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Dynamic Characteristics of Three Major Towers on Parliament Hill, Ottawa, from Recorded Vibrations during the Val-des-Bois, Quebec, Earthquake of June 23, 2010

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Abstract: The magnitude (Mw) of 5.0 Val-des-Bois earthquake that occurred in Quebec on June 23, 2010 was the biggest recent earthquake in eastern Canada. It produced the strongest shaking ever felt in Ottawa. The ground shaking was widely felt in Ontario and Quebec, and it was also felt in the US as far as Kentucky. A number of records from this event were compiled and processed by the Geological Survey of Canada. Of special importance for this paper are the recorded vibrations of three towers of the Parliament Hill buildings in Ottawa, i.e., the Peace Tower of the Centre Block, the Mackenzie Tower of the West Block, and the South-West Tower of the East Block. In total 27 records were obtained at the towers, including records at the ground level, at the middle and at the top of the towers. These are the first significant records obtained on the towers during an earthquake. The records were processed to determine the dynamic characteristics of the towers. Based on the Fourier amplitude spectra of the recorded signals, the natural frequencies of the vibration modes were determined. These were found to be very similar to those from ambient vibration tests. The results from this study are very important for seismic evaluations of the towers on Parliament Hill.

1. Introduction

The response of a given structure to dynamic loading depends very much on the dynamic characteristics of the structure. These characteristics, which normally refer to the natural frequencies and shapes of the modes, depend on the geometry of the structure in plan and elevation, the structural system, and the property of the material of the structure. The dynamic characteristic of a structure can be determined theoretically using available computer programs for structural and dynamic analysis (e.g., CSI 2000, Carr 2004). However, the computed values using such programs might be quite different from the actual values because of the uncertainties in the material properties and the approximations involved in the development of the computer model of the structure considered. The uncertainties of the computed natural frequencies and mode shapes might be especially large for heritage structures, as is the case for the towers of the Parliament Hill buildings in Ottawa. This is primarily because the towers are built of stone masonry, for which the material properties are not known, and assumptions have to be made regarding these properties.

The most reliable approach for determining the natural frequencies of a structure is based on recorded vibrations of the structure, which can be either ambient vibrations or vibrations due to strong seismic motions. The natural frequencies of the structure can be determined by considering the Fourier amplitude spectra of the recorded motions. Since the structural response is dominated by the contributions of the modal vibrations, the natural frequencies of the modes correspond to the predominant frequencies of the Fourier amplitude spectrum.

This paper describes the determination of the natural frequencies of three towers of the Parliament Hill buildings in Ottawa, i.e., the Peace Tower of the Centre Block, the Mackenzie Tower of the West Block, and the South-West Tower of the East Block. Recorded vibrations of the towers obtained during the magnitude Mw 5.0 Val-des-Bois earthquake of June 23, 2010 were used in the analyses. These are the first records from significant earthquake motions (magnitude of 5.0) recorded on the towers. The computation of the natural frequencies of the towers is one significant step in the use of these records. The records can be used in further studies for the calibration of the dynamic models of the towers and the prediction of their responses when subjected to seismic motions.

2. Natural Frequencies of the Towers

2.1 The Peace Tower of the Centre Block

2.1.1 Instrumentation

There are 12 instruments for recording acceleration time histories deployed in the Peace Tower of the Centre Block. The locations of the instruments are shown in Figure 1. It is seen from the figure that instruments are installed at four levels of the tower, i.e., ground level, level 8 (at about 2/3 of the height of the tower), level B (at about 3/4 of the height), and level E (top of the tower). There are three seismometers at ground level, two seismometers at level 8, four seismometers at level B, and three seismometers at level E. The orientation of the seismometers is such that vibrations at the instrumented locations can be recorded in North-South, East-West, and Vertical directions. For ease of understanding the records, the channel ID and the orientation of the recorded components corresponding to each of the seismometers are shown in Table 1. The abbreviations NS and EW indicate records in the North-South and East-West directions respectively.

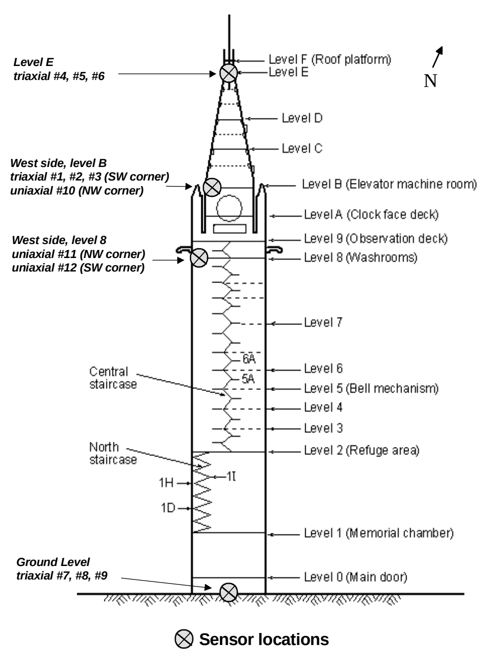

Figure 1: Layout of accelerometers on the Peace Tower.

Table 1: Peak accelerations of the records obtained at the Peace Tower.

Channel ID	Location	Recorded component	Peak acceleration (g)
1	Level B	NS	N/A
2	Level B	Vertical	0.112
3	Level B, SW corner	EW	0.077
4	Level E	NS	0.488
5	Level E	Vertical	0.150
6	Level E	EW	0.279
7	Ground	NS	0.041
8	Ground	Vertical	0.038
9	Ground	EW	0.031
10	Level B, NW corner	EW	0.086
11	Level 8, NW corner	EW	0.036
12	Level 8, SW corner	EW	0.044

2.1.2 Acceleration Time Histories and Peak Motions

With the exception of channel 1 which was not functional, all other 11 instruments were triggered during the Val-des-Bois earthquake. The digital records obtained by the seismometers are in units of "volts", and conversion to units of acceleration was done by using the corresponding conversion factors that are given for each instrument. No further processing, such as filtering and baseline correction, was conducted on the records. The acceleration time histories of the NS, EW, and Vertical components of the records are shown in Figures 2, 3, and 4 respectively. The time histories show that the tower has been exposed to quite strong vibrations for about 5 seconds, i.e., between the 10^{th} and the 15^{th} second marks on the time axis.

The peak accelerations of the recorded components are listed in Table 1. It can be seen in the table that the peak acceleration of the vibration at Level E (roof) in NS direction is 0.488 g while the peak acceleration of the vibrations at the ground level, in the same direction, is 0.041 g, i.e., the peak acceleration recorded on the roof of the tower is about 12 times larger than that recorded at the ground level.

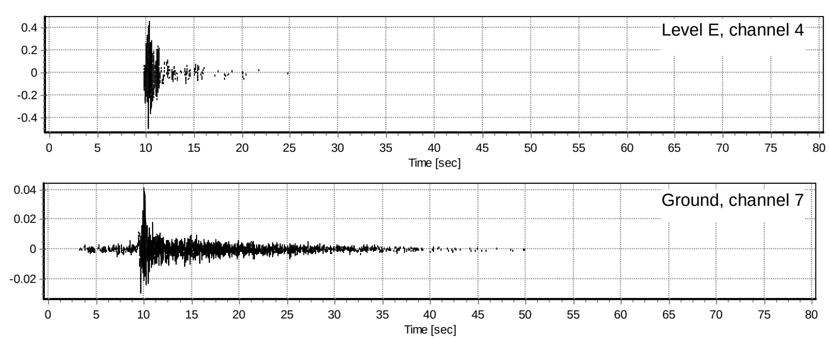

Figure 2: Acceleration time histories of the NS components recorded on the Peace Tower.

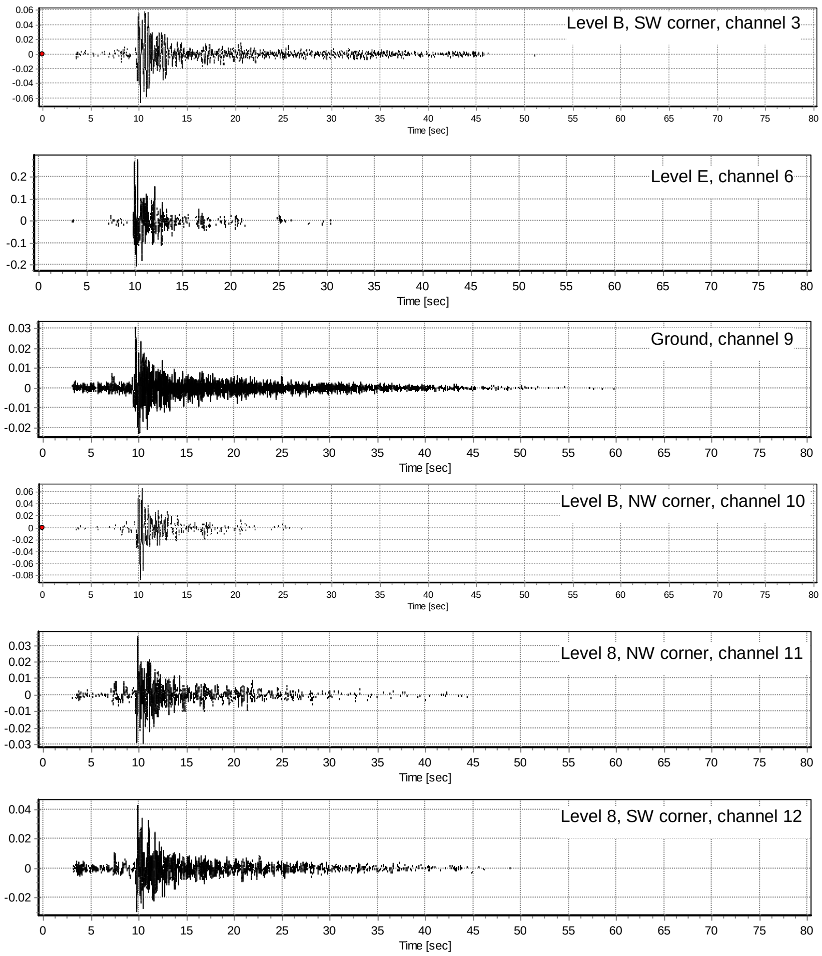

Figure 3: Acceleration time histories of the EW components recorded on the Peace Tower.

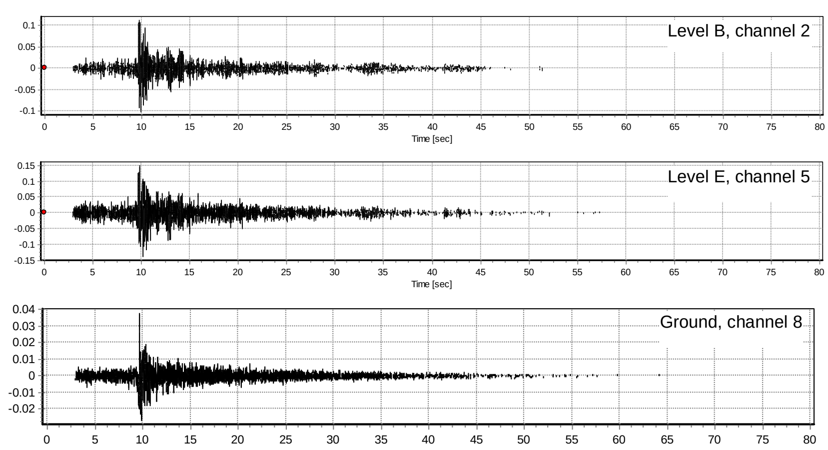

Figure 4: Acceleration time histories of the Vertical components recorded on the Peace Tower.

2.1.3 Natural Frequencies

To determine the natural frequencies of the tower, Fourier analyses were performed on the horizontal components of the records. The Fourier amplitude spectra for the NS and EW components are presented in Figure 5. Since channel 1 was not functional (as mentioned above), only the Fourier spectrum of the record at the top of the tower (level E) is used here for the identification of the predominant frequencies of the vibrations in the NS direction. Figure 5 shows that three frequencies dominate the response in the NS direction corresponding to the 1^{st}, 2^{nd}, and 3^{rd} modes of vibration of 1.1 Hz, 3.2 Hz, and 7.4 Hz respectively (i.e., 1^{st}, 2^{nd}, and 3^{rd} mode periods of 0.9 s, 0.3 s, and 0.14 s respectively). Regarding the EW direction, Figure 5 shows two predominant frequencies, i.e., the 1^{st} mode frequency of 3.2 Hz and the 2^{nd} mode frequency of 6.4 Hz (1^{st} mode period of 0.31 s, and 2^{nd} mode period of 0.16 s)

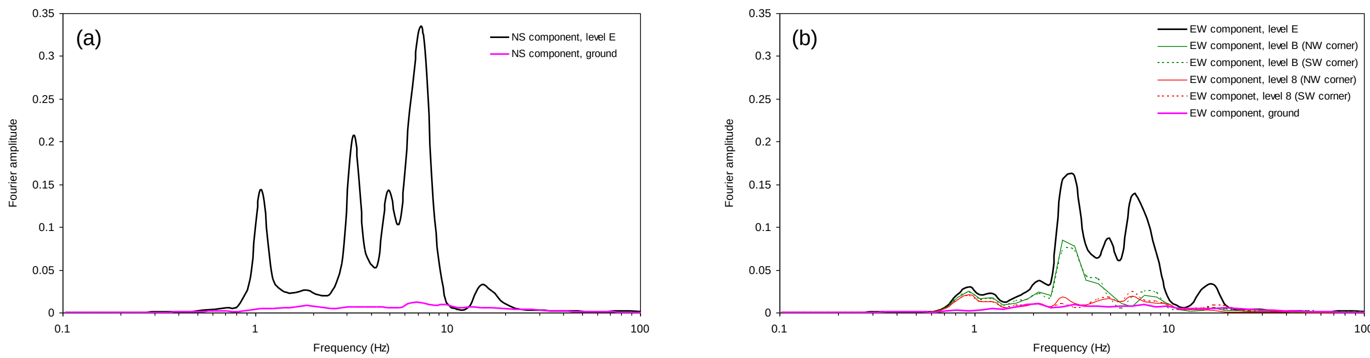

Figure 5: Fourier amplitude spectra for the records obtained on the Peace Tower, (a) NS components, (b) EW components.

2.2 The Mackenzie Tower of the West Block

2.2.1 Instrumentation

There are 3 instruments deployed on the Mackenzie Tower of the West Block. These are installed on the ground level, in the middle (i.e., level 4) of the tower, and on the top floor of the tower. The locations of the instruments are shown in Figure 6. Each instrument records three components, i.e., NS component, EW component and Vertical component. All the sensors were triggered during the Val-des-Bois earthquake, and in total nine records of the vibrations of the tower were obtained during the earthquake.

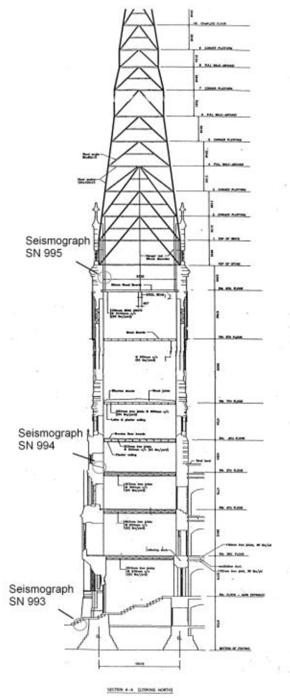

Figure 6: Layout of accelerometers on the Mackenzie Tower.

2.2.2 Acceleration Time Histories and Peak Motions

The acceleration time histories of the records obtained at the Mackenzie Tower are presented in Figures 7 to 9 while the peak accelerations of the motions are listed in Table 2. As shown in the table, the maximum acceleration of the vibrations on the top floor is around 0.10 g, and that on the ground level is about 0.04 g. Note that these values are from the vertical components. Another observation from Table 2 is that the ratio of the peak acceleration obtained on the top of the tower to that obtained on the ground level is about 2.5 for all three components.

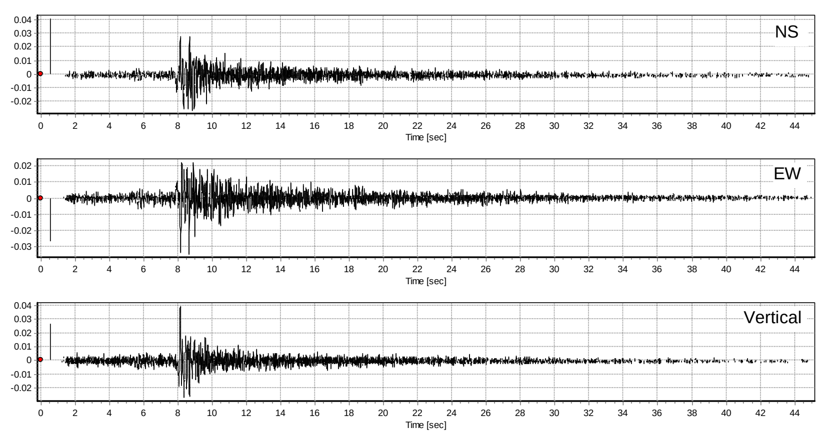

Figure 7: Acceleration time histories of the NS, EW and Vertical components recorded on the ground level of the Mackenzie Tower.

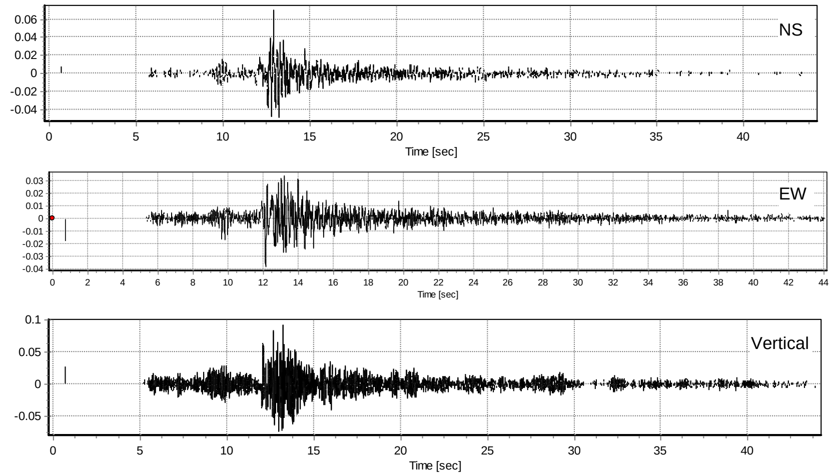

Figure 8: Acceleration waveforms for the NS, EW and Vertical components recorded on the level 4 of the Mackenzie Tower.

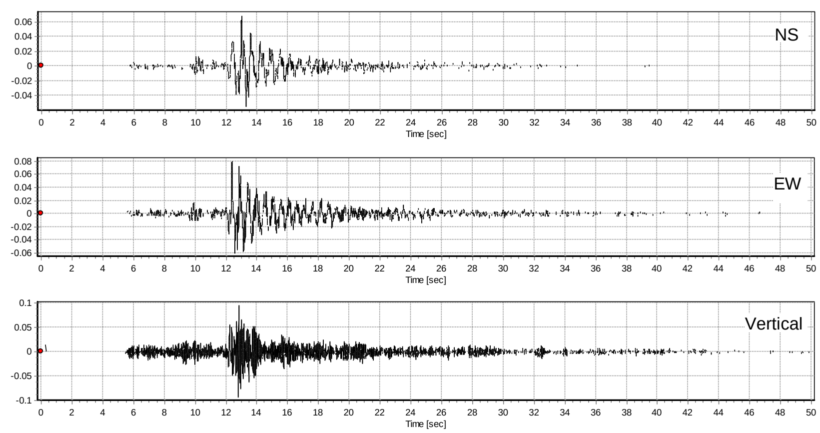

Figure 9: Acceleration time histories of the NS, EW and Vertical components recorded on the top floor of the Mackenzie Tower.

Table 2: Peak accelerations of the records obtained at the Mackenzie Tower.

Instrument ID	Location	Peak acceleration (g)		
		NS component	Vertical component	EW component
SN993	Ground	0.029	0.040	0.035
SN994	Level 4	0.070	0.093	0.039
SN995	Top floor	0.069	0.095	0.080

2.2.3 Natural Frequencies

Fourier analyses were also conducted on the records obtained at the Mackenzie Tower. The Fourier amplitude spectra for the NS and EW components are shown in Figure 10. It can be seen in the figure that the dominant frequencies of the NS and the EW components are 1.63 Hz and 1.87 Hz respectively, indicating that the first mode frequency in the NS direction is 1.63 Hz and that in the EW direction is 1.87 Hz. Expressed in terms of the periods, the first mode periods in the NS and EW directions of the tower are 0.61 s and 0.53 s respectively. It is useful to mention that the first mode periods in the NS and EW directions are very close to those based on the ambient vibration test on the tower (PWGSC, 2000). As reported in PWGSC (2000), the first mode periods in the NS and EW directions of the tower were found to be 0.56 s and 0.47 s respectively.

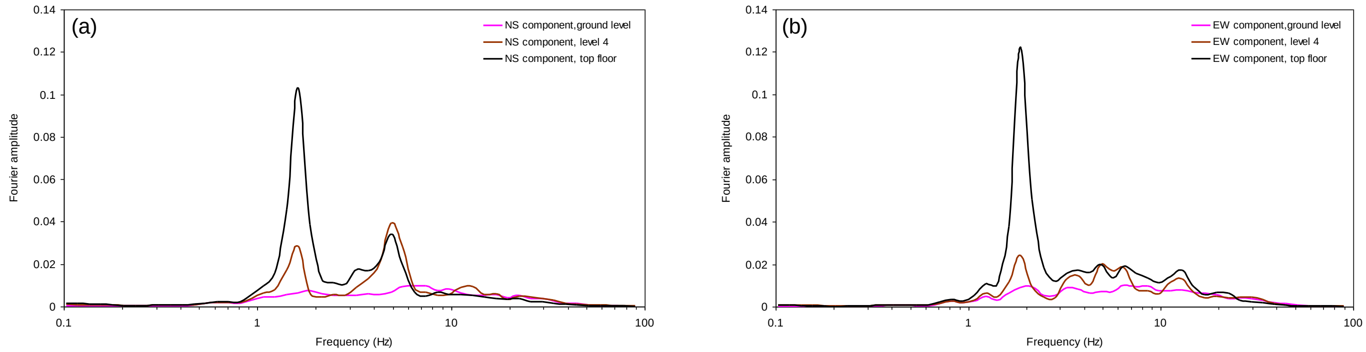

Figure 10: Fourier amplitude spectra for the records obtained at the Mackenzie Tower, (a) NS components, (b) EW components.

2.3 The South-West Tower of the East Block

2.3.1 Instrumentation

Two instruments are deployed in the South-West Tower of the East Block. The instruments are installed at the ground level and on the top floor of the tower. The locations of the instruments are shown in Figure 11. Each instrument records three components, i.e., NS component, EW component, and Vertical component. All the sensors were triggered during the Val-des-Bois earthquake.

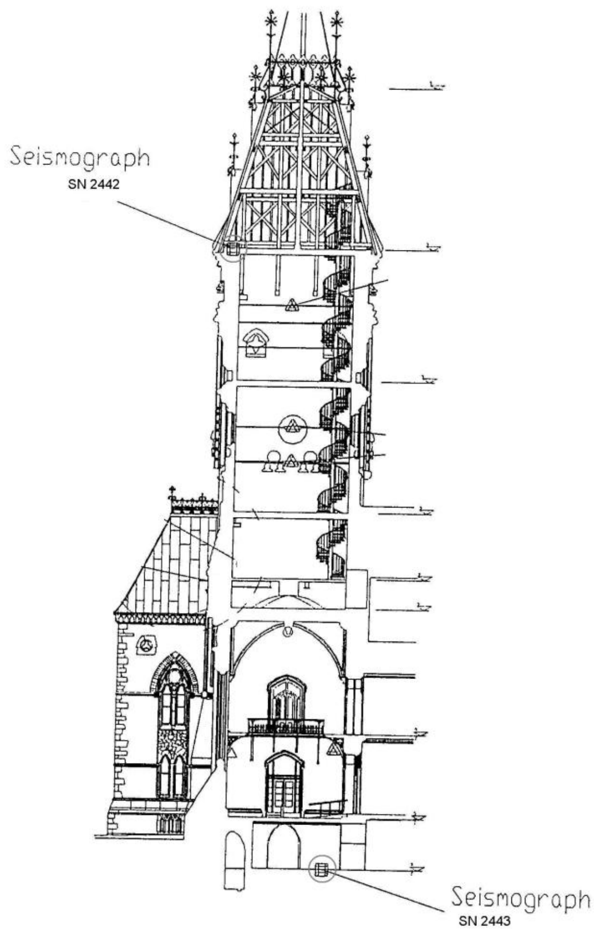

Figure 11: Layout of accelerometers at the South-West Tower of the East Block.

2.3.2 Acceleration Time Histories and Peak Motions

The acceleration time histories of the records obtained at the South-West Tower are presented in Figures 12 and 13, and the peak accelerations of the recorded components are listed in Table 3. As expected, it is seen from the table that the peak accelerations recorded on the roof of the tower are much larger than those recorded on the ground level, i.e., the maximum acceleration of the vibrations at the top floor is around 0.19 g, and that at the ground level is about 0.05 g.

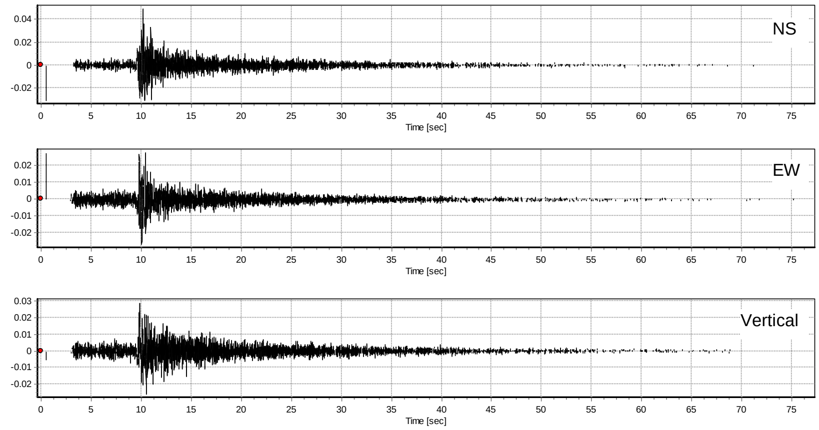

Figure 12: Acceleration time histories of the NS, EW and Vertical components recorded on the ground level of the South-West Tower.

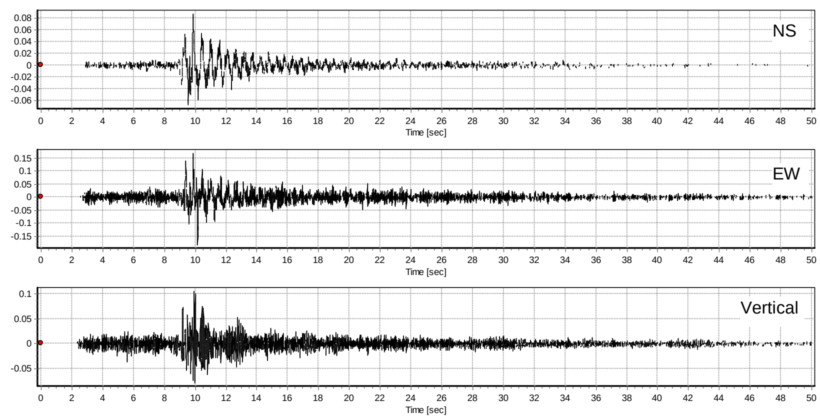

Figure 13: Acceleration time histories of the NS, EW and Vertical components recorded on the top floor of the South-West Tower.

Table 3: Peak accelerations of the records obtained at the South-West Tower.

Instrument ID	Location	Peak acceleration (g)		
		NS component	Vertical component	EW component
SN2443	Ground	0.049	0.027	0.029
SN2442	Top floor	0.087	0.105	0.187

2.3.3 Natural Frequencies

The Fourier amplitude spectra for the NS and the EW components of the records obtained at the South-West Tower are presented in Figure 14. It is seen that both the NS components and the EW components have the same dominant frequency of 1.87 Hz. This frequency represents the first mode frequency of the vibrations of the tower in the NS and EW directions. Consequently, the first mode periods in the NS and the EW directions of the tower are 0.53 s. It is interesting to observe that this period is the same as the first mode period in the EW direction of the Mackenzie tower.

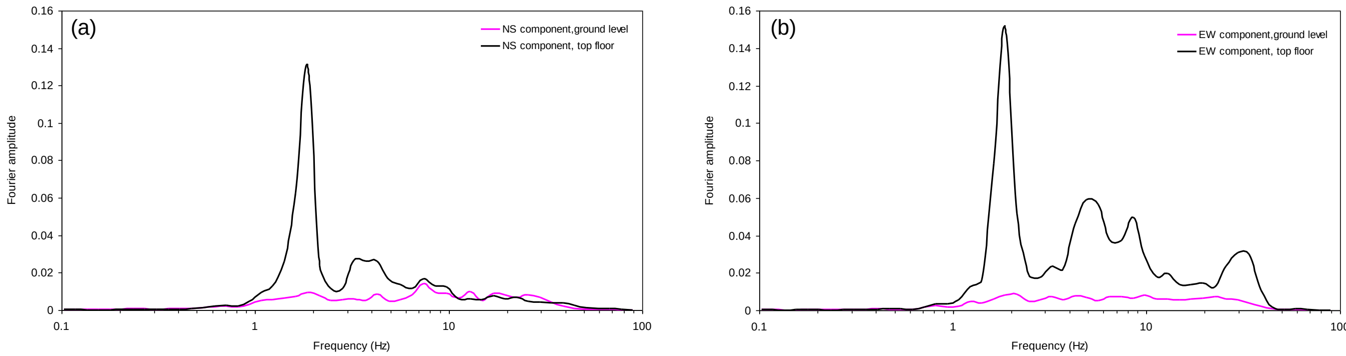

Figure 14: Fourier amplitude spectra for the records obtained at the South-West Tower: (a) NS components, (b) EW components.

3. Summary and Conclusions

This paper presents characteristics of the vibrations of three major towers, i.e., Peace Tower, Mackenzie Tower and South-West Tower (of the East Block), on Parliament Hill in Ottawa, recorded during the magnitude M_w 5 Val-des-Bois earthquake of June 23, 2010. The main objective of the study was to determine the natural periods of the vibration modes of the towers based on the recorded motions. The Fourier amplitude spectra of the records were used to determine the natural periods in the North-South (NS) and East-West (EW) directions of the towers. The findings from this study can be summarized as follows:

- The natural periods of the 1st, 2nd and the 3rd vibration modes in the NS direction of the Peace Tower are 0.9 s, 0.3 s, and 0.14 s respectively, and those of the 1st and the 2nd modes in the EW direction are 0.31 s and 0.16 s.
- The 1st mode periods in the NS and EW directions of the Mackenzie Tower are 0.61 s and 0.53 s respectively.
- For the South-West Tower, the 1st mode period is 0.53 s for both the NS and the EW directions.
- Based on the peak accelerations, the acceleration responses of the roofs of the Peace Tower, the Mackenzie Tower, and the South-West Tower are larger than the corresponding ground motion accelerations by factors of about 12, 2.5 and 4 respectively.

The natural periods and the records discussed in this paper can be used for the calibration of the analytical models of the towers and for the investigations of the performance of the towers under seismic motions.

4. References

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