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Dynamic characteristics of the west wing of East Block of Parliament Hill, Ottawa, Ontario from ambient noise recordings

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Permanent link: https://doi.org/10.4095/306517

Recommended citation
Kolaj, M., Hunter, J., and Adams J., 2018. Dynamic characteristics of the west wing of East Block of Parliament Hill, Ottawa, Ontario from ambient noise recordings; Geological Survey of Canada, Open File 8308, 16 p. https://doi.org/10.4095/306517

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ABSTRACT

To mitigate seismic risk, it is important to obtain a structure's natural frequencies and resonant amplification spectra. To this effect, ambient seismic noise data were collected at three sites of interest as well as two reference sites within the west wing of East Block on Parliament Hill in Ottawa, Canada due to the importance and historic value of these heritage buildings. The data were processed using the standard spectral ratio (SSR) and horizontal-to-vertical spectral ratio (HVSR) techniques. Processing of the ambient noise data for the South-West Tower yielded approximately the same fundamental frequency (2.0 Hz) as did the analysis of the M_w 5.0 Val-des-Bois earthquake data (1.86 Hz). Several >3 Hz spectral peaks as well as broadband amplification (3 Hz - 8 Hz) were observed at room 219 and room 314 of the west wing at the locations of previously installed three-component earthquake accelerometers. The SSR technique was found to be more reliable than the HVSR technique in identifying the dominant peaks in the spectra. This was likely due to the presence of vertical amplification at the sites which is hypothesized to be caused by coupling between the horizontal vibrational modes with that of the floor which caused it to vibrate at a comparable frequency. An ambient noise survey such as the one performed in this work is a low-cost approach for documenting the dominant dynamic properties of a structure in the linear domain.

INTRODUCTION

To mitigate seismic risk it is important to obtain a structure's natural frequencies and resonant amplification spectra. These parameters can be approximately calculated from provisions within building codes based on height, but the equations were derived for standard modern structures and not for stone-masonry heritage buildings. Considering their historical importance, numerical analysis or experimental studies are often warranted to determine such structures' responses to potentially damaging seismic vibrations (Oliveira and Navarro, 2010). Numerical analysis allows for the calculation of the dynamic properties of a structure, but requires a detailed structural plan and precise structural properties of the construction material. The latter can be particularly difficult for heritage buildings where the exact properties of the materials used are unknown. Moreover, the numerical models themselves often include approximations which may make the estimates they produce less realistic (e.g., Masi and Vona, 2010). As such, experimental validation of the results obtained via numerical analysis is critical for testing the validity of the calculated dynamic properties (Parolai et al., 2005; Ventura et al., 2005; Oliveira and Navarro, 2010; Ditommaso et al., 2013).

The best possible experimental vibration data is obtained through the analysis of real earthquake recordings from semi-permanent seismometers installed at various points within the building (Gallipoli et al., 2010). However, the installation of these monitors is not only expensive, but requires significant earthquakes to be recorded which, depending on the area, may be infrequent. For these reasons, ambient noise recordings have been suggested as alternatives, as they can provide a quick estimate of the structure's dynamic characteristics through the use of cost-effective mobile seismometers (Gallipoli et al., 2010). Two popular field and analysis techniques that have been used are: the single-station horizontal-to-vertical spectral ratio (HVSR, Nakamura, 1989) method, and the standard spectral ratio (SSR, Ivanovic et al., 2000) method. Both methods rely on estimating the fundamental resonant period(s) (period = 1 / frequency) and the spectral response of a structure as induced by background microtremors (ambient noise sources). At low frequencies (< 1 Hz) the origin of the ambient noise is typically natural teleseisms (ocean waves, small earthquake events, atmospheric-induced microseisms) while the higher frequencies (> 1 Hz) are commonly related to human activity (e.g., traffic or construction vibrations at distances > 200-500 m). Ambient noise techniques assume that this noise is the input ground motion to the building, which is then variably amplified at different frequencies depending on the dynamic properties of the structure. Strong local noise sources (wind or nearby traffic) can provide large input motions; however, care should be taken to avoid very proximal noise sources since these transmitted signals can mask the building's natural resonance (Gallipoli et al., 2010).

The ambient noise HVSR technique involves recording ambient noise with a single three-component seismometer for a suitable duration in order to calculate a reliable spectrum. The horizontal spectrum is then divided by the vertical spectrum on the assumption that the vertical spectrum is a suitable proxy to the free field motions (i.e., not subject to the same amplification factors as the horizontal components). While many examples of the method's ability to estimate the fundamental period(s) of buildings and sub-soil exist, a general consensus on the theoretical underpinnings remains unclear (Mucciarelli and Gallipoli, 2001). One possible explanation is that, ignoring rocking modes, the vertical component is not amplified in a building, so it can be approximated by a single-degree-of freedom damped oscillator (Gallipoli et al., 2009). A potential complication can arise from floor modes (resonance of the floor diaphragm) which may introduce significant vertical amplification (Parolai et al., 2005; Gallipoli et al., 2010). This effect can be minimized by placing the sensor(s) close to vertical load-bearing structural elements. Nevertheless, if significant vertical amplification is present then the fundamental(s) may be masked and/or distorted, and the HVSR data should be interpreted with caution.

The ambient noise SSR technique differs from that of HVSR by using a reference site to estimate the free-field spectrum. Care must be taken in selecting the reference site as it ideally should be free of any soil-structure interaction (Gallipoli et al., 2009). This can generally be achieved by placing the reference station on bedrock away from any influencing structures (Gallipoli et al., 2010). However, if the reference station is located on the ground/basement floor of the building being studied, it is implicitly assumed that there is no amplification between the ground and the foundation (Todorovska, 2009; Gallipoli et al., 2009). While both the HVSR and SSR techniques should be able to provide the main fundamental period(s) of a structure, the accuracy of the derived amplification factors and natural periods should be used with caution. Both methods are based on weak-motion and therefore only provide an estimate of the dynamic properties of the building in the linear elastic (i.e. low strain) domain. Moreover, the amplification factors derived from the HVSR method tend to be smaller than factors derived using other techniques (e.g., SSR) and no clear consensus on their reliability has been reached (e.g., Horike et al., 2001; Mucciarelli and Gallipoli, 2001; Chavez-Garcia et al., 2007).

An investigation into the dynamic properties of Parliament Hill in Ottawa, Canada is of particular interest due to the importance and historic value of the heritage buildings. One of these buildings currently being considered for seismic upgrades is the East Block which was built in 1859 with an additional wing added in 1910. Five permanent seismometers were installed in the East Block in two separate studies. The first of these (2004 -) involved the South-West Tower of East Block, where a sensor was installed at the top floor of the tower and another at the foundation. Data recorded from the Mw 5.0 Val-des-Bois earthquake suggested a fundamental period of 1.87 Hz based on a visual analysis of the spectra (Lin et al., 2011). The Val-Des-Bois earthquake was the strongest recorded event in Ottawa’s history and reached roughly 1/5 of the design level required for current buildings in NBCC2010 (Lin and Adams, 2011). While no significant damage was observed at East Block, strain gauges installed in cracks in parts of the South-West Tower showed a slight step increase above the expected seasonal variation (PWGSC, 2011). The second study (2016 -) involved an installation of three strong-motion seismometers (one on each floor) in the west wing of the main building of East Block (Glazer, 2016). The sensitivity of these latter instruments is quite low and no useful event (earthquake or otherwise) has yet been captured to allow the determination of the dynamic properties of the building.

An ambient noise study was therefore carried out (January 11, 2017) to overcome the limitations faced by the low-sensitivity permanent sensors and to verify the calculated dynamic characteristics of the East Block. The main goal of this study was to collect ambient noise recordings and to calculate the building’s fundamental period(s) at the sites of the permanent seismometers by employing the HVSR and SSR techniques.

METHOD

The ambient noise data were collected on January 11, 2017 using three high-sensitivity, portable, three-component seismometers (Micromed Tromino). Each site was occupied for 20 minutes, with the exception of the west wing basement site (room 58) which was occupied for the 2 hour duration of the experiment (Figure 1 and Figure 2). The measurements on the second (room 229) and third (room 314) floors of the west wing were recorded synchronously with the reference site in the basement. Similarly, the reading at the top of the tower was recorded at the same time as its reference at the basement level. The sensors were oriented along the longitudinal (approximately north-south) and transverse (approximately east-west) axes of the west wing. The data were collected between the hours of 19:00 and 21:00 UT during normal operations of the building (25km/h SSE wind).

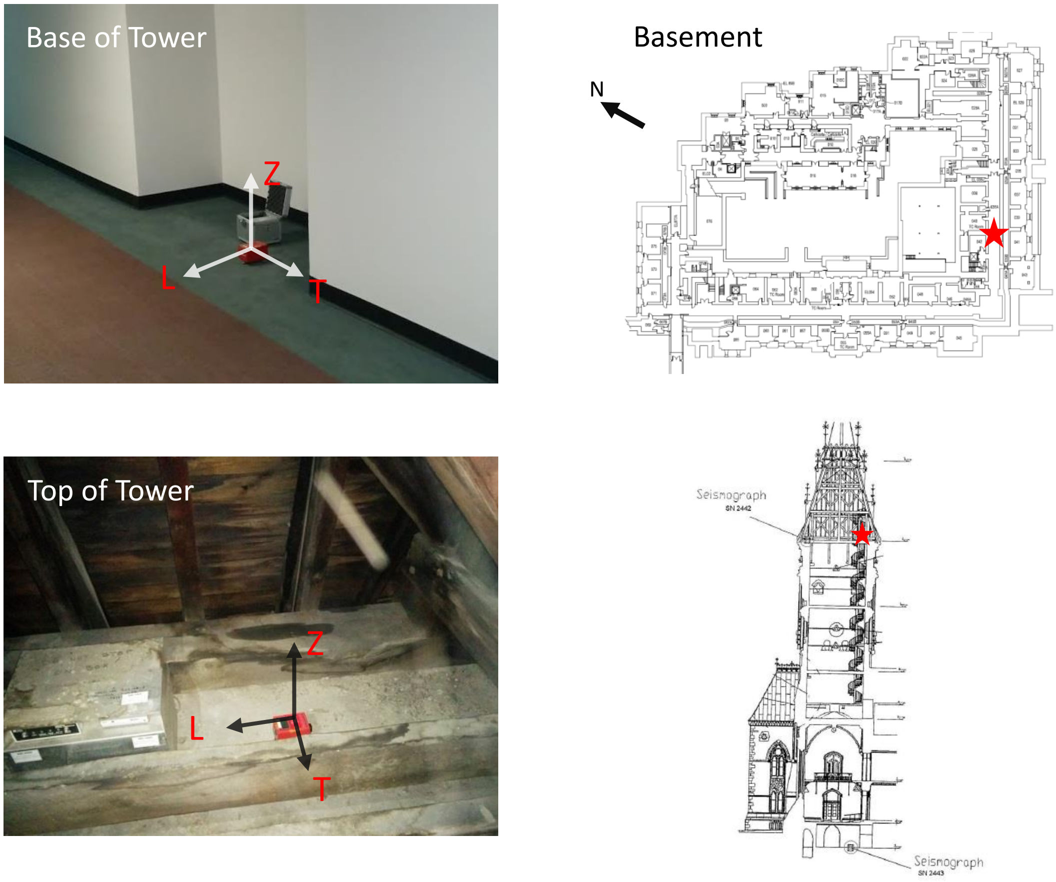

Figure 1. Locations and photographs of the South-West Tower sites. Floor plan adapted from Glazer (2016) and tower schematic adapted from Lin et al. (2011). Red stars indicate the location of the Tromino (red box). Grey box (bottom left panel) is one of the permanent seismometers which recorded the Val-des-Bois earthquake.

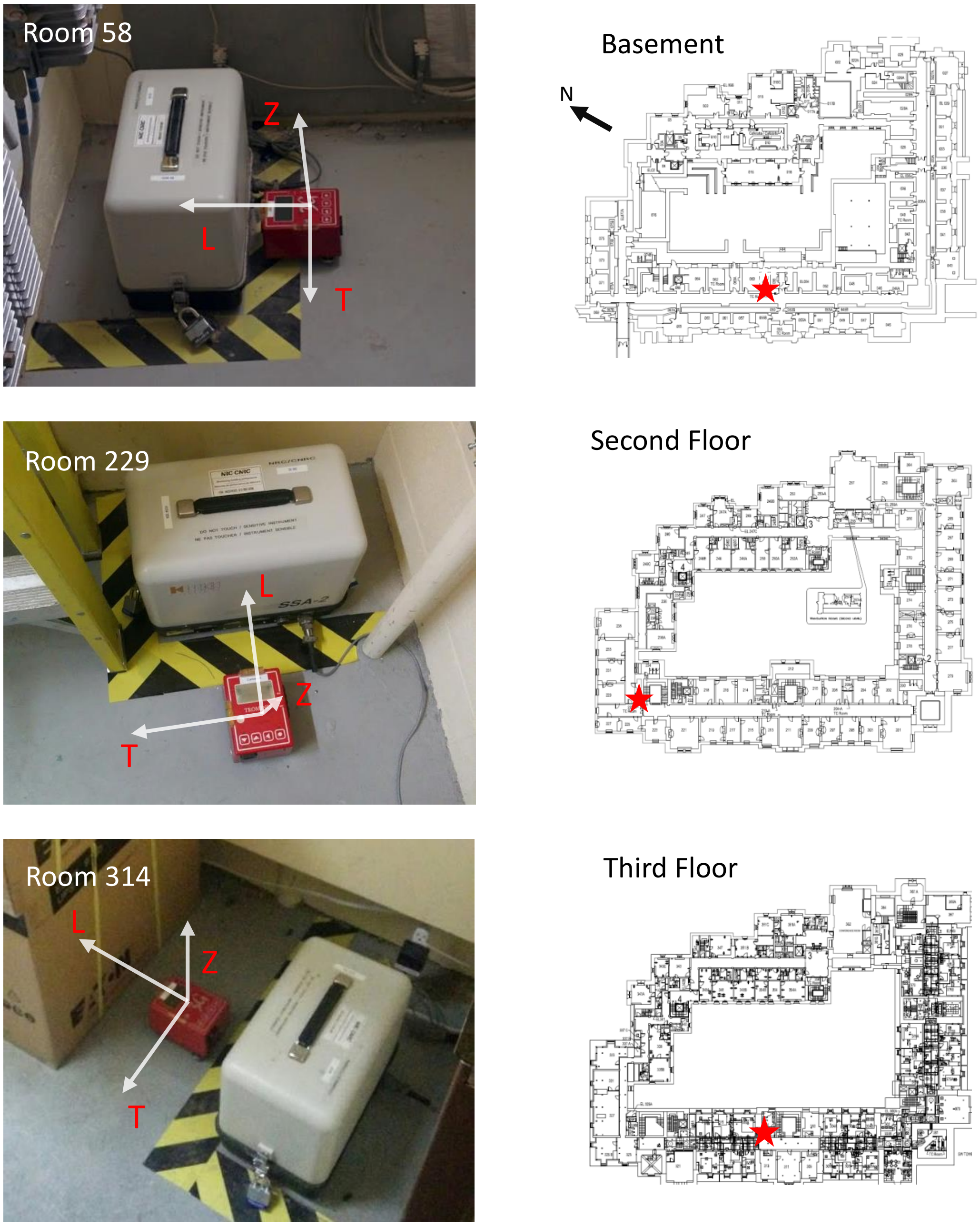

Figure 2. Locations and photographs of the west wing sites. Floor plans adapted from Glazer (2016). Red stars indicate the locations of the Tromino (red box) and the permanent strong motion seismometers (grey box).

The resultant data were processed using Micromed's Grilla software where the average spectrum of each recording was calculated using non-overlapping 30 s windows (de-trended and tapered with a Bartlett window) and a 5% triangular smoothing function. As is usual in ambient noise recordings, certain windows were excluded if the recordings were affected by local sources of intermittent noise. The average spectrum of each component was then used to calculate the HVSR and SSR. Significant high-amplitude frequencies were identified in both the HVSR and SSR plots as local maxima. The fundamental site period was interpreted as the largest peak in the range of 0.5 Hz to 10 Hz. A 10 Hz upper cut-off was used since the spectra had significant noise interference above 10 Hz, likely due to local sources (heating fans, etc.). A 30 s window provided a frequency resolution of approximately 0.03 Hz and as a result, the identified spectral peaks were rounded to three significant digits.

The M_w 5.0 Val-des-Bois earthquake data which was recorded in the South-West Tower was imported into the same software and processed identically. A 30 s non-overlapping window resulted in only two windows for the average spectra and the slightly higher sampling rate of 200 Hz provided a frequency resolution of 0.025 Hz. The Tromino was positioned adjacent to the location of the strong-motion seismometer at the top of the tower, but the basement level sensor was not located so an alternative site in the basement was selected (Figure 1).

RESULTS AND DISCUSSION

Velocity Spectra

The velocity spectrum of each site can be seen in Figure 3. The amplifying effects of the building are visible when comparing the top panel of Figure 3 with the corresponding reference site in the bottom panel. The relatively flat spectrum of the reference sites across all components suggests that there is little or no site effect in the frequency band of interest, and that the basement reference is not significantly affected by the movement of the upper floors. As such, they are likely suitable sites despite being located in the basement and not offset from the building (which would be ideal for a free-field site).

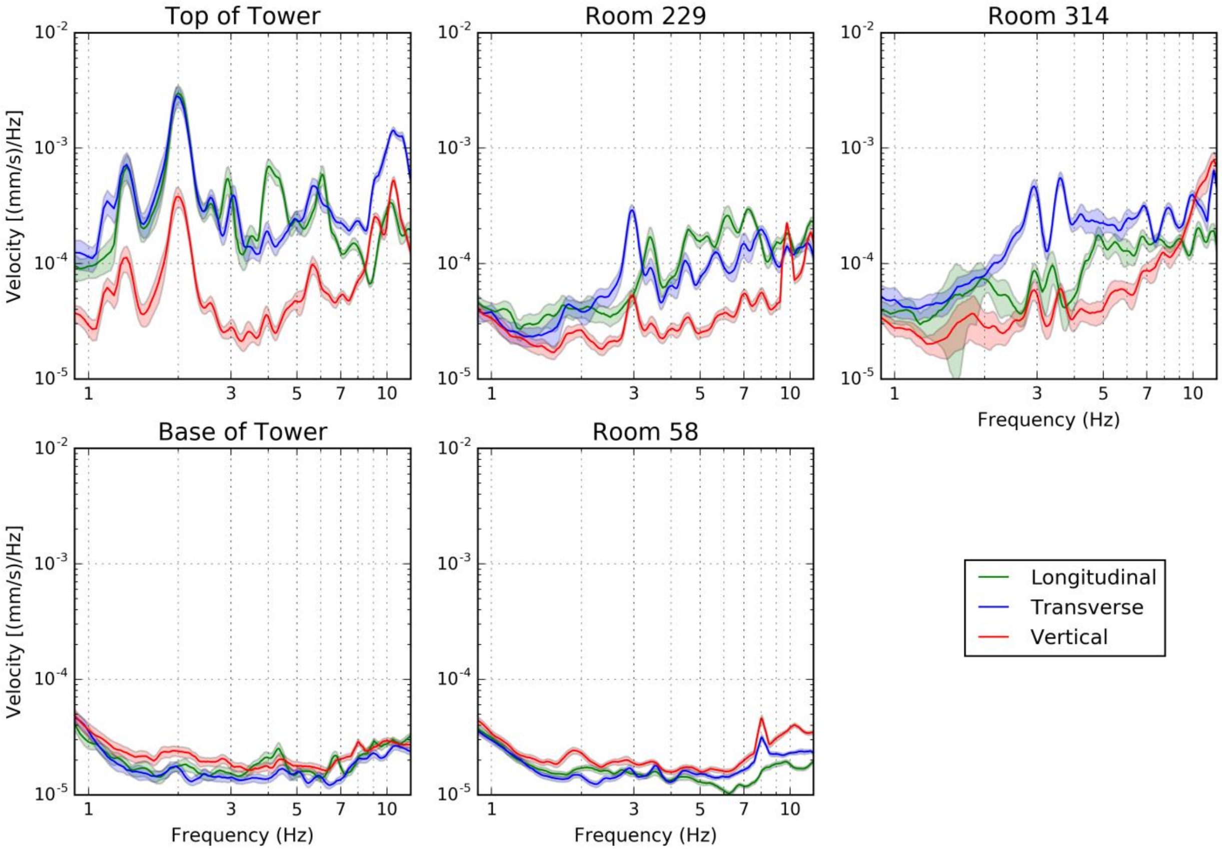

Figure 3. The velocity spectra of each occupied site. Average spectrum (solid line) and ± 1 standard deviation (shaded band) are shown.

South-West Tower

The spectral ratios for the South-West Tower can be seen in Figure 4 (SSR top panel, HVSR bottom panel) with identified peaks listed in Table 1. The SSR of the M_w 5.0 Val-des-Bois earthquake data (green lines) shows results similar to those found by Lin et al. (2011), being a large fundamental resonant peak centered at ~ 1.86 Hz with few other modes. However, the fundamental peak is at the slightly higher frequency of 2.00 Hz on the ambient noise data and the amplification factor (ratio) in the ambient noise data is 5 to 8 times larger. It is possible that this discrepancy is due to the onset of a non-linear building response from the earthquake as the peak acceleration at the top of the tower reached approximately 0.19 g (Lin et al., 2011). A non-linear effect tends to lower the natural frequency and increase the damping of the structure (Gallipoli et al., 2009; Oliveira and Navarro, 2010) which is consistent with the above findings. This hypothesis is also supported by preliminary observations which suggest that the frequency shift is largest for the windowed data which includes the strongest motions. Other potential factors which may have contributed to the discrepancy include variable environmental conditions such as the time of year (e.g., seasonal variation related to temperature) and/or wind speed. The location of the reference site was not identical to the site used in the earthquake recording, but this is not considered to be an important factor as the location of the reference site need only be in the vicinity in order to approximate the non-amplified excitation signal.

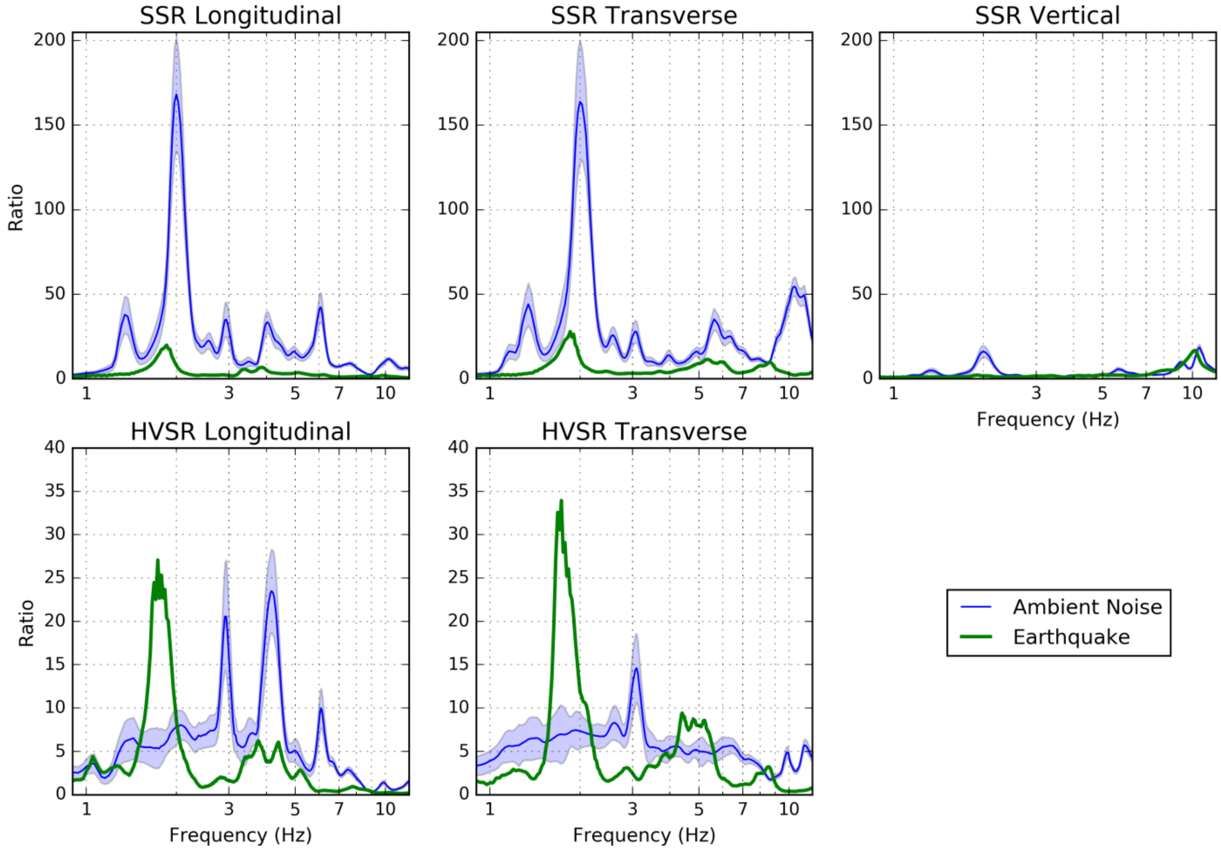

Figure 4. Spectral ratios of ambient noise and the Val-des-Bois earthquake for the South-West Tower. Standard spectral ratio (SSR, top panel) and the horizontal to vertical spectral ratio (HVSR, bottom panel) were calculated using the average spectra depicted in Figure 3. Error (shaded band) shown for the ambient noise data. Note the different amplitude scale for the SSR and HVSR data.

Table 1. Identified peaks using the SSR and HVSR techniques on ambient noise and earthquake (eq) data for the South-West Tower. Interpreted fundamental (f_0), other modes and longitudinal (L) and transverse (T) components shown. Peaks for other modes have been grouped together based on frequency.

Method	**f_0 (Hz)**		**Other modes (Hz)**											
	L	**T**	**L**	**T**	**L**	**T**	**L**	**T**	**L**	**T**	**L**	**T**	**L**	**T**
SSR	**2.00**	**2.00**	1.34	1.34	2.56	2.56	2.94	3.06	4.03	3.97	6.06	5.63	10.3	10.4
eq SSR	**1.86**	**1.86**							3.5			5.5		8.5
HVSR							2.91	3.09	4.16		6.09			
eq HVSR	**1.74**	**1.74**							4.0	4.8				

Several additional smaller peaks (Table 1, other modes) are also evident on the ambient noise data: 1.34 Hz (below the fundamental), 2.56 Hz, 2.94 Hz & 3.06 Hz, 4.03 Hz & 3.97 Hz, 6.06 Hz & 5.63 Hz, 10.25 Hz & 10.41 Hz where the “&” indicates different results on the longitudinal and transverse components, respectively. One possible interpretation is that some of frequency peaks are higher order harmonics of the significant modes (e.g., ~6 Hz peak is the first odd harmonic of the fundamental at 2 Hz). The earthquake data indicates a small contribution to higher modes with some energy centered at roughly 5.5 Hz and 8.5 Hz on the transverse component and at 3.5 Hz on the longitudinal component. However, apart from the fundamental no simple direct comparison can be made. The earthquake data may not have been able to identify these additional harmonics and modes due to the small recording length (limited by the duration of the earthquake) and/or that the earthquake did not excite the same modes.

The SSR of the vertical component shows a peak (16:1) at the fundamental of 2.00 Hz on the ambient noise data (Figure 4, panel 3). This result is unexpected, as there should be zero-to-minimal vertical amplification in a simple structure. A possible explanation is that there is a rocking mode and/or some coupling between the horizontal resonance of the tower with that of the floor which caused the floor to vibrate at a comparable frequency (and/or in a complex membrane mode, Parolai et al., 2005; Gallipoli et al., 2010). The SSR of the vertical earthquake data shows a smaller (2:1) peak at roughly 1.9 Hz which is approximately consistent with the expected difference in ratios between the earthquake and ambient noise data (factor of 5 to 8 times smaller). For both the ambient noise and earthquake data there is also a peak (~ 17:1) centered at approximately 10 Hz (slightly smaller frequency on the earthquake data).

As vertical amplification is present, the applicability of the HVSR method comes into question. Nevertheless, the HVSR for the earthquake data provides a comparable fundamental frequency (1.74 Hz) to the earthquake SSR data. However, the HVSR of the ambient noise data provides drastically different results as it lacks a strong peak at the interpreted fundamental of 2 Hz. It only identifies two similar amplitude peaks for the longitudinal component at 2.91 Hz and 4.16 Hz, and a single peak for the transverse component at 3.09 Hz. Note that these peaks approximately coincide with similar peaks identified in the SSR of the same data. The inability to identify the fundamental period using the HVSR approach can be explained by observing that the spectral shape of the fundamental peak in the vertical component is essentially identical to that of the horizontal components (Figure 3, panel 1 “Top of Tower”). It is unclear why this effect is not pronounced in the earthquake data.

West Wing

The spectral ratios for the second and third floors of the west wing can be seen in Figure 5 (SSR top panel, HVSR bottom panel). For room 229 (blue line) the first significant SSR peak is at 3.38 Hz for the longitudinal component and 2.97 Hz for the transverse component. It is important to note that for the longitudinal components the first peak is overshadowed (by a factor of 1.5 to 3) by large, broadband amplification from approximately 4 Hz to 8 Hz. This same amplification is also seen in room 314 (green line) where the longitudinal component shows a small double peak at 2.94 Hz and 3.63 Hz followed by larger amplification from roughly 4 Hz to 8 Hz. While the fundamental peaks on the transverse component of room 314 are easily identified (double peak at 2.94 Hz and 3.63 Hz) there also appears to be similar amplification in the observed spectra over a wide range of frequencies (3 Hz to 7 Hz). In contrast to the South-West Tower, the HVSR technique for the west wing correlates approximately with the same peaks as the SSR technique. However, the interpretation would likely be more difficult without the reference assistance from the SSR technique and/or analysis of the individual spectra (Figure 3) as they are, in general, not simple single isolated peaks. As with the South-West Tower there does appear to be some vertical amplification (SSR of the vertical component is not flat and is greater than 1) which has the effect of reducing the amplitude of the HVSR peaks as compared with the SSR method.

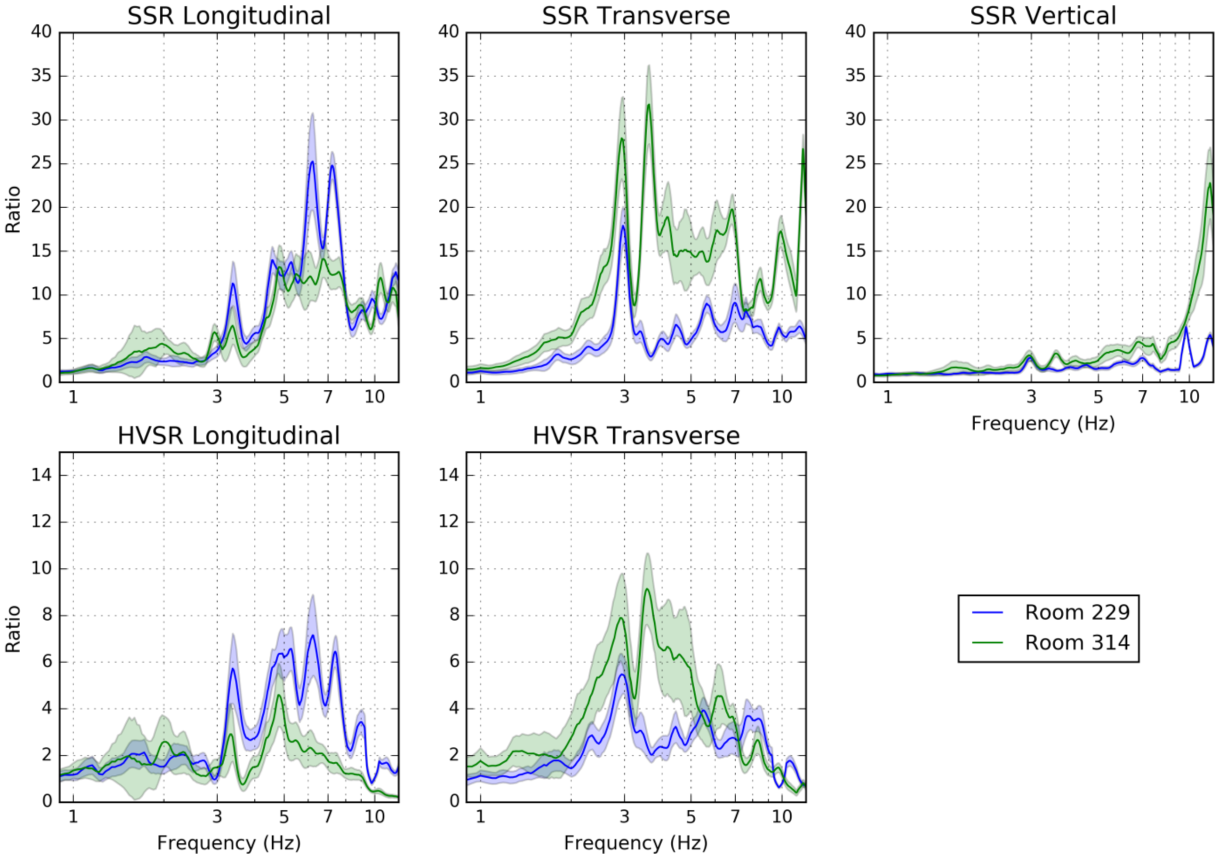

Figure 5. Spectral ratios of ambient noise for the second and third floors of the west wing. Standard spectral ratio (SSR, top panel) and the horizontal to vertical spectral ratio (HVSR, bottom panel) were calculated using the average spectra depicted in Figure 3 (error depicted with shaded band).

Despite the broadband amplification over a range of frequencies, the observations suggest that for the transverse component, the fundamental frequency is at 2.94 Hz for both rooms with an additional equally significant mode at 3.63 Hz in room 314. The origin of the double peak in room 314 is difficult to interpret with a single measurement site, but it suggests that there are two equally significant modes both acting predominantly in the transverse direction. However, this mode is not strongly observed in the transverse component of room 229 and may be due to the fact that they are located in different sections of the west wing (Figure 2; northwest corner versus western centre). Moreover, the results are also complicated by the complex multi-phase construction history of East Block where the different sections of the building may be sensitive to different vibrational modes. For the longitudinal component, there is a common peak at 3.38 Hz for both rooms but significant amplification occurs from roughly 4 to 8 Hz. Also noteworthy is that while the transverse component shows the expected relative amplification between floors (larger for higher floors), the longitudinal component has the reverse trend whereby the higher floor exhibits lower amplification.

DISCUSSION AND CONCLUSION

The present ambient noise data interpretation for the South-West Tower of the west wing has yielded approximately the same fundamental frequency (2.0 Hz) as did the analysis of the M_w 5.0 Val-des-Bois earthquake data (1.86 Hz) from Lin et al. (2011). The difference in amplification factors and slight shift in frequency may be due to the onset of a non-linear building response during the earthquake.

The ambient noise technique has revealed additional high frequency resonant peaks and variable broadband spectral amplification that should be compared with available numerical estimates from structural modeling. Specifically, it should be determined if the observed high frequency (>3 Hz) peaks as well as the broadband amplification observed in the west wing correspond to known vibrational modes.

The interpretations made in this report are based on ambient noise data collected from only three sites of interest (plus two reference sites) and future ambient noise work could focus on collecting data at several additional sites within the west wing. With multiple vertically-aligned sites, the observed variation in the spectral response of the building could be mapped with much greater detail. For instance, it is currently unknown whether the double peak present in room 314 is a vibrational feature characteristic of the room, or a larger feature of the third floor and/or centre of the west wing. Future work can also be done to estimate the variation in the broad-band spectral amplification throughout the building, resonant peak modal shapes, and building damping, using ambient noise processing techniques.

In this work, the SSR technique was found to be more reliable than the HVSR technique in identifying the dominant peaks in the spectra, particularly in the South-West Tower. This was likely due to the presence of vertical amplification at the sites, hypothesized to be caused by coupling between the horizontal vibrational modes with that of the floor which caused it to vibrate at a comparable frequency (and/or in a complex membrane mode). If this is the cause of the vertical amplification, then it should be possible to reduce its effect by placing the portable sensors even closer to vertical load bearing structural elements at all survey sites. By placing multiple sensors at different parts of the room, it should also be possible to confirm the floor resonance effect.

For this study we used the SSR method with a reference located in the basement of the building. Although no visible site or building effect was observed in their spectral responses (Figure 3), a free-space site on bedrock away from the structure may be warranted if additional detailed surveying is to be performed. Moreover, while the measurements were taken synchronously, the SSR data were not processed synchronously, as different windows were used. This may be required for future work in which modal shapes are to be estimated.

An ambient noise survey such as the one performed in this work is a low-cost approach for documenting the dominant dynamic properties of a structure in the linear domain. If future remedial work is undertaken in other parts of Parliament Hill, such as the Centre Block, it is recommended that a detailed ambient noise survey be conducted before and after any major construction, such as seismic retrofitting, to experimentally assess change in the building's dynamic properties.

ACKNOWLEDGEMENTS

The authors would like to thank Heather Crow, Danielle Luesby and Myles McDevitt for their assistance with the logistics and planning of the ambient noise data collection and Carleton University for the use of their Trominos.

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