Seismic Risk Management Program for Municipal Bridges in the City of Vancouver, B.C.

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ABSTRACT

The City of Vancouver owns and maintains over 50 bridge assets, which form a part of its transportation network. The inventory is very diverse in nature ranging from single span overpass and pedestrian structures, to multi-span downtown viaducts. Each of these structures form a vital part of the City's transportation network.

The City recognizes the importance of its assets and is in implementing a comprehensive seismic risk management program for its bridges as part of its overall asset management program. This program not only includes seismic performance assessments and retrofits of its assets, but is also tools including seismic performance drawings, post-earthquake inspection manuals for each structure, and checklists to aid emergency response personnel and engineers in post-earthquake inspections and decision-making. Seismic performance assessments are being completed for all bridges that carry or cross important roadways. This includes not only the three bridges over False Creek, but also many more road bridges. The scope of these studies is to determine the probable performance and identify retrofit needs to improve performance. This has enabled City to identify which crossings, and thus routes, should be targeted for post-earthquake response, and which routes should be avoided. It has also enabled the City to quantify priorities and budgets for retrofit programs.

Based on the assessments completed, the City has developed a multi-year seismic retrofit program, which prioritizes retrofits not only on cost, but relative importance of the route and the retrofit's value, based on degree of performance improvement. Many tools are being developed to aid engineers and emergency response personnel following an earthquake event. Seismic Performance drawings have been developed for each bridge that has been assessed. These comprise a graphical overview of the gravity and lateral force-resisting systems and design criteria. The intent of these drawings is to aid inspectors during post-earthquake inspection. The drawings act as a guide for inspectors to make rapid decisions about bridge safety and next steps. Post-earthquake inspection manuals have also been developed. Separate manuals have been developed for the City's three major bridges. The remaining structures are addressed in a combined manual which consists of a combination of drawings and annotated photos identifying locations of safe access, good vantage points, critical elements, and the pre-earthquake condition of the bridge for comparison purposes.

The above program demonstrates a holistic approach to seismic risk management of bridge assets as part of a network, rather than as individual structures and is an important part of the City's objective to be a resilient City.

Keywords: Asset Management, Road, Network, Bridge, Earthquake, Risk

INTRODUCTION

Background

Vancouver, pictured in Figure 1 below, owns and maintains over 50 bridge assets, which form a part of its transportation network. The inventory is very diverse in nature ranging from single span overpass and pedestrian structures, to multi-span downtown viaducts and significant crossings including the Burrard, Granville and Cambie Bridges across False Creek into the downtown core. Each of these structures form a vital part of the City's transportation network. Given its location near the interface of the North America Plate and the Juan de Fuca Plate, Vancouver is located in one of the highest seismicity zones in North America.

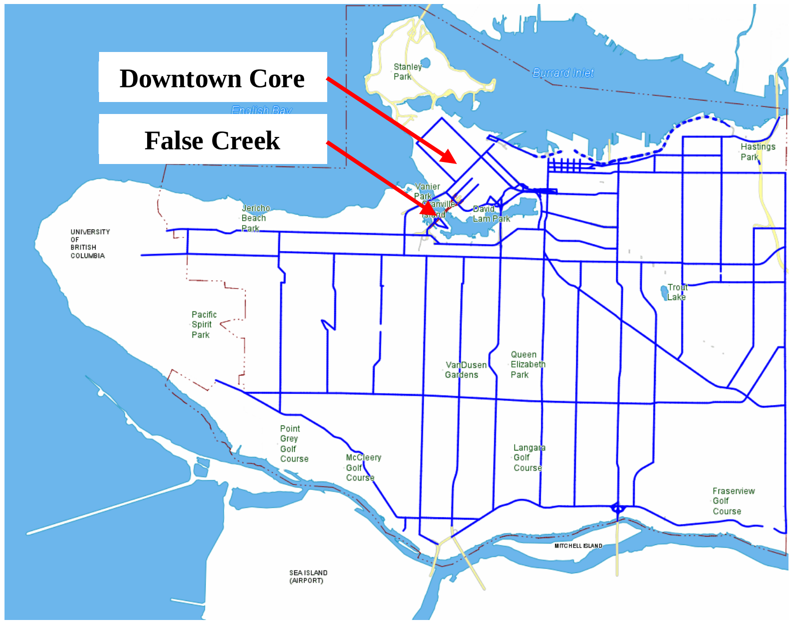


Figure 1. Major roads in Vancouver [1])

In recognition of its bridge assets and their importance within the regional road network, the City has developed a comprehensive bridge seismic risk management program as part of its overall asset management program. This program not only includes seismic performance assessments and retrofits of its assets, but is also tools including seismic performance drawings, post-earthquake inspection manuals for each structure, and checklists to aid emergency response personnel and engineers in post-earthquake inspections and decision-making.

RISK MANAGEMENT PROGRAM

Seismic Performance Assessments

As a first step in implementing its risk management program, the City undertook seismic performance assessments of many of its bridges. The bridges were selected based on their importance in the transportation network, such as being located on an emergency response route, and/or spanning over important infrastructure. Based on this prioritization, the City worked with consultants to perform the assessments.

Seismic performance assessments were conducted in accordance with the Canadian Highway Bridge Design Code CAN/CSA-S6-14 (S6-14). The City sought to use performance-based design principles to quantify the structural response and determine the expected performance of each structure. This included evaluation for the 475-, 975- and 2,475-year return period earthquakes. The performance was compared to S6-14 cl. 4.4.6.2 'Performance Levels', for 'Major-route Bridges' and 'Other Bridges', as shown in Figure 2 below.

Seismic ground motion probability of exceedance in 50 years (return period)	Lifeline bridges		Major-route bridges		Other bridges	
	Service	Damage	Service	Damage	Service	Damage
10% (475 years)	Immediate	None	Immediate	Minimal	Service limited*	Repairable*
5% (975 years)	Immediate	Minimal	Service limited*	Repairable*	Service disruption*	Extensive*
2% (2475 years)	Service limited	Repairable	Service disruption	Extensive	Life Safety	Probable replacement

**Optional performance levels unless required by the Regulatory Authority or the Owner.*

Figure 2. City-selected Performance Levels for Seismic Performance Assessments [2]

These performance levels were set as a baseline for evaluation purposes, as the City recognized that they are intended for new structures only, and that existing structures were designed using force-based design principles and often to a much lower seismicity than what is currently used in practice.

The results of the seismic assessments were compared to the Performance Levels in summary reports for use by the City. Where the seismic performance of the existing structures were deficient, high-level retrofit concepts were presented to improve the seismic performance to meet either the S6-14 Performance Levels, or a reasonable lower standard. Reasonably modern structures designed within the last 25 years were often found to have insufficient capacity to meet S6-14, but were reasonably proportioned and detailed, allowing for retrofit to meet the Performance Levels to be feasible with reasonable economy. Older structures and those founded on very poor soils could often not be economically retrofit to meet the above Performance Levels, but a 'Life Safety/Probable Replacement' was achievable.

Based on the performance assessments and retrofit concepts, rough-order-of-magnitude costs for retrofit were developed and presented in a summary report. The results of these assessments allowed the City to identify seismic vulnerabilities in its road network and make re-evaluate its preferred post-earthquake response routes and seismic retrofits based on overall cost and value within the system. The City also used this information to inform their budgetary needs for capital planning purposes.

Seismic Safety Retrofits

Following the assessment phase of this risk management program, the City selected candidate bridges for seismic retrofit. These bridges were chosen holistically based on a variety of factors, including

1. Importance of bridge to post-earthquake response road network;
2. Seismic retrofit cost (at both route and individual bridge level);
3. Achievable performance level; and
4. Asset management synergies (such as being combined with other planned maintenance/rehabilitation work).

Based on these factors, multi-year retrofit planning was undertaken, and continues presently to upgrade the selected bridges. Among these bridges are Burrard, Granville and Cambie, three major crossings over False Creek. Each of these bridges connect South Vancouver with the downtown core and provide access for motorists, public transportation, cyclists and pedestrians.

Burrard Bridge was constructed circa 1930, and comprises a steel through-truss marine span, deck truss back spans and concrete T-girder approaches. This structure underwent a seismic retrofit in the 1990s, primarily to address short seat lengths and loss-of-span' considerations. It has very brittle substructure, making a resilient, repairable retrofit challenging. Given this, the City used the information and analysis provided by consultants to determine that Burrard Bridge, and thus Burrard Street do not provide a viable link to the downtown core following an earthquake.

Granville Bridge was built circa 1955, and comprises a deck truss main span and concrete T-girder approaches on brittle reinforced concrete piers. The bridge carries considerable traffic, and spans over not only False Creek, but Granville Island, a popular tourist destination with densely populated zones and considerable cultural importance. The bridge underwent a minor seismic retrofit in the 1990s. In 2011, the City sought to replace the original truss bearings, due to the presence of toxic PCB lubricants in the rollers. As part of this task, the City considered the synergy of combining these works with a seismic retrofit and after evaluation with the consulting team, proceeded with the retrofit. The existing truss bearings were replaced with lead-rubber isolation bearings, designed using project-specific performance-based design criteria. As of this writing, all on-shore bearings have been replaced, with marine pier bearings slated for replacement in 2019. As the bearings required replacement regardless of seismic performance goals, the incremental cost of seismic isolation bearings was small relative to the overall project cost of bearing replacement but provided significant value to the City in protecting this important link between the two cores. Granville Bridge is shown in Figure 3 below.

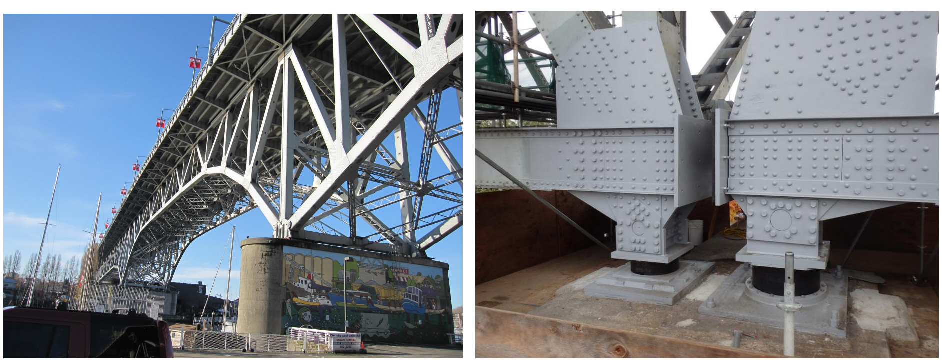


Figure 3. Granville Bridge: (a) elevation view, (b) replacement isolation bearings

Cambie Bridge was built circa 1984, and comprises post-tensioned spine beams on reinforced concrete piers at both the main span and approaches. Though relatively modern, it was designed to a 100-year return period earthquake, and is quite stiff and brittle. As the most modern and heavily trafficked route over False Creek, Cambie Road is an important link connecting the two cores of Vancouver. The City has undertaken seismic performance assessments, including geotechnical investigations, and has recognized its seismic vulnerability. It is currently engaging with consultants to study the determine appropriate performance targets and retrofit strategies for this structure, with construction expected to begin in 2020. The expected timing of this construction is to maximize synergy with a large infrastructure project in close proximity to the North approach spans, which will reduce costs, when compared to conducting a standalone retrofit. Cambie Bridge is shown in Figure 3 below.

Figure 3. Cambie Bridge

Post-earthquake Inspection Guides

In addition to the seismic retrofits undertaken and planned for its bridges, the City worked with consultants to develop visual guides for post-earthquake inspection of these structures. The purpose of these guides is to assist inspectors rapidly assess the structural integrity of bridges immediately following an earthquake and determine the next steps. Immediately following an earthquake, City resources and consultants will have limited capacity and access for route assessment. As such, these guides were written with the expectation that inspection staff using them will likely be familiar with civil engineering principles, but may not familiar with bridges or other structures. These guides are bridge-specific and have two formats: manuals and drawings.

The post-earthquake inspection manuals were developed for the Burrard, Granville and Cambie Bridges over False Creek. Contained in each manual is a simplified description of the bridge, including the articulation, vertical and lateral load resisting systems. The manual also contains information about access and vantage points for inspection. Following this introductory information, the manual provides information about expected earthquake damage types and locations for the bridge, including descriptions, sketches and photographs explaining not just the type of damage (such as deck joint misalignment, bearing unseating, approach settlement, column flexural and shear damage), but also examples of different degrees of damage severity. As an example, an inspection guide for concrete column flexural damage shows the examples of following damage states:

1. Horizontal cracking;
2. Cover spalling, longitudinal reinforcement and core concrete intact; and
3. Core concrete degradation, reinforcement buckling and/or necking.

Based on these damage examples, the manual provides a colour coded system with recommendations to the inspection team. This system generally conforms to the following standard:

1. **GREEN:** Bridge has sustained little to no damage, and is safe to re-open to public. Further assessment required to determine long-term health of the bridge.
2. **YELLOW:** Bridge has sustained moderate damage. The bridge may be safe to operate with restricted usage, such as emergency vehicles. Further assessment may be required to verify this, and certainly before reopening to public traffic.
3. **RED:** Bridge has sustained major damage, or the extent of damage is difficult to determine from rapid assessment. The bridge should be completed closed to traffic until further assessment can be done.

Figure 4 below shows an example of these recommendations from the Granville Bridge Manual.

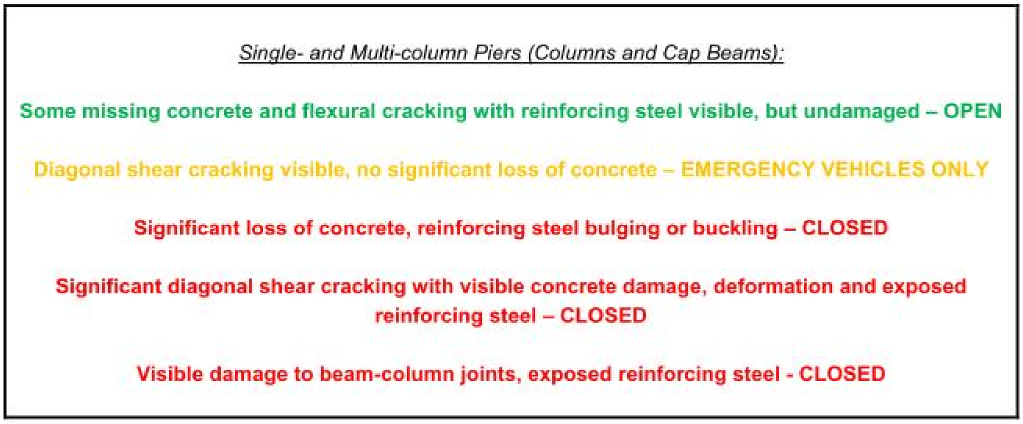


Figure 4. Post-earthquake inspection manual recommendations

The variety and complexity of structural systems on the bridges over False Creek necessitated a manual for inspection guidance, however the City also owns numerous overpasses and viaducts that will require rapid inspection following and earthquake. For these less complex structures, the City developed bridge-specific inspection drawings. Similar to the manuals, these drawings provide inspectors with at-a-glance information about the bridge location, photos, utilities, access and vantage points and inspection guidance. Figure 5 below shows an example of a post-earthquake inspection drawing.

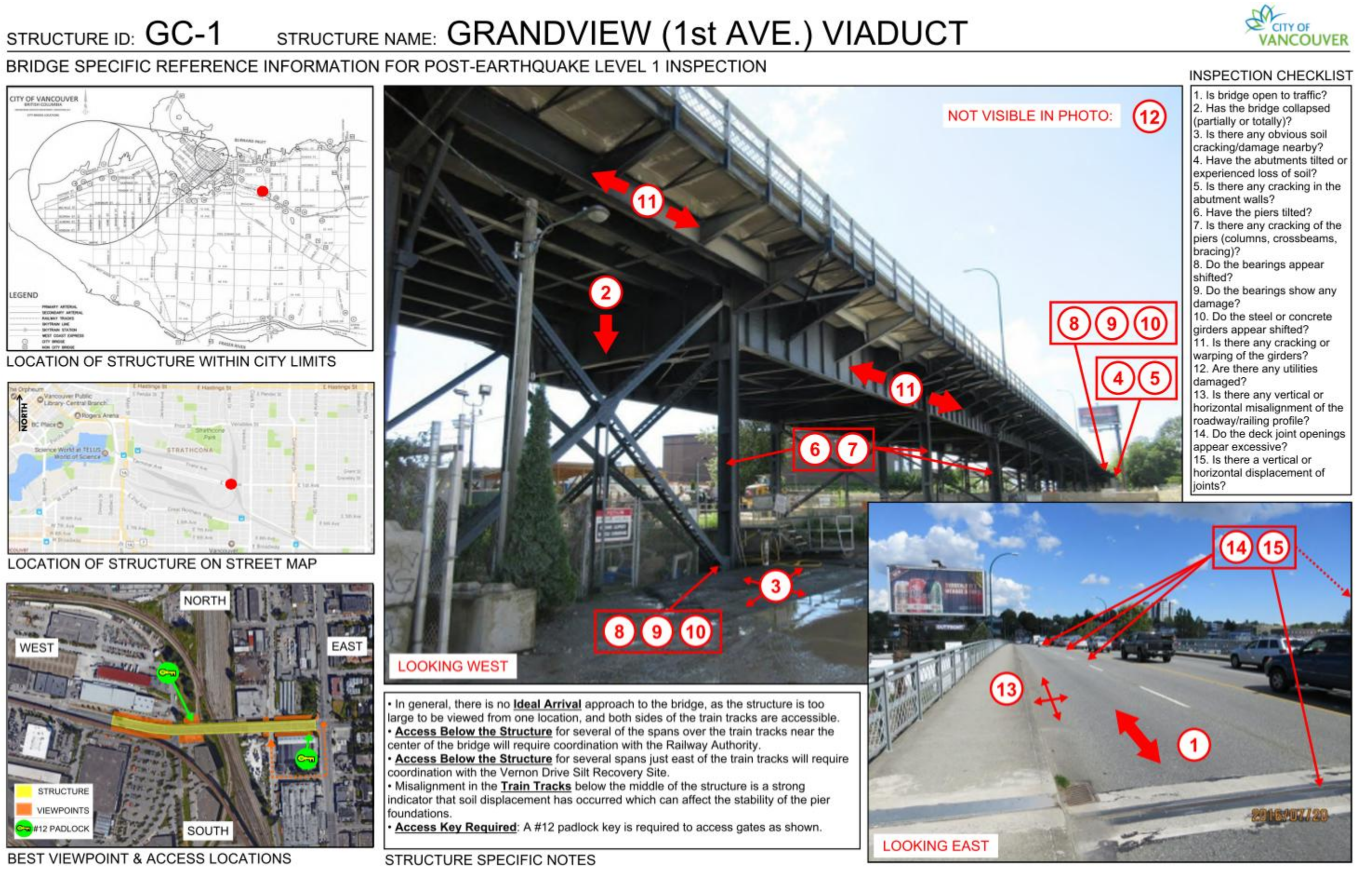


Figure 5. Post-earthquake inspection drawing

Hard copies of post-earthquake inspection manuals and drawings are stored not only in the City's Engineering Department, but also in several emergency response containers throughout the City, along with record drawings and other relevant information about the surrounding infrastructure. This allows for rapid access by City staff closely following an earthquake.

Seismic Performance Drawings

The post-earthquake inspection guides are intended to provide teams with vital at-a-glance information about the bridge characteristics and assessment points of interest. To pair with these guides, the City developed seismic performance drawings to provide a guide for more detailed investigation and analysis of the structures following the initial inspection. These drawings are intended for use by inspectors in the field and bridge engineers. They generally provide the following information:

1. Detailed description of the lateral load resisting system;
2. Seismic design criteria including design code, current uniform hazard spectra, anticipated period of vibration;
3. Seismic performance levels (service level and damage level as defined by S6-14);
4. Geotechnical conditions;
5. Descriptions of expected damage at various design earthquake (475-, 975- and 2,475-year);
6. Expected damage states, similar to the post-earthquake inspection guides; and
7. Damage-dependent recommendations for bridge usage, similar to the post-earthquake inspection guides.

Figure 6 below shows an example of a seismic performance drawing developed for the City by a consultant.

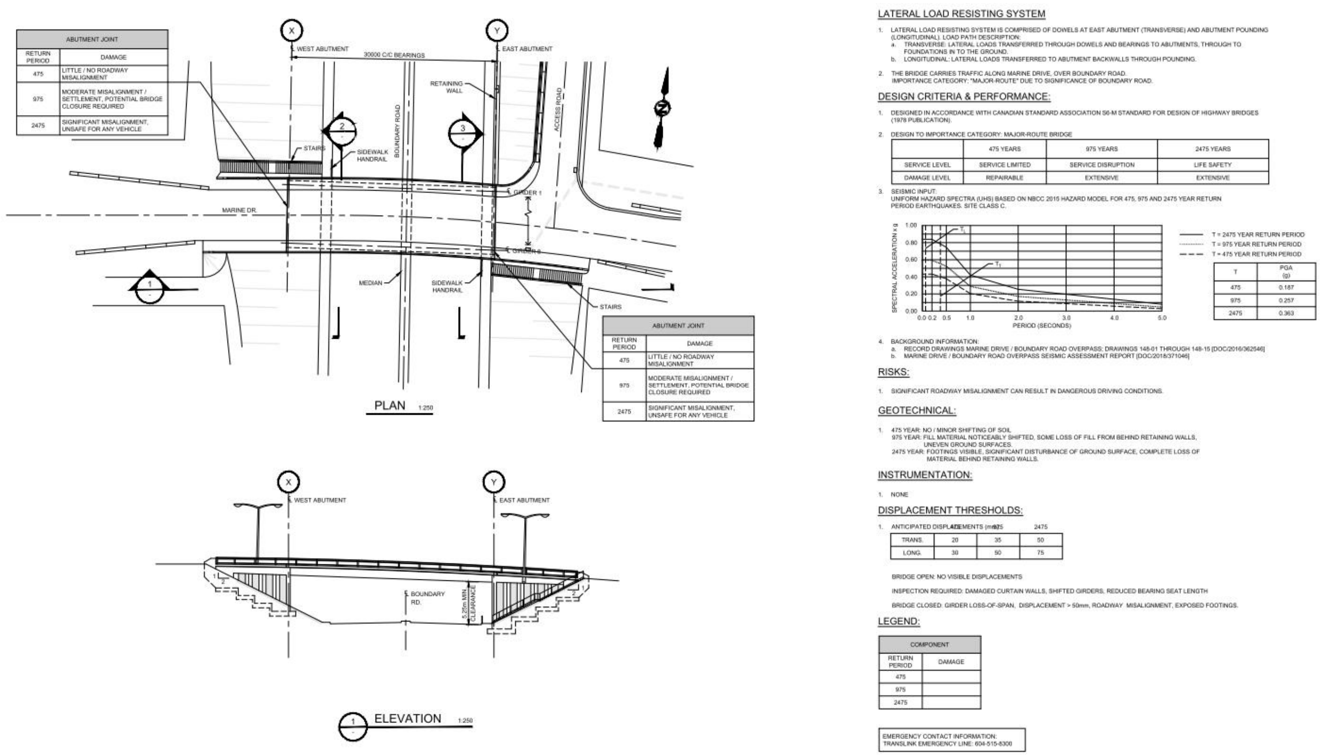


Figure 6. Seismic Performance Drawing

When combined with the initial rapid assessment (and additional inspections, as necessary), this information will help engineers make important determinations about the earthquake characteristics and bridge performance. Perhaps more importantly, it will help engineers quantify the bridges' post-earthquake condition and provide confidence in City-led decision making regarding availability of routes within the transportation network to carry emergency response and/or public traffic in the days and weeks following an earthquake.

In addition the benefit provided in the immediate aftermath of an earthquake, these performance drawings also provide valuable information for future use by engineers, who may be working to conduct seismic assessments or retrofits. The City is currently refining the format of these drawings on existing bridges, but recognizes that significant benefit will be realized when these are generated as part of new design and retrofits, as comprehensive design and performance information is often not well documented on design drawings, making it challenging to gather information in the years and decades following.

Bridge Evaluation Forms

To expedite the initial rapid assessment process, the City has developed inspection forms. These forms provide the inspection teams with a clear, consistent format to document their findings. It is formatted to ask direct questions with simple 'yes' or 'no' answers, a space for comments, and a simplified sketch of the typical bridge components for marking. Figure 7 below shows an example of these evaluation forms.

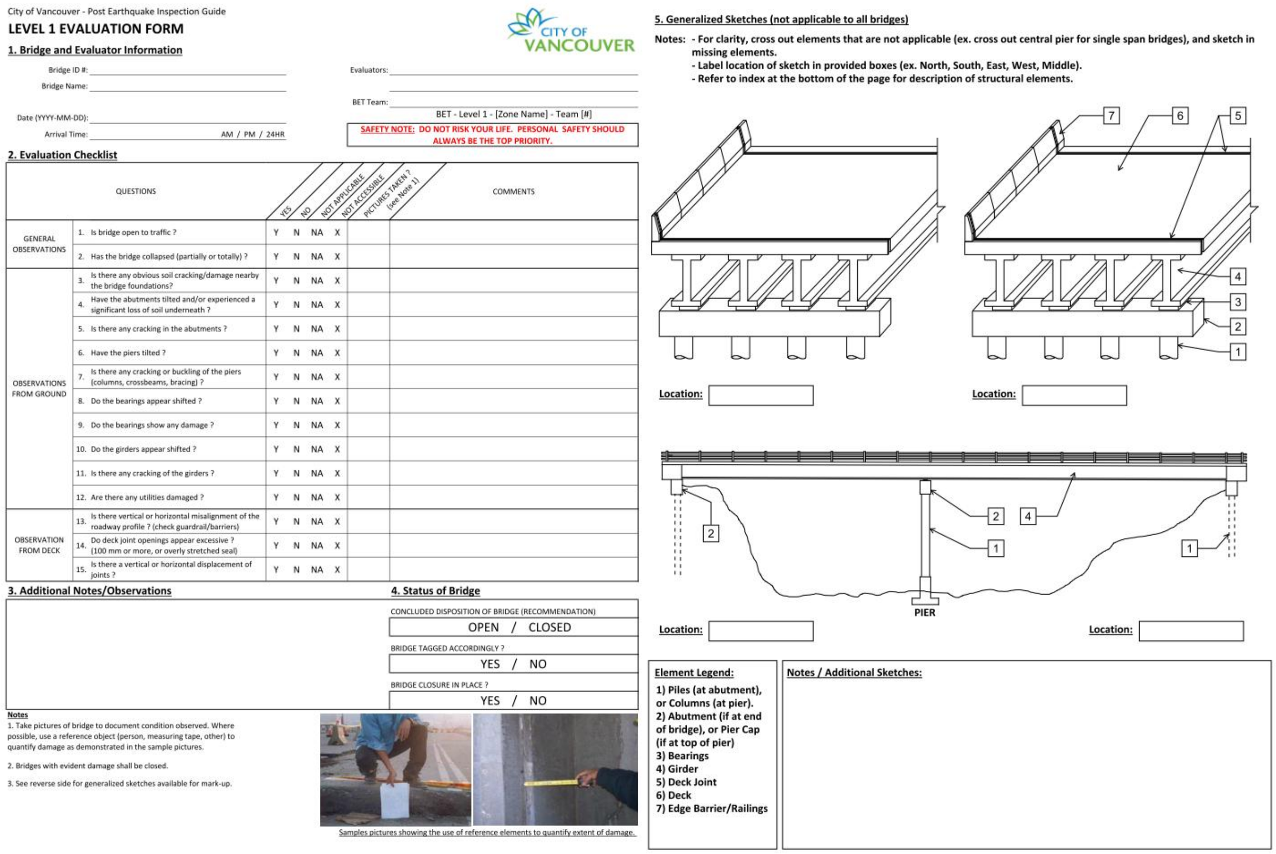
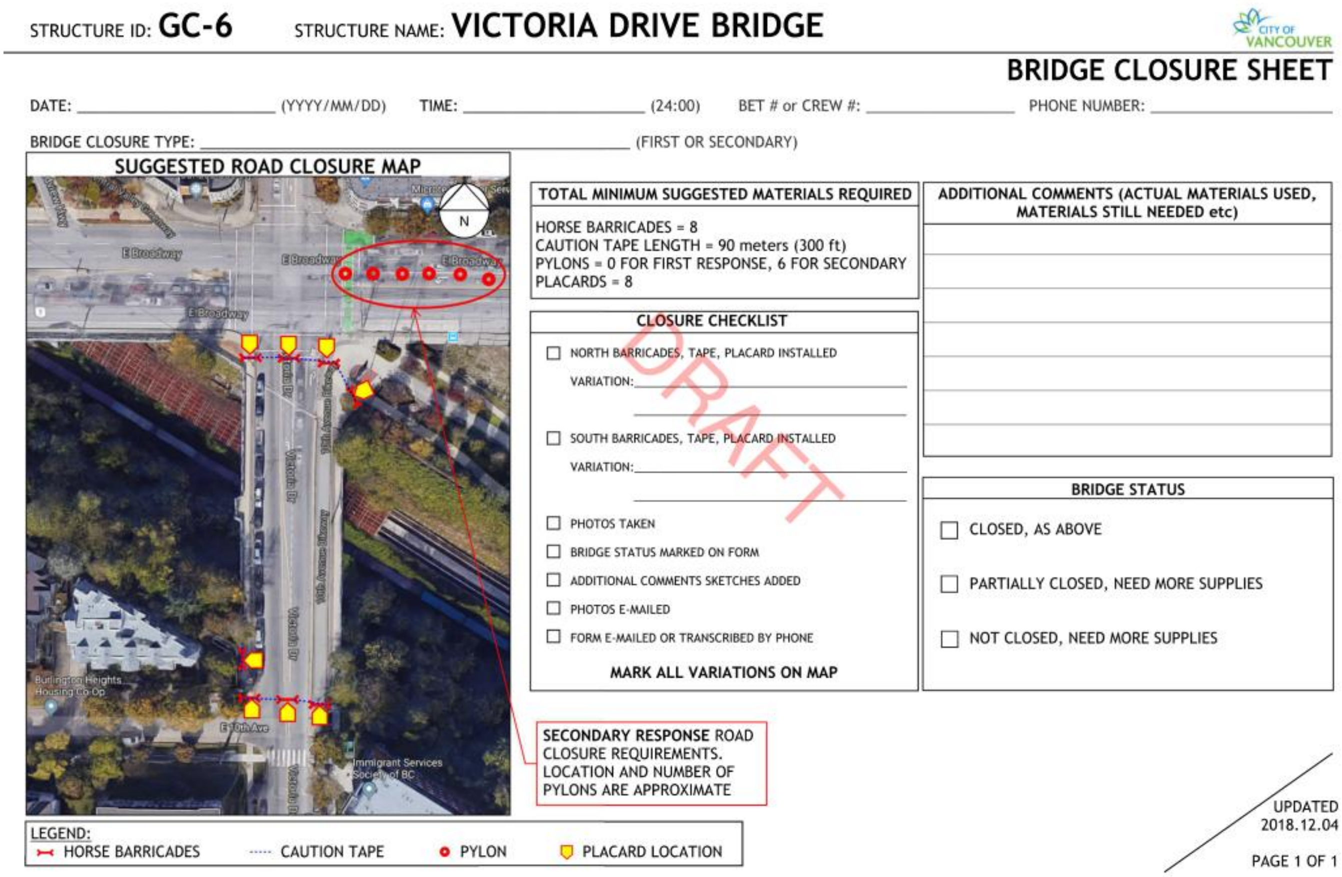


Figure 7. Bridge Evaluation Form

Bridge Closure Sheets

The City has also developed bridge closure sheets, in the event that the initial rapid assessment and/or additional investigations lead the City to close a bridge. These sheets are bridge-specific and are intended for use by City operations and traffic management staff to aid in implementing the closure. These forms include suggested barricade, caution tape and placard placement, plus a checklist for City staff regarding actions taken. Figure 8 below shows an example bridge closure form.


STRUCTURE ID: GC-6 STRUCTURE NAME: VICTORIA DRIVE BRIDGE

CITY OF VANCOUVER

BRIDGE CLOSURE SHEET

DATE: ____________ (YYYY/MM/DD) TIME: ____________ (24:00) BET # or CREW #: ____________ PHONE NUMBER: ____________

BRIDGE CLOSURE TYPE: ____________ (FIRST OR SECONDARY)

SUGGESTED ROAD CLOSURE MAP

TOTAL MINIMUM SUGGESTED MATERIALS REQUIRED

HORSE BARRICADES = 8
CAUTION TAPE LENGTH = 90 meters (300 ft)
PYLONS = 0 FOR FIRST RESPONSE, 6 FOR SECONDARY
PLACARDS = 8

ADDITIONAL COMMENTS (ACTUAL MATERIALS USED, MATERIALS STILL NEEDED etc)

CLOSURE CHECKLIST

- ☐ NORTH BARRICADES, TAPE, PLACARD INSTALLED
  VARIATION: ____________
- ☐ SOUTH BARRICADES, TAPE, PLACARD INSTALLED
  VARIATION: ____________
- ☐ PHOTOS TAKEN
- ☐ BRIDGE STATUS MARKED ON FORM
- ☐ ADDITIONAL COMMENTS SKETCHES ADDED
- ☐ PHOTOS E-MAILED
- ☐ FORM E-MAILED OR TRANSCRIBED BY PHONE

MARK ALL VARIATIONS ON MAP

DRAFT

BRIDGE STATUS

- ☐ CLOSED, AS ABOVE
- ☐ PARTIALLY CLOSED, NEED MORE SUPPLIES
- ☐ NOT CLOSED, NEED MORE SUPPLIES

SECONDARY RESPONSE ROAD CLOSURE REQUIREMENTS. LOCATION AND NUMBER OF PYLONS ARE APPROXIMATE

LEGEND: HORSE BARRICADES ····· CAUTION TAPE ● PYLON PLACARD LOCATION

UPDATED 2018.12.04

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Figure 8. Bridge Closure Form

CONCLUSIONS

The City has developed a comprehensive framework to manage its bridge inventory with regards to earthquake readiness, short- and long-term response. The tools developed and presented in this paper will allow the City to holistically manage its risk at the road network level and make informed plans and decisions about the seismic resiliency of its assets.

ACKNOWLEDGMENTS

We would like to acknowledge the support of the City of Vancouver for providing information contained in this paper, and thank them for their contribution.

REFERENCES

References should be cited in the text in square brackets (e.g., [1], [2-4]), numbered according to the order in which they appear in the text. Only list references that are referred in the text. A complete reference should provide enough information to find the article.

[1] City of Vancouver, "VanMap" 30 January 2019, http://vanmapp.vancouver.ca/pubvanmap_net/default.aspx

[2] Canadian Standard Association - CSA (2014). *CAN/CSA-S6-14: Canadian Highway Bridge Design Code*. Prepared by the CSA, Toronto, ON.