12TH CANADIAN CONFERENCE ON EARTHQUAKE ENGINEERING
JUNE 17-20, 2019
CHÂTEAU FRONTENAC
QUÉBEC, QC.
12ÈME CONFÉRENCE CANADIENNE DU GÉNIE PARASISMIQUE
17-20 JUIN 2019
CCEE 2019

Structural Health Monitoring of Bridges in British Columbia

Yavuz Kaya[1], Carlos Ventura[2]

[1] Structural Health Monitoring Engineer, Bridge Engineering Department, Ministry of Transportation and Infrastructure - Coquitlam, BC, Canada.

[2] Professor, Department of Civil Engineering, University of British Columbia - Vancouver, BC, Canada.

ABSTRACT

This paper presents a Structural Health Monitoring (SHM) network in British Columbia (BC), Canada that involves 14 bridges, 1 tunnel and 12 public schools. The SHM system is part of a province-wide monitoring network, the British Columbia Smart Infrastructure Monitoring System (BCSIMS). The SHM network automatically retrieves structural vibration data from these instrumented structures on a regular basis and makes them available for public to download on the BCSIMS website (www.bcsims.ca). The collected data is then automatically analyzed and permanently stored in a data center located at the University of British Columbia. The objective of the SHM network is to provide the ministry with information on the performance of instrumented structures following a significant event such as a strong earthquake or powerful wind. Such information is then used to assess the structural safety and health state of these structures to help and support the inspection and maintenance program. The SHM network is designed to automatically issue structural reports following a significant earthquake. The entire system has been tested and validated by an earthquake which occurred on December 29th, 2015 on Sidney Island, BC. The SHM system responded to the earthquake as it was designed to and provided the required information that the engineers needed to make immediate decisions and respond to the emergencies in an efficient manner

Keywords: Structural Health Monitoring, Real-Time Data Analysis, Instrumentation, Emergency Response, Damage Detection.

INTRODUCTION

The southwest coast of British Columbia (BC) is located over an active Cascadia Subduction zone, which can produce large earthquakes up to magnitude 9.0 [1-2]. This seismic activity poses a hazard to the area and the risk to the infrastructure structures built in the area. To mitigate the risk, the BC Ministry of Transportation and Infrastructure (MOTI) and University of British Columbia (UBC) started a program in 2009, and it is called the British Columbia Smart Infrastructure Monitoring System (BCSIMS), which integrates data from the instrumented structures and the strong motion network.

The MOTI together with the Geological Survey of Canada (GSC) have being maintaining an urban strong motion network of over 170 acceleration sensors for more than 15 years. These instruments have been deployed across BC to monitor and report the seismic activity in the region. These sensors constitute the Strong Motion Network (SMN), and it automatically generates shake-maps that can be used to identify the level of shaking experienced by MOTI's bridges and facilities located in the earthquake affected region. This process helps the decision-makers to effectively implement a risk management program.

The MOTI has installed seismic SHM system on bridges and tunnels since early 1990s with the help of UBC. SHM system processes structural vibration data and delivers results and related reports in real-time to predefined recipients such as bridge inspectors at the MOTI. The BCSIMS system can provide immediate notifications after an earthquake event. The goals of the system are: (i) to provide a real-time seismic structural response system to enable rapid deployment and prioritized inspections of the MOTI's bridges and tunnels; (ii) to develop and implement a structural health monitoring program to address the need for safe and cost-effective operation of structures in BC; and (iii) to provide a real-time working platform (www.bcsims.ca) that can integrate many aspects of seismicity in BC [3].

BCISMS ARCHITECTURE

Figure 1 shows the BCSIMS architecture. It involves several sub-systems: hardware and software, data acquisition system, data storage and processing tools, network communications, etc. In general, the BCSIMS network involves two main components: the SMN and the seismic SHM network.

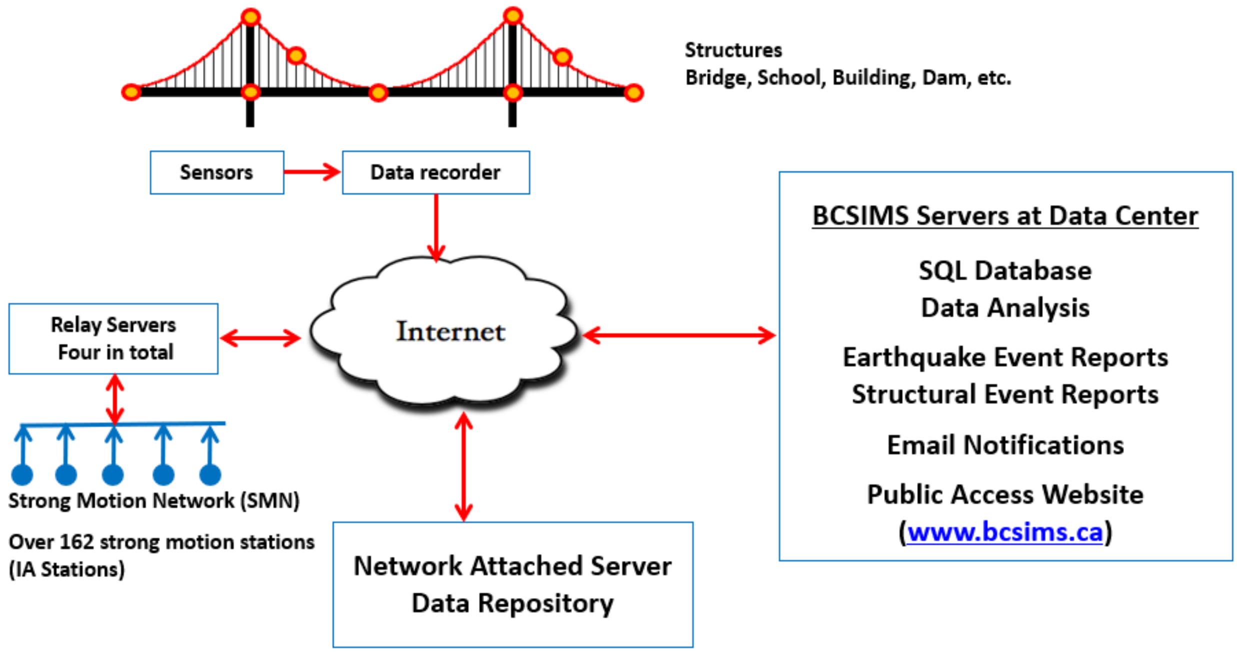


Figure 1. The components of the BCSIMS: servers, hardware and software, data acquisition system, data storage and processing tools, and network communications.

Recorded data from each structure (e.g., bridge, school, dam, tunnel, etc.) is synchronized via Internet in near real-time with the BCISMS servers. The raw data is continuously stored in data repository. All communication between BCSIMS servers and data repository is over local area network; therefore, the data lost between servers are minimized due to earthquake. Data recorders located at each structure can store at least one week of data on-site; therefore, this data can be retrieved manually in case of connection lost between BCSIMS servers and data recorder after a significant earthquake.

Strong Motion Network

Figure 2 shows a screen shot of the BCSIMS website (www.bcsims.ca). The SMN consists of approximately 170 Internet Accelerometers (IA) stations [4]. The IA stations are designed to detect an earthquake and analyze shaking data in real-time to calculate important strong motion parameters such as the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD) and various spectral intensity scales such as Katayama's Spectral Intensity (kSI) [5]. Those parameters are immediately sent to BCSISM data center in the form of several string messages immediately after the shaking is over.

Shake-maps will be created and posted on the BCSIMS website for every earthquake if the following three criterions are met (1) the epicenter of the earthquake is less than 200 km from the nearest IA earthquake station; (2) the magnitude of the earthquake is bigger than 3; and (3) at least one IA station is triggered. Ground Motion Prediction Equations (GMPE) [6-7-8] are used to estimate the PGA in between triggered IA stations. Shake-maps are immediately posted on the BCSIMS website, and they can be viewed with many superimposed layers such as bridges, buildings or schools. Shake-maps are used by many organizations such as federal, provincial, and local, both public and private, for post-earthquake response and recovery as well as for preparedness exercises and disaster planning. This enables emergency responders and maintenance personnel to quickly assess the shaking intensity across the urban areas and at the location of critical infrastructure. It also allows these agencies to prioritize and maximize the effective use of their scarce resources available.

An earthquake with a magnitude of 4.79 (USGS) occurred near Sidney Island in BC on Wednesday December 30th, 2015 at 07:39 AM UTC. Fifty strong motion stations were triggered due to this shaking. The locations of the triggered stations are depicted in Figure 3. The BCSIMS system automatically registered this earthquake, and a shake-map was generated automatically. An earthquake report is automatically generated, and the report is immediately made available on the BCSIMS website. The report includes the following (1) the metadata of the earthquake; (2) the snapshot of the earthquake area affected; (3) tables to show the expected PGA at the location of each structure; and (4) list of strong motion stations that are triggered by that earthquake and peak responses. The earthquake data from triggered IA stations is automatically analyzed, and the results are also included in this report [9]. The entire process was completed within 5 minutes following the earthquake, and no human interaction was needed.

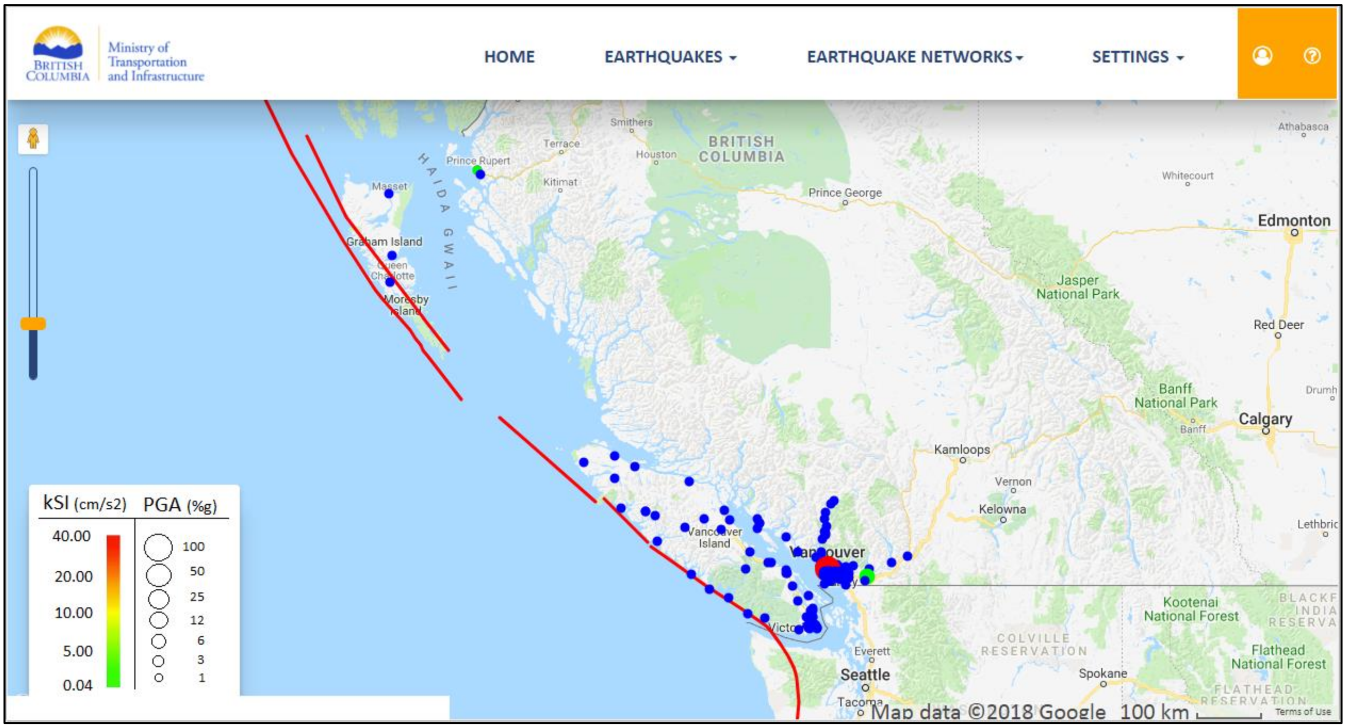
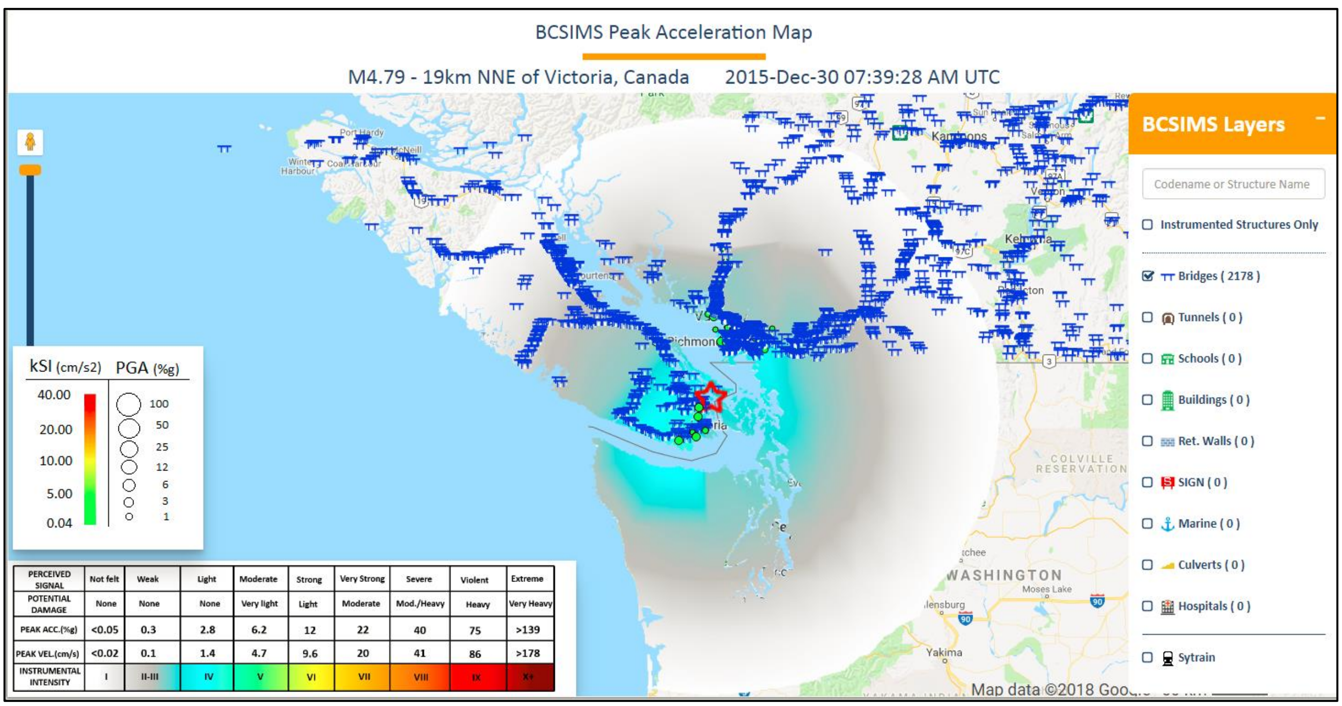


Figure 2. The IA stations (blue circles) are connected to the BCSIMS network in real-time. The size and color of the circles change in real-time based on the reported PGA and kSI values at that SM station. The size of the circle indicates the maximum measured PGA, and the color depicts the maximum calculated kSI value. This feature allows the user to immediately assess the shaking intensity in real-time across the region. (www.bcsims.ca)



PERCEIVED SIGNAL	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	None	None	None	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3. Calculated shake-map for the Mw4.79 earthquake that occurred near Sidney Island in BC, Canada. The location of the epicenter is indicated by a red star on the map, and the circles (50 in total) on the map show the locations of the triggered IA stations due that shaking (www.bcsims.ca).

The shake-map as shown in Figure 3 provide valuable information at or near the bridges that have no seismic SHM system installed. This information is particularly very important because it provides the MOTI personnel (e.g., bridge inspectors and bridge area mangers) with additional immediate information on the shaking intensity experienced by the bridges across the earthquake affected area. The shake-map can be viewed with different superimposed layers such as bridges, schools, tunnels, hospitals, etc. Therefore, these shake-map can also be used by different public and private agencies other than MOTI.

Structural Health Monitoring Network

A total of 28 structures (14 bridges, 1 tunnel, 2 building, and 11 public schools) in the BCSIMS network are currently installed with a SHM system. Table 1 shows a list of the structures that have seismic SHM system installed and are currently being monitored in real-time. The type and the number of the sensor used depend on the dynamic characteristics of the structure as well as the intentions of the SHM system installed. It is capable of remote configuration and can automatically upload data to multiple remote servers via the Internet. The SHM network for bridges in BC is growing very fast: there are currently two bridges that are being installed with SHM system in BC (e.g., Lions Gate Bridge and Pattullo Bridge).

The collected data from each of these structures is archived and analyzed in real-time in the data center. The data processing includes drift analysis, modal identification, and the calculation of the important statistics of each data channel such as mean, root-mean-square (RMS) and standard deviation and so on. Finite element model updating, the damage detection, and structural event reports are other important features that have been developed and implemented in BCSIMS. The results of all these analyses are permanently stored on data center. The SHM data center was originally located at UBC but is being transferred to MOTI's infrastructure in Kamloops with a back-up server located in Calgary, Canada.

Table 1: List of bridges and tunnels that are instrumented with SHM systems and are currently being monitored in real-time in the BCSIMS network

No	Structure name	Total length	Year instrumented	No of channels	Type of sensor
1	French Creek (FC)	200 m	1997	12	A
2	George Massey Tunnel (GMT)	660 m	1996	11	A P
3	Queensborough Bridge (QB)	914 m	1996	12	A P
4	Ironworkers Memorial Second Narrows Crossing (IMSNC)	1,290 m	2011	122	A S W T
5	Pitt River Bridge (PR)	380 m	2009	46	A W
6	William R. Bennett Bridge (WRB)	1,077 m	2008	12	A
7	Portage Creek Bridge (PCB)	129 m	1983	41	A S
8	Port Mann Bridge (PM)	850 m	2013	336	A W D T H P
9	176th Underpass (176B)	75 m	2013	26	A T H
10	Gaglardi Way Underpass (GWU)	65 m	2013	22	A T H
11	Kensington Avenue Underpass (KAU)	75 m	2013	30	A T H
12	Fraser Heights - Wetlands (FHW)	476 m	2013	20	A T H
13	BNSP Sunbury Bridge	68 m	2014	36	A H W D
14	BNSF Viaduct East Mill Access	195 m	2014	84	A H W D
15	Hwy-17 Deltaport Bridge	133 m	2014	36	A H W D

Note: A, acceleration; P, piezometer; S, strain gauge; W, wind; T, temperature; D, displacement; H, humidity.

Description of the Port Mann Bridge

The Port Mann Bridge instrumentation includes a total of 336 measurement channels including displacement transducers at the expansion joints, vibration sensors, and further sensors to record environmental and operational variables. The instrumentation is primarily meant to record structural vibrations under strong motions, and to study the combined effects of the soil and structure interaction. The secondary objective of the instrumentation is to keep track of the modal properties of the bridge (e.g., modal frequency, modal damping ratio and mode shapes) and use them to develop customized damage detection and localization algorithms for the bridge. The instrumentation is distributed across the entire structure, including boreholes, foundations, approach viaducts, and the cable stay.

The cable-supported part of the Port Mann Bridge is instrumented through 34 acceleration sensors (70 channels in different directions), 12 displacement transducers, and 2 weather stations as shown in Figure 4. Weather stations are located at the top of each tower and measure the temperature and humidity, as well as the wind speed and its direction, which sums up to 8 channels per station. The displacement transducers are located at the expansion joints at either side of the cable stay bridge to measure the displacement due to temperature variations, traffic, and external loads. A toll station at the south end of the bridge records both the number and length of vehicles crossing the bridge. This information is used to determine the correlation between calculated modal properties of the bridge (e.g., modal frequency) and the traffic load acting on the bridge deck.

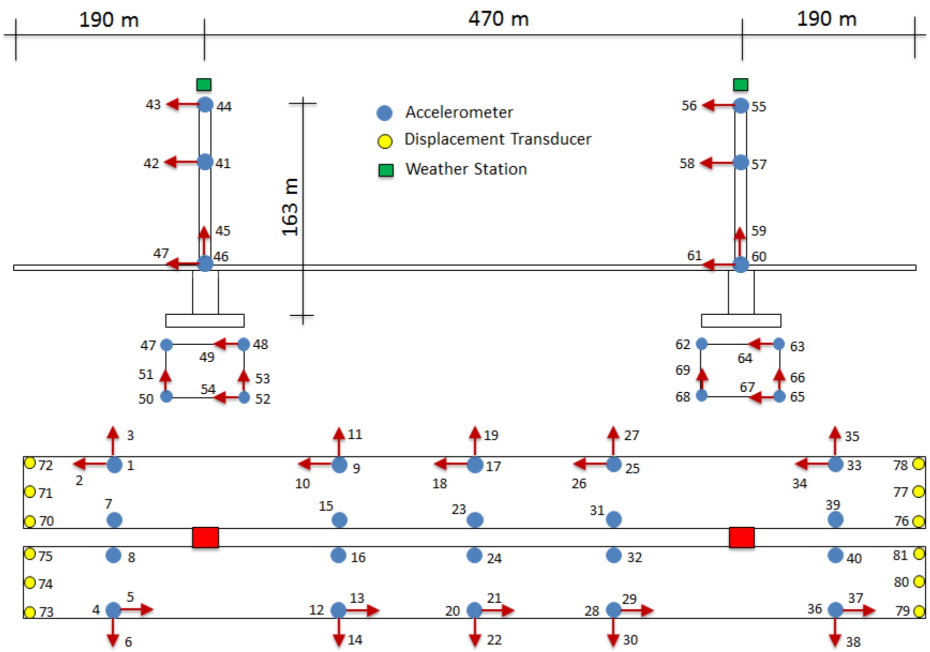


Figure 4. Instrumentation map for Port Mann Bridge (deck, towers and foundation only)

SHM Data Archiving

Archiving includes the development of new binary file format of Virtual Input Files (VIF), which contains raw data from all the sensors. This VIF files are further compressed to minimize the disk space on servers. The default length of VIF files are selected as five minutes because this length currently enables servers to keep up with the post analysis of the data from all the structures simultaneously. The raw data or event data (e.g., earthquake or strong wind) are archived and made available for public and registered users to download via the BCSIMS website (www.bcsims.ca).

A certain amount of raw data from each structure is permanently stored every day; for example, 75 minutes of raw data for Port Mann Bridge and 30 minutes of data for Ironworkers Memorial Second Narrows Crossing Bridge. The length of such data is structure specific and determined based on the dynamic characteristics of each structure. They are then used to test the new tools and techniques that are continuously developed as part of the SHM network.

Tracking Long Term Statistics

The data analysis in the BCSIMS is done in real-time for each channel. The SHM system can track slow changes in the characteristics of structure such as those due to aging, change of usage, traffic patterns, and other environmental factors (e.g., temperature, wind, rain, etc.). Statistical relationship between the structural changes and the factors that might cause such changes are established using mean, standard deviation, root-mean-square, etc. These parameters help to better understand the dynamic behaviour of the bridge under different loading conditions. This enables building up a statistical history of the correlation between the dynamic response of the bridge and the environmental factors so that the effect of environment can be adequately accounted for in the recorded data [10-11].

Figure 8 shows the time variations of the calculated statistics if maximum amplitudes and standard deviation for the selected channel #20, which is located on the mid-span of the Port Mann Bridge and recording the structural vibrations in vertical direction. The statistics are calculated at 5-minute intervals. The SHM system on the Port Mann Bridge automatically calculates the variation of the statistical parameters for each recording channel on the bridge, and they could used to detect abnormal behavior on the structure.

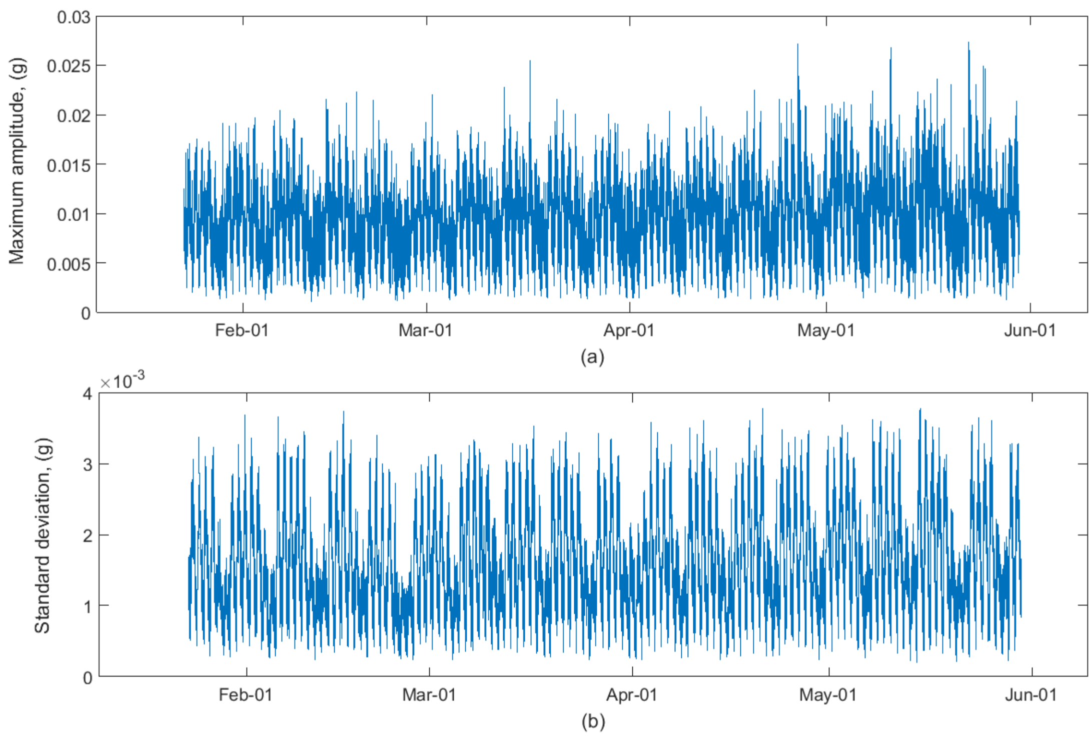


Figure 8. Time variation of statistics parameters for the selected vertical channel #20 on the Port Mann Bridge: recorded for three months from mid January to the end of May in 2018: (a) maximum amplitudes and (b) standard deviation.

Drift Calculation

Drift is defined as the relative displacement of the column top with respect to its base, and it is strongly controlled by the displacement demand, and it is one of the decisive control parameters for damage. Drift can be controlled by imposing displacement (or drift) limits on these structural members. Drift is controlled by SHM system for bridge piers, bridge towers, or building columns. To calculate the drift, the displacements need to be measured or estimated at the top and the base of the column. It is possible to calculate displacements from acceleration data by integrating over the recorded accelerations twice. However, the integration operation on raw data significantly increases the noise amplitudes in the integrated signal and can lead to misleading results [9]. Several tools have been developed in the BCSIMS to minimize such noise increase: the response of a bridge pier at resonant frequency has higher signal-to-noise ratio; therefore, the noise influence during the integration and differentiation is minimal.

Tracking Modal Parameters

Dynamic modal properties (e.g., modal frequencies, modal damping ratios, and mode shapes) of the bridges are estimated from output-only data and continuously monitored in real-time using the stochastic subspace identification (SSI) method, principal component [12, 13, 14, 15, 16, 17]. The mode tracking is done through an automated mode tracking procedure that compares both frequency and mode shapes [18]. No human interaction is required in this process.

The modal parameters provide very important information about the dynamic characteristics of the structure. As soon as new vibration data from any structure becomes available on the server in the data center, the modal properties of that structure are automatically estimated in near real-time using the SSI method, and the results are permanently stored in the data center.

The change of modal properties of the structure especially due to environmental conditions can be larger than the change due to the damage; therefore, the effect of environmental conditions on modal properties of structure must be accounted for as they can completely mask the change of modal properties caused by actual damage [10].

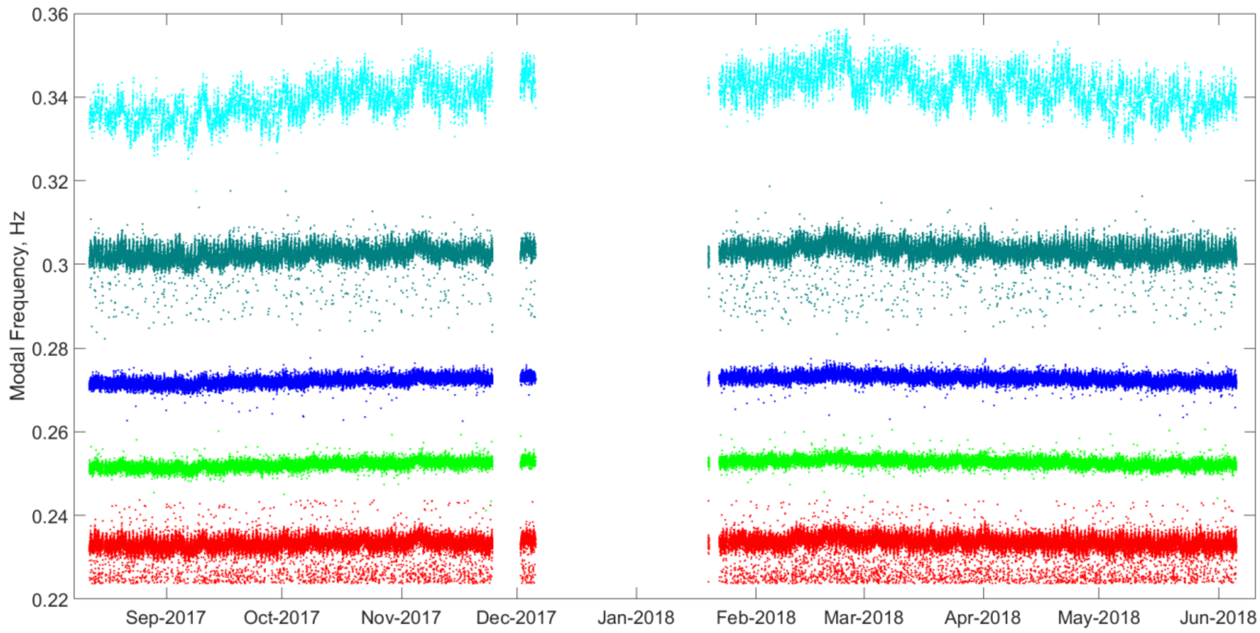


Figure 9. Time variation of modal frequencies of the Port Mann Bridge between October 2017 and June 2017.

SHM Structural Event Reports

As soon as an earthquake is registered with the BCSIMS, the SHM network automatically initiates an event recording for each instrumented structure. Earthquake recordings are permanently stored on the server and are immediately made available on the BCISMS website for download after the seismic event is over. The event data is then analyzed, and a structural report is generated for each instrumented structure in the SHM network. The structural reports are then e-mailed to a predefined subscribers list and are then published on the website.

This report provides key information on the status of each bridge after an earthquake. One report will be issued for each structure, and it provides bridge inspectors and MOTI engineers with the shaking amplitude at the various locations of the bridge as well as the amplitude of the ground shaking. The calculated structural parameters (e.g., drift ratio of a pier or recorded displacement at bearings) for each structure are automatically compared with user selectable thresholds in the report. Any recorded or calculated structural parameter that exceeds the predefined thresholds is clearly indicated in the report by graphs and figures, and recommendations are also given in the report regarding the actions to be taken. The threshold values are determined in accordance with the code-specified design values or the detailed seismic analysis of the structure.

CONCLUSION

In collaboration with local, provincial and federal organizations, a comprehensive SHM network has been designed, installed, and maintained since 2009 for the bridges owned by the BC MOTI, and it is part of a province-wide seismic monitoring system (BCSIMS). The SHM network collects raw vibration data from all instrumented structures and monitors the structural health state of each structure in real-time by evaluating drift values, statistical parameters and modal attributes. The SHM network effectively organizes and processes structural vibration data in an efficient manner and delivers the collected information along with analysis results to the appropriate parties such as bridge engineers in the MOTI.

ACKNOWLEDGMENTS

Authors greatly acknowledge the Ph.D. student Alexander Mendler at the University of British Columbia for his support in providing computer programs for the SSI algorithm.

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