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Seismic Resiliency of the Ministry's Critical and Key Routes – A Highway 99 Pilot Study

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ABSTRACT

British Columbians live in one of the most high-risk seismic zones in Canada. As a global leader in seismic technology and earthquake science, the British Columbia Provincial Government understands well the need to improve the province's earthquake preparedness and resilience. This paper presents results from a pilot study project commissioned by the Ministry, to build on their long history of seismic retrofit and preparedness, using HAZUS software to model the infrastructure along the Highway 99 corridor and investigate the effects of two scenario earthquakes. The model used in the study considers much of the built infrastructure that contributes to the resiliency of the transportation route after an earthquake, and uses simple relationships to estimate damage, repair costs and restoration effort. Information is combined from multiple sources to assemble an infrastructure database along the corridor, data is catalogued and prepared for use in the current pilot study, and any future expanded studies. The results highlight the effect of the Ministry's previous seismic retrofit program works completed, and the principal remaining vulnerabilities along the corridor. In places, liquefaction triggering is expected in relatively moderate earthquake scenarios and many assets, including roadway embankments, geotechnical systems, utilities and bridges are vulnerable to ground displacement. The main affected zones are in the Richmond, Delta, and Surrey corridor segments due to the resulting large ground displacements. 78% of the assessed inventory losses are from highway bridges, the George Massey Tunnel and culverts. Damage to utilities is also due mostly to ground displacements, which leads to rotation and deflection of pipes and their connections. Though utilities only represent 3% of the total estimated repair costs, they play a vital role in network functionality. This pilot study highlighted some corridor vulnerabilities and suggested planning recommendations, regarding hazard preparedness, mitigation, response and recovery.

Keywords: Network Resiliency, Planning Study, Seismic Retrofit, Hazard.

INTRODUCTION

Lessons from large earthquakes around the world in past decades, highlighted recently in Turkey and Syria, show how important a functioning transportation network, and response planning can be to short- and long-term response and recovery following a damaging earthquake. This report summarises a pilot study [1], which assembled much of the transportation infrastructure data along the Highway 99 corridor from the US/Canada border to Horseshoe Bay, and investigated the high-level damage and functionality consequences of two scenario earthquakes. The data set was obtained from multiple sources and comprised bridges, culverts, tunnels, signs, geotechnical systems (walls, embankments, cut slopes), electrical systems and utilities.

The assembled data was incorporated into HAZUS [2], a geographic information system-based natural hazard analysis tool developed and freely available from FEMA, which catalogues the data and draws on relatively coarse general relationships available within the scientific literature, to estimate damage, functionality, and repair costs. HAZUS is a convenient planning-level tool, suitable for assembling large datasets and drawing conclusions based on general data. Its strengths emanate from the convenient collation of relationships developed by many scientists, engineers and owners, allowing users to easily apply these relationships to their own infrastructure dataset, and if used fully for its intended purposes, it can build up a very useful picture of the performance and resource needs in response to scenario hazard events.

An examination of the inventory data shows that there has been some improved performance resulting from the work to date on the Ministry seismic retrofit program, but that ground movements are causing substantial performance problems and require mitigation. The study concluded that the methodology is appropriate for the intended purpose, and should be expanded to consider broader economic and societal consequences of the damage in a future continuation of the work. It also found that recommendations relating to the design of seismic upgrades should be driven in large part by repairability and time to restore functionality.

HIGHWAY 99 CORRIDOR

The Ministry selected Highway 99 as the pilot corridor to be investigated from their Critical and Key routes, to identify the vulnerabilities and expected seismic performance, damage, and return to service potential. The project corridor is highlighted red in Figure 1, and includes the 41 km stretch from the US border to Oak Street Bridge north abutment and the 19 km stretch from Lions Gate Causeway to Horseshoe Bay Ferry Terminal (including Highway 1 from Highway 99 Exit 3 to start of ferry terminal). Note that the City of Vancouver portion is omitted from the study. The Highway 99 corridor relies on a complex system of interconnected infrastructure comprised of 85 highway and railway bridges, geotechnical systems, 116 culverts and a major tunnel, hundreds of sign structures and electrical distribution circuits, kilometres of potable water and sanitary water pipelines and other utilities. It is a suitable candidate for a pilot study given that many of the typical range of conditions and hazards encountered throughout the region are encountered along its length.

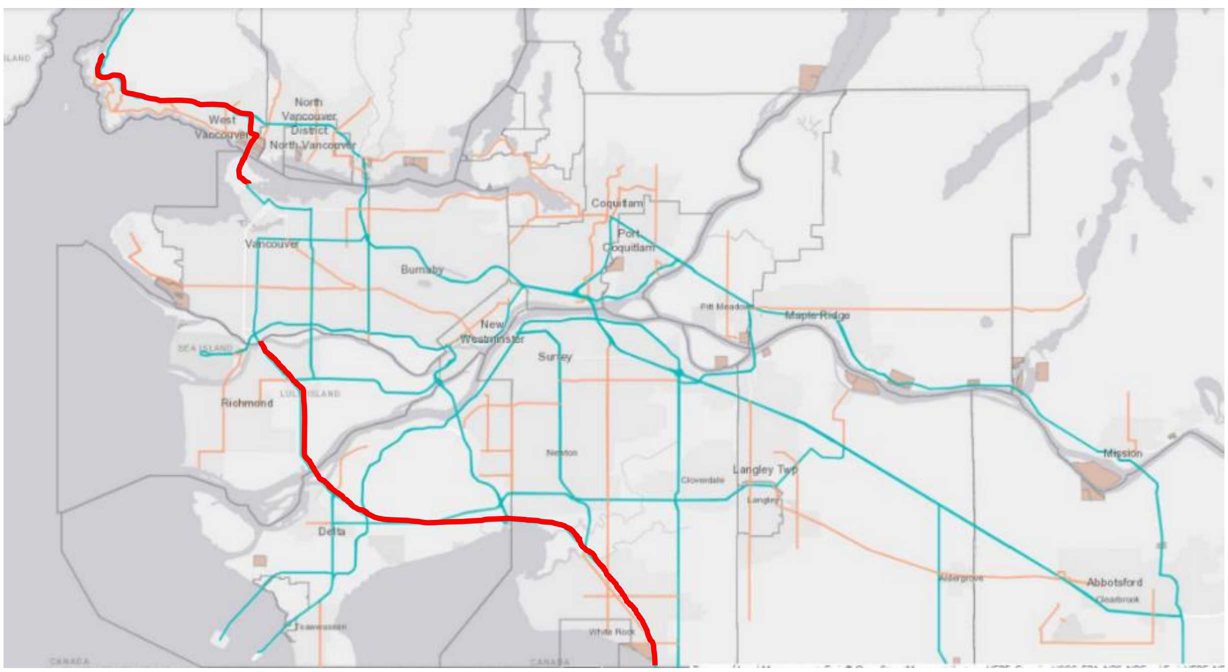

Figure 1. Critical route map in the Vancouver area (after: BC MoTI, 2023 [3]).

Emergency Management BC (EMBC) have recently published the Provincial Earthquake Immediate Response Strategy (PEIRS) [4], which is a component of the Comprehensive Emergency Management Plan (CEMP). The PEIRS outlines 'the foundation for addressing a shared hazard and responsibility through coordinated and integrated efforts, and sets the conditions for sustained response and recovery'. PEIRS details how the Province will lead and coordinate during the immediate response to two scenarios events. This work extended transportation routes to critical infrastructure and established Critical and Key routes, Figure 1 shows the Critical route map, to guide further upgrading works to allow the networks to function for response and recovery from a large, shallow M7.3 earthquake scenario in Vancouver.

Geotechnical Conditions

The Highway 99 corridor crosses a wide variety of geotechnical conditions including bedrock in the mountains, ice age sediments in the Uplands, and modern sediments in the Lowlands. The coast mountains in West Vancouver consist mainly of granitic rock, with sections of volcanic rock and sandstone near the Lions Gate north viaduct. Major geotechnical seismic hazards in this region include rockfalls and landslides on steep slopes due to the presence of faults, fractures, and sedimentary layers. Thin sediments covering bedrock can slide into stream channels during rainstorms triggering high-velocity debris flows. Because the West Vancouver segment of the corridor includes large, steep embankment fills that support the highway and bridge abutments the consequences of an earthquake can be substantial due to these hazards.

Uplands cover the higher parts of the Fraser Valley, about 15 m to 250 m above sea level. This includes Vancouver, north Surrey and White Rock areas. Sand and gravel from ice age glacier deposits extensively occupy this zone. Most cities and towns in this region were built on the uplands to avoid the flood and drainage problems of the lowlands. Upland sediments are good foundation materials and are generally not susceptible to liquefaction.

The flat Lowlands occur where Capilano River meets Burrard inlet, and along the Fraser River and its tributaries, encompassing Richmond, Delta and South Surrey along the Serpentine and Nicomekl Rivers. The Serpentine and Nicomekl Rivers deposits include peat, silt, clay and sand, with depths exceeding 300 m along the corridor for the Fraser River and 50 m to a 100 m for the Nicomekl and Serpentine Rivers.

These Lowlands areas along the Fraser river are often susceptible to cut-and-fill slope instability as well as liquefaction with associated ground displacements. Bridge foundations, highways, buildings and buried utilities can be highly damaged by such movements. The low-lying areas adjacent to Serpentine and Nicomekl Rivers and the seashore are also vulnerable to flooding due to their poor drainage characteristics. Dykes in these zones are at risk from large river floods, high tides and storm surge, in addition to the inherent risks due to the inertial loading from and earthquake itself.

Infrastructure Data

There are a significant number of structures and infrastructure components along the highway corridor. These include bridges, tunnels, culverts, walls, embankments, cut slopes, sign structures, utilities and electrical systems. Only those infrastructure components whose performance directly affect the functionality of the highway were included within the dataset to be analysed on this pilot study, and the specific criteria for each inventory item were determined rationally in turn. Applying the developed criteria, resulted in a significant number of structures along the corridor that require cataloging and specific attention and consideration for incorporation within the hazard analysis software – they are listed in Table 1 for reference. Highway and Geotechnical Systems combine walls, embankments and cut slopes, as these components are analysed together using the same procedure (described below).

Table 1. Infrastructure components incorporated in analyses.

Category	Infrastructure Component	Segment Length / Number of Components
Highway and Geotechnical Systems*	North Shore Segment	21 km
	Oak Street Bridge to George Massey Tunnel Segment	8 km
	George Massey Tunnel to UB Border Segment	33 km
Highway Structures	Highway Bridges	83
	Major Tunnels	1
	Culverts and small tunnels	116
	Rail Bridges	2
Utilities	Potable Water	204
	Sanitary Water	94
	Sign Structures	139
	Electrical Systems**	122

* Highway and Geotechnical Systems are analysed at 10 m intervals along the highway.
** Electrical systems classified as a utility within software.

The databases referenced, data processing and analysis information for these components are omitted from this paper, but are discussed at length in our full report [1].

BC Bridge Seismic Retrofits

The Ministry has designed bridges to meet improved earthquake design standards since 1983. The basis of those designs were laid out in the guide document ATC-6, *Seismic Design Guidelines for Highway Bridges* [5]. Authorship of that document included engineers from New Zealand and drew on seismic design methods developed there in the 1970's. Bridges in the

Ministry's inventory designed prior to ATC-6 provisions are well known to be far more vulnerable to collapse or major damage from even modest earthquakes. This vulnerability has been demonstrated clearly in numerous moderate and large earthquakes in similar seismic and infrastructure environments to BC, and in laboratory testing of details used in older bridges.

In 1989, the Ministry initiated a bridge seismic retrofit program to improve the earthquake resistance of older bridges. The objectives of the program were to:

- Reduce the risk of bridge collapse to a 475-year return period hazard level.
- Preserve important highway routes for disaster response and economic recovery.
- Reduce damage and minimise loss of life and injury during earthquakes.

The design criteria adopted an earthquake hazard having a return period of 475-years (10% in 50-year probability of exceedance). The minimum seismic performance targeted a life-safety (collapse prevention) damage level, and introduced a *superstructure* retrofit category. This was to be part of a Safety level, or collapse prevention retrofit as a minimum. The Ministry's requirements also specified that future higher, or Functional, retrofit and performance levels were to be considered and not precluded by the retrofit strategies adopted.

At that time, roughly 500 bridges on numbered routes in British Columbia's higher seismic areas were screened as potentially seismically vulnerable and as candidates for the seismic retrofit program. Prioritisation was done based on both the route and bridge importance. A system of highway and regional roads were designated as Disaster Response Routes (DRRs) and Economic Sustainability Routes (ESRs) in the Lower Mainland and Vancouver Island. These reflected both their importance for emergency response and for economic recovery purposes. With significant progress made with this first seismic retrofit program, the current pilot study is a natural next step, extending the resiliency concept past the major bridge structures, to the highway corridor in general.

Nine major crossings in the Lower Mainland were classified as Lifeline Structures due to their size and strategic importance. Each of which received at least a Safety level of initial retrofit. Three of these major crossings are within the Highway 99 corridor, and their seismic retrofit and expected performance levels are summarised in detail in individual studies [6,7].

Dikes

A series of dikes surround Delta and Richmond to protect against coastal flooding and riverine flooding from the Fraser River. As well, lowland areas of Surrey, in proximity to Mud Bay, are protected by a series of "official" and "unofficial" sea and river dikes. The river dikes extend along both banks of the Serpentine and Nicomekl Rivers. During a significant seismic event, there is the potential that the existing dike systems throughout the region could be damaged or deformed. These Dikes have not been included within the analyses of this pilot study, but to illustrate the potential flooding exposure for the Highway 99 corridor in the absence of dikes, we compared the existing road elevations to the range of tidal elevations in the region (a simple cursory review of roadway and tidal elevations, no analysis).

There is potential for an extreme coastal and/or riverine flood event to occur following a seismic event; however, the combined probabilities for these occurrences has not been considered in this pilot study. Rather we comment on the potential flood threat to the highway that may be present during "typical" conditions if there was a major dike breach.

To assess the range of tidal elevations, we reviewed data from three Environment Canada gauges in the region. Given the proximity of the various gauges to the Highway 99 corridor, and considering the strong similarity between the Roberts Bank gauge and the White Rock gauge, we adopted the Tidal Station 07592 Roberts Bank tidal values as representative for the area and used them to apply a single set of water level values for this simplified assessment. We looked at a range of tidal values in our study and presented the highest of those here - Higher High Water Large Tide (HHWLT): the average of the annual maximum high water values over 19 years of prediction, which is 1.844 m for Roberts Bank (CGVD2013).

To assess the existing elevations along the Highway 99 corridor, we acquired 1m × 1m LiDAR (Light Detection and Ranging) data from Lidar BC – Open Data LiDAR Portal. We sampled the existing ground elevations at 100 m intervals along the highway, assigning the highest elevation from each 100 m long segment to the representative point. The result of this process is shown in Figure 2.

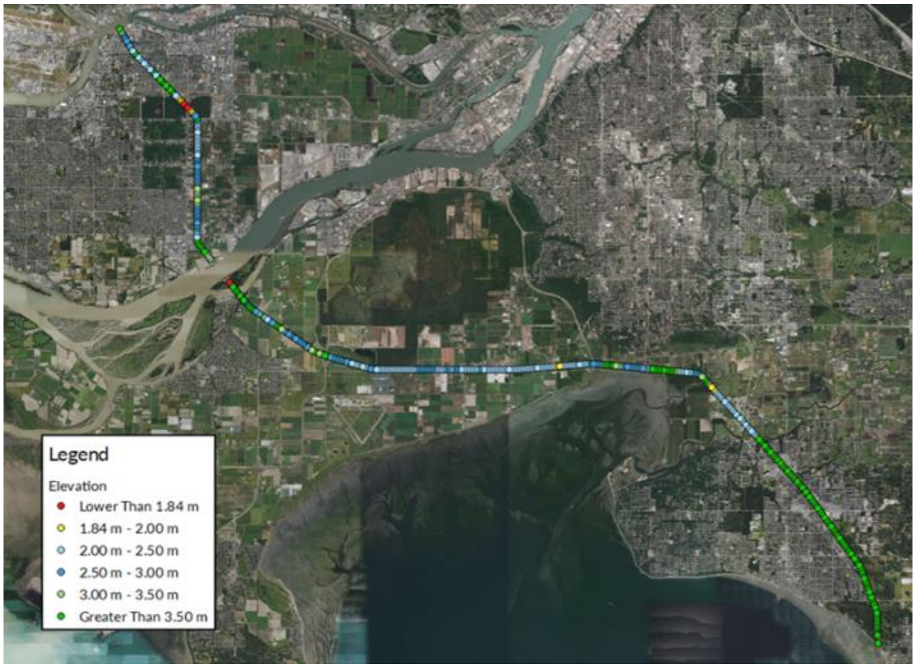

Figure 2. Existing Road Elevations along Highway 99 Corridor length.

As seen in Figure 2, there are only a few locations where Highway 99 is lower than the HHWLT elevation of 1.844 m. One of these points is at the south entrance of the Massey Tunnel; the others are located in proximity to the Highway 99 - Highway 91 interchange in Richmond. There are a few general locations where the existing road elevation is between 1.844 m and 2.0 m. One of these locations is near the Serpentine River crossing in Surrey that is protected by an “unofficial” dike. A significant portion of the remaining corridor varies between elevation 2.0 m and 3.0 m, and the rest is above elevation 3.0 m.

ANALYSIS

Scenario Events

Two earthquake scenario events were used for this pilot study, selected on the basis that a statistical analysis of historic events in the region suggests they are relatively likely events to occur. An M6.8 Subcrustal earthquake scenario was selected, based on recent work by NRCan [8], which showed that a moderately strong earthquake within the subducting Juan de Fuca Plate, just off the Lower Mainland could result in a level and extent of damage, human displacement, and impacts to critical infrastructure, suitable for emergency response planning and evaluation of the resilience purposes. The second event selected for this pilot study was is an M9.0 Cascadia Subduction earthquake scenario. The scenario events are deterministic events, simulating realistic future potential earthquakes. In approximate terms, they are roughly comparable to the 2019 CHBDC 10% probability of exceedance hazard levels.

Software and Procedure

HAZUS, the hazard analysis software developed by FEMA, runs on the ESRI ArcGIS platform and performs analysis on aggregated data, individual assets and linear features. HAZUS has analysis algorithms for infrastructure features such as Transportation (bridges, tunnels, roads, railway tracks and stations), Essential Facilities (hospitals, schools, fire and police stations), and Utilities (water and sanitary water pipelines and facilities, oil or natural gas pipelines and facilities, electric power facilities, and communication facilities). HAZUS has been extended for application in Canada for this project as described below. The HAZUS functionality is shown graphically in Figure 3.

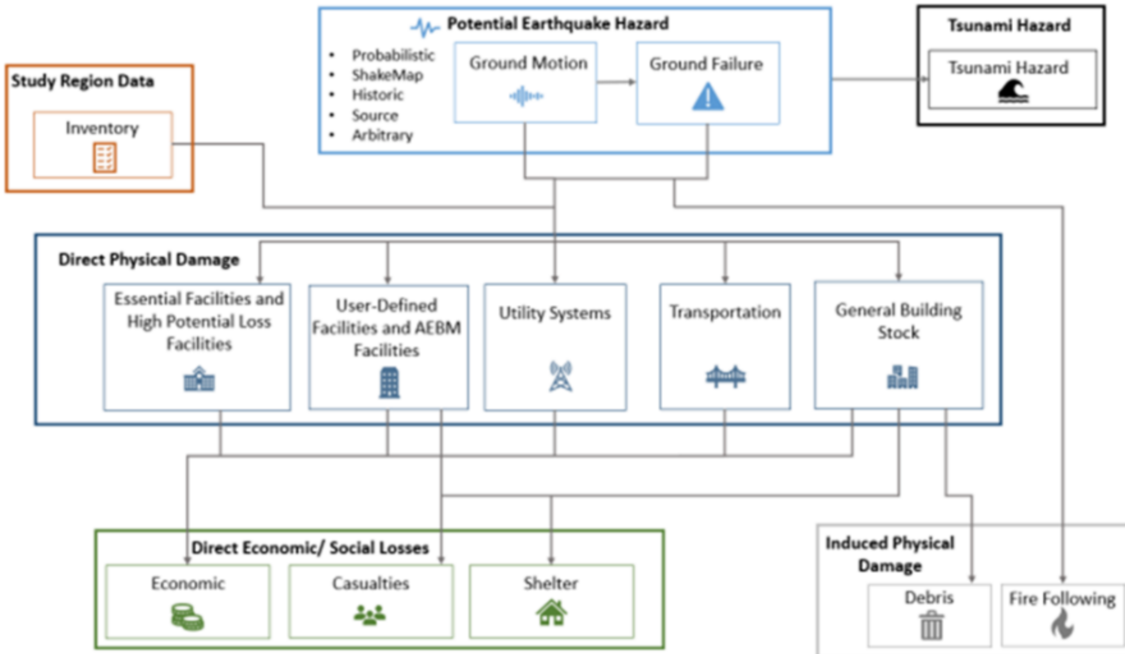

Figure 3. HAZUS Earthquake Model Methodology (after: FEMA, 2020 [9]).

To simulate the effects of the anticipated earthquake a "scenario" is defined in HAZUS. The following hazard maps have been generated outside of HAZUS, and input to define the scenarios and study the effects of these earthquakes on the corridor infrastructure.

HAZUS uses curves, typically determined from large datasets, to relate earthquake shaking to damage, repairs costs and functionality. Damage functions (fragility curves) are lognormal distributed functions that give the probability of reaching or exceeding specific damage states given a specific earthquake event. Restoration curves are generally similar to fragility curves, those for highway roadways for example, were developed after a curve fitting process to Applied Technology Council data, presented in their *Earthquake Damage Evaluation Data for California report* (ATC-13, [10]). The damage and cost data are applied differently for each infrastructure component type (e.g. by area, broken or leaking pipe, etc.). Fragility and Restoration data for all classification types can be found in the HAZUS Earthquake Model Technical Manual [9].

Damage of infrastructure is analysed due to both earthquake scenarios. Impact from ground shaking and related ground failure, including liquefaction and landslides, are expressed in the five categories known as *None*, *Slight*, *Moderate*, *Extensive*, and *Complete*. Functionality of infrastructure will be based on HAZUS manual recommendations - a functional structure/utility is one that can continue functioning and serving its intended purpose after an earthquake event, while a non-functional infrastructure is the one that can no longer be used.

We will describe the procedure briefly for Geotechnical Systems and Bridges below. Other data included within the analysis included tunnels, culverts, potable water pipes, sanitary pipes, stormwater pipes, electrical systems and sign structures. The databases referenced, data processing and analysis information for these components are omitted from this paper, but are discussed at length in our full report [1].

Geotechnical Systems Data

Geotechnical Systems covers a wide variety of elements and has a broad definition. The highway is subdivided within the analysis framework, into highway segments - a continuous series of geotechnical systems, including cut slopes, fill slopes and walls (including pavement structure). To create this inventory, the Ministry LiDAR survey was used to extract detailed slope geometry along the corridor. Calculation points were placed at 10 m intervals along the entire corridor, and query lines were extended 30 m from the pavement edge at each point. For each query line, elevations were recorded at 0.5 m intervals. With this information, the maximum slope at every point was recorded along with the elevation of the roadway. An example of the processed LiDAR data is shown in Figure 4, for reference. All this data together with the surficial geology map of the zone and the relative PGA for both earthquake scenarios were used in the evaluation of landslide and liquefaction risk.

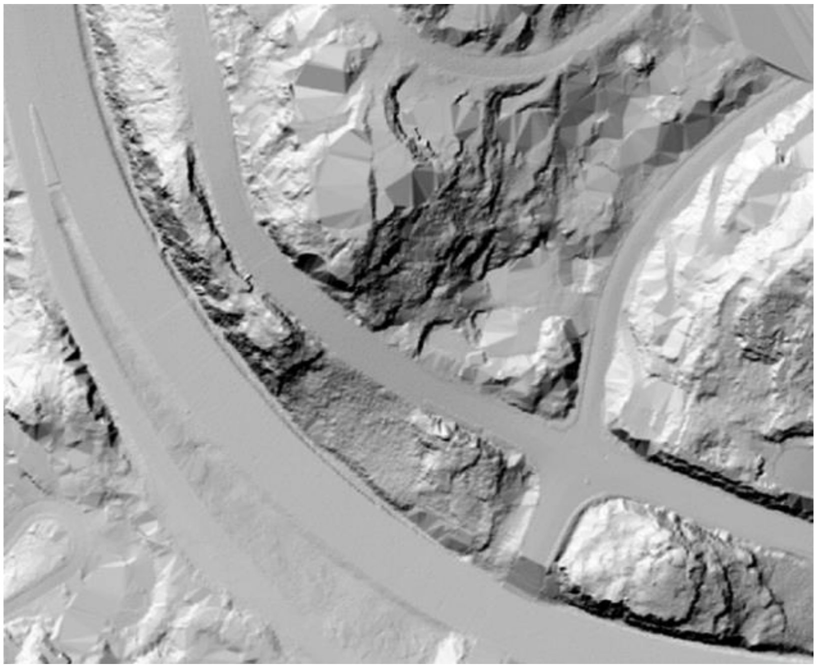

Figure 4. Hillshade Rendering of LiDAR Survey – Rock Cut West of Caulfield Drive.

Recognising that the Highway 99 corridor contains a wide variety of geotechnical conditions, with associated risks of liquefaction, landslide, slope failure and rock fall, we have refined the analysis beyond the default method available within HAZUS, developing a more thorough analysis taking into consideration available site-specific, and more accurate data.

PGDs from landslides occurring in cut slopes, fill slopes and retaining walls are possible along the entire corridor whereas PGDs from liquefaction can only occur where liquefiable soils are present. Accordingly, for the purposes of this study, the project was split into two major categories: non-flood plain and floodplain. Only PGDs from landslides were considered as possible in non-floodplain areas. PGDs from landslides and liquefaction were considered as possible in floodplain areas but the PGDs from liquefaction are expected to be much higher than the PGDs from landslides.

Similar to the method shown in the HAZUS manual, the calculation of the PGDs for landslides is based on Newmark analysis. The PGDs are calculated for the maximum slope extracted from the LiDAR data query lines. This PGD data can then be used in evaluation of damage to various infrastructure elements along the corridor (bridges, walls, culverts, pipelines, geotechnical systems, slopes, etc.).

Liquefaction triggering analyses were completed using available Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data along the floodplain portions of the corridor, and lateral spreading displacements were estimated using the Zhang et al. (2004) method [11], with some minor refinements.

Defined relationships, or functions, are used to determine the likelihood of damage for infrastructure components subject to scenario earthquake events and the subsequent restoration times. For highways, which are dominated by geotechnical systems (predominantly cuts and fills), the damage is directly related to PGD. Each curve has its corresponding median value and dispersion factor based on the damage state. There are five damage states for highway roadways, divided by three damage functions: slight/minor, moderate, and extensive/complete. Damage states are related to the ratio of repair to replacement cost for evaluation of direct repair cost.

Bridges

There are a significant number of structures along the corridor that require cataloging and specific attention and consideration for incorporation within the hazard analysis software. Bridges are among the most impactful structures along the corridor when it comes to earthquake performance and potential consequences or disruption. There exists a wealth of bridge performance data that can be used to relate seismic response to damage, restoration and cost information. Striving for efficiency and to reduce the study costs where possible, we have taken advantage of the data compiled by previous Engineers and Research Scientists. Basöz and Mander (1999) [12] describe the process of developing the inventory of damage and restoration functions available in HAZUS – a process that used measured data to generate 112 damage functions for ground shaking and 112 for ground failure, and resulted in a total of 28 classes (HWB1 through HWB28). Definitions and examples for the classes used in this study are described below. A summary of all the classes can be found in the *HAZUS Earthquake Model Technical Manual* [9].

After reviewing all available information, we sorted the Highway 99 bridge catalog into the available HAZUS classes, in order to utilise the available reference data. There are 25 bridge structures along the corridor that have been previously retrofitted, we have re-classified these retrofit structures within an available HAZUS classification based on their expected retrofit performance. Direct damage output for highway bridges includes physical damage correlated to direct repair costs, and bridge functionality. For bridges, a total of five damage states are defined in HAZUS: *None*, *Slight*, *Moderate*, *Extensive*, *Complete*.

The nomenclature in HAZUS is often different than that employed in the Canadian Highway Bridge Design Code (CHBDC) [13], and the Damage States are no exception. Although they are not directly comparable, they can be approximately related to the more-familiar CHBDC terminology. The HAZUS *Slight* Damage State is approximately comparable with the CHBDC *Minimal Damage* Performance Criteria (associated with Immediate Service Performance Level). Similarly, the HAZUS *Moderate* Damage State is approximately comparable with the CHBDC *Extensive Damage* Performance Criteria (associated with *Service Disruption* Performance Level), and the HAZUS *Extensive* Damage State is approximately comparable with the CHBDC *Probable Replacement* Performance Criteria (associated with *Life Safety* Performance Level). The *none* and *complete* Damage States are self-explanatory.

HAZUS evaluates independently both the ground shaking and ground failure related damage probabilities, and then combine them for a final damage state of the bridge. With the resulting damage state from the damage functions, the physical damage of the bridge expressed in terms of the damage ratio is calculated. The inputs to HAZUS, required to calculate damage loss for a particular bridge includes the bridge classification (HWB1 through HWB28), location, number of spans, Peak Ground Acceleration (PGA), PGD, and Spectral Accelerations (Sa) at 0.3 seconds and 1.0 seconds.

Replacement costs for highway and railway bridges were taken as generic high-level estimations, and were assumed to be the following:

- Single span bridges: \$10,000/m^2
- Multi-span bridges: \$10,000/m^2
- Special span bridges: \$30,000/m^2
- Railroad bridges: \$20,000/m^2

These costs are based on general experience in Lower Mainland bridge construction and represent crude order-of-magnitude replacement costs. They are not total project costs and do not include construction- and project-specific considerations that are required for detailed cost planning purposes, but rather represent broad comparative costs useful for qualitative planning purposes, and should not be thought of as appropriate for quantitative analysis. Similarly, the direct repair costs do not consider broader societal costs, economic impacts or costs related to interdependencies within the region.

Results and Uncertainty - Median Damage

The analysis procedure utilized in HAZUS does not produce typical results, in the form of say, a certain quantity of a damage metric, but rather probabilities of a certain damage state. That is, HAZUS performs a type of Probabilistic Seismic Hazard Assessment (PSHA). Uncertainty is an essential consideration in any PSHA, and there are two main sources of uncertainty inherent in a seismic hazard model: aleatory uncertaint (due to randomness in natural processes, such as earthquakes), and epistemic uncertainty (uncertainty in knowledge). Aleatory uncertainty cannot be reduced by collecting additional information, but the epistemic uncertainty can be reduced with increased data.

Given that the analysis is probabilistic rather than deterministic, there is a level of uncertainty with the results due to assumptions with the inputs and damage functions. Therefore, we have adopted the median damage for the assessment and presentation of results of the inventories.

Permanent Ground Deformations

The analysis methodology described above yielded PGDs for geotechnical systems listed in Table 2 for both the subcrustal and subduction scenario events. Figure 5 shows the damage states listed in Table 2 graphically, for the corridor between Oak Street Bridge to Highway 10.

Table 2. Summary of Damage States for PGDs.

		Northbound		**Southbound**	
Damage State	PGD (mm)	Subcrustal	Subduction	Subcrustal	Subduction
ds1	< 50	59%	58%	44%	43%

ds2	50-150	12%	12%	15%	14%
ds3	150-300	8%	8%	12%	12%
ds4/5	>300	22%	22%	29%	30%

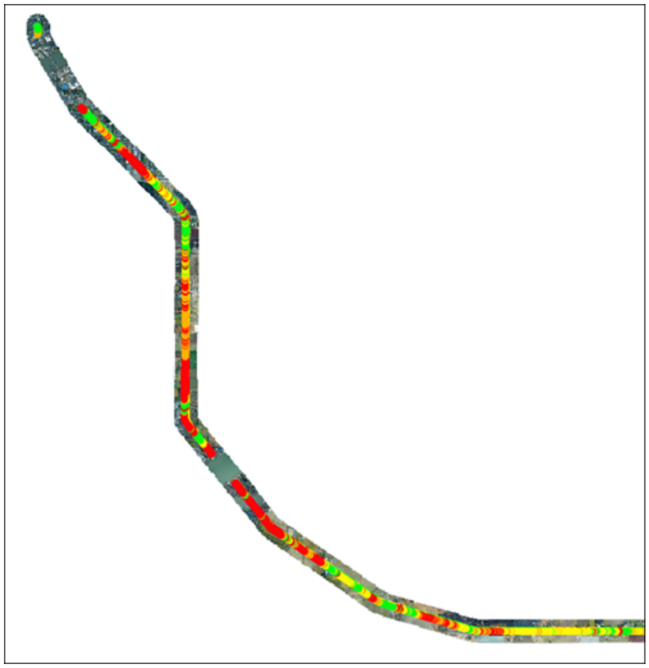

Figure 5. Damage State – Oak Street Bridge to Highway 10 (Subcrustal Scenario).

Results

A summary of the damage state of every highway bridge after the Subduction earthquake is shown in Figure 6, and a comparison table of the damage experience under each earthquake scenario is shown in Table 3. As can be seen, results were very similar for both, and hence only the subduction scenario event results will be discussed for the rest of the categories.

Figure 6. Median Damage to Bridges for the Subduction Scenario.

Table 3. Summary of Damage States for PGDs.

		Damage				
Earthquake Scenario	Total # of Bridges	*None*	*Slight*	*Moderate*	*Extensive*	*Complete*
Subduction	83	38	2	1	12	30
Subcrustal	83	37	2	1	12	31

Figure 7 summarises the damage percentages for culverts, bridges and tunnels.

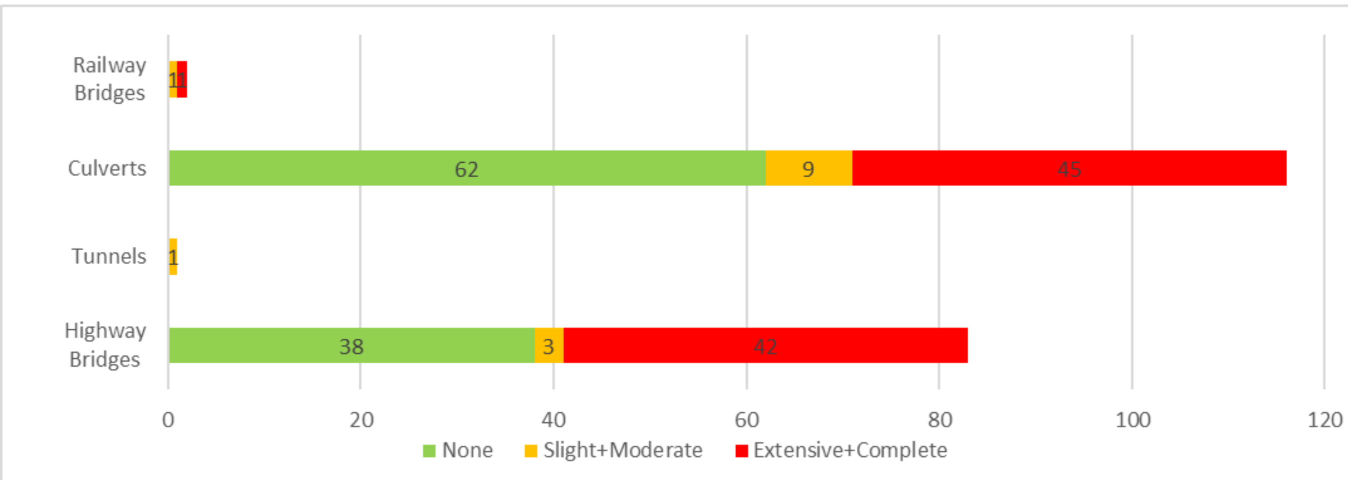

Figure 7. Extent of Damage to Culverts, Tunnels, Railway and Highway Bridges.

For highway bridges, more than half of the inventory falls into either the *Extensive* damage (12 bridges) or *Complete* damage (30 bridges) categories. Having reviewed the data provided by HAZUS, it is clear that the variable responsible for these results is the high PGD as a result of ground liquefaction and ground movements, rather than the highway bridge classification system or the age of the structure. HAZUS damage categories for ground failure depend on the number value (in inches) of displacement. For a structure with displacement greater than 3.9" (~4") but less than 13.8" (~14") HAZUS assigns the *Extensive* damage category. Bridges with displacement of more than 14" are classified in the *Complete* damage category. Considering that the number of highway bridges with PGD over 4" are approximately half of the inventory (45 bridges out of 83), the results appear reasonable. As many as 23 bridges are expected to have more than 50 inches of ground displacement. Figure 6 shows that most *Complete* damage structures are located in the Cities of Delta, Richmond and Surrey, where there are highly liquefiable zones.

Repair costs from HAZUS analysis are estimated based on the proportion of the infrastructure that is damaged after the earthquake event and the estimated structure replacement cost. They represent the financial resources required to repair or replace the damaged infrastructure, with the idea that replacements are like-for-like structures. That is, repair costs are not estimated for all repair scenarios for all structure types, but rather, the replacement costs of all structures is estimated, and repairs costs are a percentage of this amount depending on severity. The replacement costs are based on industry guidelines and research. These repair costs currently consider 'construction only' costs (not project costs) associated directly with repairing infrastructure damage, and do not include the economic losses from loss of function or services over time. A more complete assessment of direct and indirect economic losses can be done once the regional mapping and assets are included, and economic cost relationships and interdependencies are also modelled within HAZUS. This would provide a far more holistic consideration of the economic impacts of damaging earthquakes, although substantial uncertainty would remain given the complexity and uncertainty of the hazard, soils, element models and system interdendency modelling.

Direct repair costs for the inventory items considered in this study for the entire Highway 99 corridor after the Subduction scenario are estimated to be in the order of $418 million in 2022 dollars. Table 4 describes the inventory repair costs, and percentage loss for every group analysed with respect to the total inventory cost.

Table 4. Inventory Repair Cost

Inventory	Segment Length / # of Assets	Inventory Cost	% Loss	Repair Cost	% of Total Repair Cost
Highway and Geotechnical Systems					
North Shore Segment	21 km	N/A	N/A	$13M	3.1%
Oak Street Bridge to George Massey Tunnel Segment	8 km	N/A	N/A	$16M	3.8%
George Massey Tunnel to UB Border Segment	33 km	N/A	N/A	$52M	12.4%
Highway Structures					
Highway Bridges	83	$2,612M	9%	$237M	56.7%
Major Tunnels	1	$2,000M	3%	$50M	12.0%
Culverts and small tunnels	116	$67M	54%	$36M	8.6%
Rail Bridges	2	$18M	11%	$2M	0.5%
Utilities					
Potable Water	204	N/A	N/A	$6M	1.4%
Sanitary Water	94	N/A	N/A	$4M	1.0%
Sign Structures	139	$5M	20%	$1M	0.2%
Electrical Power Systems	122	$5M	20%	$1M	0.2%
		Total		**$418M**	

As seen in Table 4, the highway and geotechnical systems represent 19%, the highway structures represent 78% of the total repair cost, and utilities only 3%. Highway bridges represent 57% of the total repair cost with ~$237 million, followed by highway and geotechnical systems, tunnels and culverts with $81, $50 and $36 million, respectively. It is important to note that the percentage loss of culverts (54%) is higher than bridges (9%) even when the complete damage of structures is similar in bridges and culverts as seen in Figure 7. This can be explained by analysing the damage ratios used by HAZUS. For bridges, the complete damage ratio is 1.0 for single span or two-span bridges. Bridges with more than two spans get modified by a factor equal to [2/(number of spans)], taking into consideration that it is unlikely that there is complete collapse of every single span of a multi-span bridge under the complete damage category. In the case of culverts, the damage ratio for complete damage is 1.0, assuming that culverts that collapse will fail as a unit. Since 63 out of 83 bridges have more than two-spans, the difference in percentages of replacement cost makes sense.

Retrofit Options

Risk-based planning helps minimise potential future losses, and discussion of retrofits naturally follow on from the results describing damage. It is straightforward to simulate the effects of retrofits within HAZUS, by augmenting the fragility curves and other damage relationships, and this would be an additional refinement in studies involving hazard software such as HAZUS. However, as seen from in the results presented, the characteristics of the scenario events with this pilot were such that, damage was largely associated with ground deformations, and there was much less damage associated with the inertial loading itself. As a result, ground improvement options to mitigate the damage associated with ground deformations are a suitable inclusion in a future continuation of this work.

CONCLUSIONS

This paper summarises the pilot study of the seismic resilience of the infrastructure on the Ministry's Critical and Key routes, using the Ministry's infrastructure on the Highway 99 route from the US/Canada border to Horseshoe Bay. A trial database has been assembled and described, utilising available infrastructure data, existing damage and restoration functions, scenario shakemaps for two earthquake events, and simple order-of-magnitude costs. The database was analysed using the HAZUS seismic and hazard risk assessment tool, to present and comment on the consequences of the two scenario events on the performance of Highway 99. Within the restrictions of the incomplete database and limited analysis methods, the utilised procedure identifies the high-level vulnerabilities and expected seismic performance, damage and return to service estimates for the corridor infrastructure.

The HAZUS modelling process, results and our Team's related assessments provide an indication of the risk and impacts from the two scenarios considered. 78% of the assessed inventory losses are from highway bridges, the George Massey Tunnel (performance of the future replacement tunnel were considered) and culverts. Liquefaction triggering is expected in relatively moderate earthquake scenarios and many assets, including road embankments, geotechnical systems, utilities and bridges are vulnerable to ground displacement. The main affected zones are in the Richmond, Delta, and Surrey corridor segments due to large ground displacements arising from soil liquefaction. Damage to utilities is also due mostly to ground displacements, which leads to rotation and deflection of pipes and their connections.

Though utilities only represent 3% of the total repair costs, they play a vital role in the network functionality. The consequences of the broader network outside of the Highway 99 corridor on the corridor itself, were not considered as the required interdependencies in the network not included in our analysis. Electricity and potable water are essential for businesses and daily operations, and disruption of this services can result in a great economic impact in the long term. Economic losses resulting from these impacts were not analysed here.

An examination of the inventory data shows that there has been some improved performance resulting from the work to date on the seismic retrofit program, but that ground movements are causing substantial performance problems and require mitigation. Design of seismic upgrades should be driven in large part by repairability and time to restore functionality. Repairs measured in days ideally for all or some segments, but perhaps up to a week (which is a lot post-earthquake response terms). Repairs times on the order of a couple of days is far better for use of the route for immediate post-earthquake response and recovery. It would be extremely costly to upgrade embankment, roads, interchange ramps, small culverts and small to modest walls, other utilities, etc. affected by the large PGDs, and hence it is not practical. But, assuming there are enough resources available, the associated repair times are generally on the order of days, and hence it makes more sense to plan and be prepared to respond to carry out these repairs than attempting the retrofits. However, damaged bridge end spans and end fills would likely take weeks to months to repair, and hence it is recommended to upgrade to prevent (mitigate) that type of damage and outage.

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REFERENCES

[1] Associated Engineering, (2023). Seismic Resiliency Study of Critical & Key Transportation Routes - Pilot Study - Highway 99 in the Vancouver Area Report, May, 2023.

[2] HAZUS (2023). Using HAZUS-MH for Risk Assessment How-To Guide, FEMA 433. Federal Emergency Management Agency, August 2004. Available at: https://www.fema.gov/pdf/plan/prevent/hazus/fema433.pdf (accessed April 7, 2023).

[3] BC Ministry of Transportation and Infrastructure (BC MoTI), 2023. Critical Road Routes Web App. Available at: https://bcgov03.maps.arcgis.com/apps/webappviewer/index.html?id=b466053fad1140c6a9bf310fd19a23de (accessed April 7, 2023).

[4] Provincial Earthquake Immediate Response Strategy (PEIRS). 2022. Emergency Management BC, 2022.

[5] Applied Technology Council (ATC), (1981). Seismic Design Guidelines for Highway Bridges (ATC-6), Berkeley, California, USA. Available at: https://www.atcouncil.org/pdfs/atc06.pdf (accessed April 7, 2023).

[6] WSP Canada Inc. and BASIS Engineering Ltd. 2022. 01380 Oak Street Bridge – Seismic & Vessel Collision Study Seismic Retrofit Strategy Memo Rev. 0, March 25, 2022.

[7] Fraser River Tunnel - Government of British Columbia. 2022, June 10. Available at: http://engage.gov.bc.ca/fraserrivertunnel/about-the-project/ (accessed May 25, 2022).

[8] Journeay, J.M., Dercole, F., Mason, D., Weston, M., Prieto, J.A., Wagner, C.L., Hastings, N.L., Chang, S.E., Lotze, A., and Ventura, C.E., 2015. A profile of earthquake risk for the District of North Vancouver, British Columbia; Geological Survey of Canada, Open file 7677, 223 p. doi:10.4095/296256.

[9] Federal Emergency Management Agency (FEMA), (2020). HAZUS Earthquake Model Technical Manual, October 2020. Available at: https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals (accessed April 7, 2023).

[10] Applied Technology Council (ATC) (1985). Earthquake Damage Evaluation Data for California report (ATC-13). Available at: https://www.atcouncil.org/pdfs/atc13.pdf (accessed April 7, 2023).

[11] Zhang, G., Robertson, P. K., Brachman, R. W. I., (2004). Estimating Liquefaction-Induced Lateral Displacements Using the Standard Penetration Test or Cone Penetration Test. Journal of Geotechnical and Geoenvironmental Engineering, 130 (8), 2004.

[12] Basöz, N. and Mander, J. (1999). Enhancement of the Highway Transportation Lifeline Module in HAZUS. National Institute of Building Sciences, Washington, DC, USA.

[13] Canadian Standards Association (2019). CAN/CSA-S6-19 - Canadian Highway Bridge Design Code. Canadian Standards Association, Rexdale, Ontario, Canada.