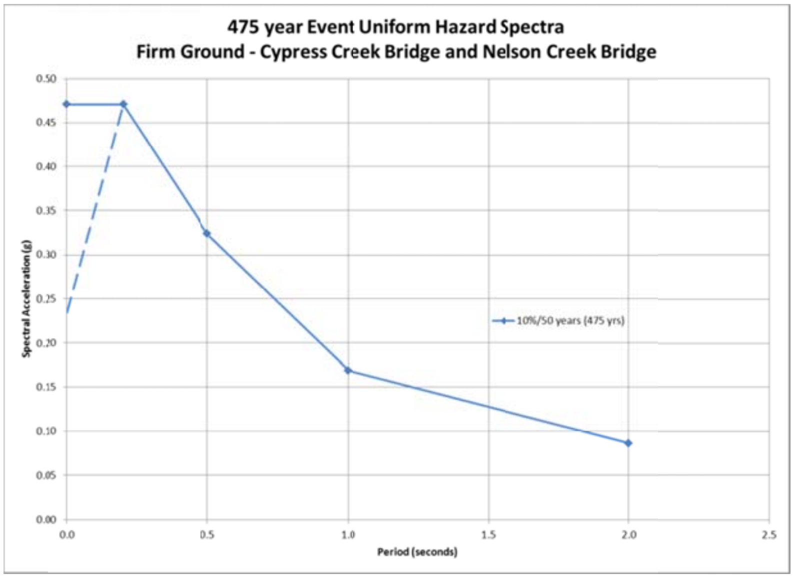


Fig. 2 - Uniform Hazard Spectrum 10% Probability of Exceedance in 50 Years

4. Structural FEM Modelling and Analysis

We used Midas Civil 2012 to perform a variety of analyses on the structures. These include both local and global models as appropriate to accurately capture the behaviour of these bridges.

Our global models captured the bridge specific geometry, ballast wall interaction with end fills, and any retrofit restraints that alter the bridge articulation. In the concept planning phase of this project, we recognized that a continuous deck diaphragm would significantly improve the seismic performance of both structures, regardless of the other retrofit strategies adopted, as well as improve the joint durability. As such, our baseline global assessment models reflected the presence of link-slabs. Sensitivity analyses were performed without link-slabs (i.e. as-built) to confirm behaviour.

4.1. Analysis and Assessment Methodology

Multi-mode Response Spectrum Analysis (RSA) was employed to determine elastic demands and peak global deformations on the structural components, particularly the pier columns and abutments. Based on conceptual evaluation of the existing structural systems and load paths, we expected the columns to remain linear or near-linear.

We used cracked section properties for the substructure reinforced concrete elements. We anticipated that the force effects and load paths through the piers would be sensitive to the effective stiffness of the link and grade beams and as such, we conducted sensitivity analyses to confirm appropriate section properties for our assessment and design. We also accounted for degrading concrete column shear capacity as a function of curvature ductility where appropriate.

We performed non-linear static (pushover) analyses of the piers for both bridges to determine the probable pier displacement capacities and expected nonlinear behavior for both the existing and retrofit configurations.

5. Seismic Performance and Vulnerabilities

5.1. Nelson Creek Bridge

Based on our analyses and our seismic performance assessment, we identified several seismic ‘Vulnerabilities’ within the Nelson Creek Bridge. ‘Vulnerabilities’ are defined as deficiencies within the facility, including foundations, piers and superstructure, that render the crossing incapable or at unacceptable risk of not meeting the seismic performance objectives.

A summary of the structural vulnerabilities and implications on performance objectives follows:

- West abutment pier columns at various locations were vulnerable in both flexure and shear. Portions of these columns are partially buried, creating the potential for brittle shear failure. Failure of these columns would result in the loss of gravity support and possible collapse beneath the west approach span and suspended span.
- Shear keys at the east abutment and all piers were inadequate to provide transverse span restraint. This deficiency could result in increased pier column demands, the horizontal misalignment of the bridge following a design level earthquake, or even a loss of span during a more severe event.
- East abutment was vulnerable to transverse sliding on the underlying soil. Consequences of this vulnerability are increased pier column demands, horizontal misalignment the easternmost suspended span and damage to the abutment components, such as wing walls and the back wall.
- East, centre and west pier columns have poor confinement, 90 degree rebar hooks and widely spaced single bar column ties. This deficiency means that the column core does not have reliable flexural or axial capacity once the cover concrete has spalled off, which could result in the loss of a pier under seismic attack.
- East, centre and west pier columns have additional rebar extending down from the pier table, which curtails below the table soffit. This would force a plastic hinge to occur at the curtailment within the column length, which would cause significant local concentration inelastic curvatures. Due to the poor confinement, this inelastic behaviour would significantly decrease gravity load capacity and increase risk of collapse. Additional rebar also extends from the top of the grade beams at the east and west piers, creating a vulnerability at the curtailment above the grade beams A similar situation was prone to occur here.
- Grade beams on the east, centre and west piers, and the link beams on the centre pier were deficient in both flexure and shear. In addition, the beam’s longitudinal rebar has marginal embedment / development length into the pier columns. A failure in either flexure, shear, or bar pullout would result in increased effective column length, and greatly increased demands in the columns under seismic loading.
- The pier table concrete corbels are vulnerable to failure under seismic loading. Effects such as deck torsion, longitudinal forces and vertical accelerations can locally increase bearing reactions, and require a robust, ductile load path to provide resistance. The pier table concrete corbels are a non-ductile system.

5.2. Cypress Creek Bridge

Similar to Nelson Creek Bridge, we identified several seismic ‘Vulnerabilities’ within Cypress Creek Bridge. Given the similar detailing of the two structures, several of the vulnerabilities are similar to Nelson. A summary of the structural vulnerabilities and implications on performance objectives follows:

- Shear keys at both the east abutments were inadequate to provide transverse span restraint. This deficiency could result in increased pier column demands, the horizontal misalignment of the bridge following a design level earthquake, or even a loss of span during a more severe event.
- Both abutments were vulnerable to transverse sliding on the underlying soil. Consequences of this vulnerability are increased pier column demands, horizontal misalignment the easternmost

suspended span and damage to the abutment components, such as wing walls and the back wall.

- The west approach embankment is prone to moderate deformations and settlements. This could result in settlement of the west abutment, span misalignment, and increased demands on the west pier.
- East and west pier columns have poor confinement, 90 degree rebar hooks and widely spaced single bar column ties. However, the pushover analysis shows that a low curvature demand is expected at plastic hinge locations. Consequently, no concrete degradation is expected at hinge location and therefore no column retrofit is necessary at joints and pier columns.
- Similar to Nelson, the pier table concrete corbels are vulnerable to failure under seismic loading. The pier table concrete corbels were poorly detailed with a very limited redundancy at load path.

6. Seismic Retrofit Design

Based on our assessment findings, we developed seismic retrofit strategies for both bridges. These strategies reflect the significantly different seismic response of the two structures.

6.1. Nelson Creek Bridge

We considered several strategies to improve the seismic performance of the bridge. We elected to provide movement restraint at the abutments, thus reducing the displacement demands at the slender piers, and create a continuous deck diaphragm to tie the system together. Other alternatives, such as strengthening the columns, were also evaluated, though we determined that the installation of concrete or steel jackets would be uneconomical, given the access constraints. We also determined that the performance benefits of column jackets relative to abutment restraint would not provide good value to the Ministry.

To provide restraint at the west abutment, we converted the approach span and pier into a voided abutment by adding longitudinal and transverse shear walls, which were anchored into the exposed bedrock. This conversion included bearing replacement and concrete shear keys to ensure proper engagement of the superstructure. At the east abutment, steel piles were added alongside the existing footing to provide restraint and prevent transverse sliding.

With restraint provided at the abutments and a deck diaphragm established, the design pier displacement demands were significantly reduced, and the columns could thus remain nominally elastic. With the exception of the west pier, costly column retrofit works were avoided. Despite the demands being reduced, framing forces in the grade beams still exceeded their capacity. We retrofitted these beams with shear-connected concrete jackets, with longitudinal reinforcement dowelled into the columns, to increase the capacity. Figure 3 shows several partially completed grade beams. Given the skew of the west pier columns relative to the superstructure, we found biaxial effects to be significantly greater than the other two piers, and as such, dowelled surface anchors, consisted of high-strength rod and plate washers, were added in zones of rebar curtailment and deficient confinement, to delay the onset of cover concrete spalling. These surface anchors are shown in Figure 4.

Fig. 3 – Typical Grade Beam Retrofit

Fig. 4: West Pier Column Surface Anchors

In order to create a continuous deck diaphragm, we designed link slabs to replace the existing compression seal joints at each of the piers. Link slabs create a continuous deck surface of the length of the structure, thus altering the articulation for thermal response. Making the deck continuous required that all thermal movement be accommodated at the abutments. While both abutments have sufficient expansion gaps to allow the increased movement, the east abutment elastomeric bearings were short and unreinforced, and thus could not accommodate the increased shear requirements. As such, we replaced the east abutment bearings with tall laminated elastomeric bearings.

To strengthen the pier half-joints, we dowelled high-strength bars through the corbels, and cast them into a new reinforced concrete diaphragm between the existing girder end diaphragm and pier table wall, as shown in Figure 5. These high strength bars tie into the pier table deck reinforcement, providing a more direct load path than the corbels were previously relying upon.

Fig. 5: Half-joint Diaphragm Rebar Being Placed

In designing the half-joint strengthening, we recognized the opportunity to make the bridge fully continuous, thus reducing the structural demands and providing increased redundancy to the superstructure. To achieve continuity, we needed to retrofit the structure to handle moment reversal near the points of contraflexure, which occurred near the half-joint bearings. We accomplished this by modifying the link slabs with additional longitudinal reinforcement for negative bending, and by adding offset flanges to the drop-in span girders, which are dowelled into the face of the half-joint corbel. These slabs are shear-connected to the suspended-span girder bottom flanges using dowelled rebar.

The work completed on Nelson Creek Bridge not only provides the Ministry with value in the event of a design earthquake, but also under service loading, with its increased structural strength and redundancy. The works undertaken will allow the bridge to function as a significant crossing on a vital corridor through West Vancouver.

6.2. Cypress Creek Bridge

The following retrofit design strategy options were considered to address determined seismic vulnerabilities.

1- Adding shear keys into the bays at abutments that have no shear keys, to provide transverse restraint of the deck and girders at the abutments.

2- Connection of the superstructure using link-slabs. These act to provide a robust load path, allowing the abutments and continuous deck to act as a stiff transverse system, significantly reducing pier demands, better distributing seismic forces to substructure components, and adding redundancy to the structure under seismic loading. Installation of link-slabs required expansion joint retrofit at the abutments to accommodate the increased thermal displacement demands, which we also implemented.

3- Installation of concrete-filled steel piles to provide additional necessary lateral resistance at the abutment. The reinforced concrete pile-cap was detailed to provide lateral resistance only, preserving the longitudinal abutment behaviour under service loading.

4- There is a significant gap between end of each girder and abutment back wall. This gap allows the bridge to freely move longitudinally with little resistance before contacting the back wall. Longitudinal displacement of the bridge causes the pier columns to experience significant deformation at the anticipated plastic hinge locations. To avoid pier column retrofit, we limited the maximum longitudinal displacement of the bridge by providing steel ‘bumper’ plates at end of the each girder. These plates where anchored to the abutment back wall.

7. Conclusions

Cypress and Nelson Creek Bridges, while having similar structural systems and detailing, respond differently to earthquakes. Our seismic assessment revealed these differences and allowed us to develop two different retrofit strategies to improve not only the seismic performance of the bridges, but also provide the Ministry with increased structural strength and durability throughout the remainder of these structures' lives.

8. Acknowledgments

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9. References

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