The 11th Canadian Conference on Earthquake Engineering

Canadian Association for Earthquake Engineering

STUDIES OF WEAK GROUND MOTION RECORDINGS OVER SOFT SEDIMENT FILLED BASINS IN OTTAWA, ONTARIO

Sylvia HAYEK

Carleton University, Ottawa, ON, Canada
SylviaHayek@cmail.carleton.ca

James HUNTER

Dr., Geological Survey of Canada, Canada
James.Hunter@nrcan-rncan.gc.ca

Dariush MOTAZEDIAN

Carleton University, Ottawa, ON, Canada
Dariush.Motazedian@carleton.ca

Pascal AUDET

University of Ottawa, Canada
pascal.audet@uottawa.ca

Stephen CRANE

Carleton University, Ottawa, ON, Canada
StephenCrane@cmail.carleton.ca

ABSTRACT:

Recordings from local weak motion (M3-5) earthquakes were studied over a soft-sediment filled basin in the Ottawa region to determine the effects of the two- and three-dimensional bedrock topography on the ground motions at the surface using a pair of seismographs installed over the basin, and on nearby bedrock.

Given the high contrast between the shear wave velocity of the soft sediment (~180m/s) and the underlying bedrock (~2700m/s), the predicted site amplification due to impedance (1-D effect) is calculated to be five times that of the nearby rock site. However, the recorded amplification in the sediment-filled basin, which was mainly horizontal, was often greater than 40 times. There is an extended duration of surface wave recordings at the soil site, whereas the bedrock site recorded no surface waves from these local weak motion events.

We investigated the particle motion of the horizontal records over the Orleans basin to look for preferred directions in the incoming energy, which might indicate the influence of multi-dimensional effects. No orientation or predictable pattern was apparent in relation to the earthquake azimuth and hence the generated surface waves must be controlled mainly by the basin not the azimuth of the earthquakes.

1. Introduction

Several soft-sediment filled basins have been discovered in the Ottawa-Montreal region of Canada. Ongoing studies are examining whether the ground motion amplification from an earthquake as recorded over these buried basins can be explained by impedance alone or whether two- and three-dimensional effects, such as resonance, focussing (and defocussing) and basin-edge effects, add to the ground motion recorded at these sites.

In order to identify the contribution of 3D effects on ground motions on the basin we studied the recordings of a pair of stations: one sited on the Orleans basin, located in the east end of the city of Ottawa, and the second on nearby bedrock. We looked at both the frequency content and the particle motion of the recordings to determine the amount of amplification and if the azimuth of the recorded particle motions on the soil site are oriented as expected with respect to the source, as they are on the rock site.

2. Background

The existence of site effects has been known for many years, but was brought to the forefront after the 1985 Michoacan Mexico earthquake, which caused great damage within Mexico City despite the epicentre being approximately 400 km away (Singh et al., 1988).

In general, known site effects are impedance, resonance, focusing/defocusing and basin edge effects (Hunter et al., 2010). The one-dimensional impedance effect is theoretically the easiest to quantify. The equation defined by Shearer and Orcutt (1987) to calculate the amplification due to impedance, not taking attenuation into account, is:

$$A_{imp} = \sqrt{\frac{\rho_{rock} Vs_{rock}}{\rho_{soil} Vs_{soil}}}, \qquad (1)$$

where ρ is density and *Vs* is the shear wave velocity, respectively, of the rock or soil. This equation works well for regions where the density and shear wave velocity of the soil and bedrock are known, without drastic changes in the properties of soil and rock. When there is a large contrast between shear wave velocities of soil and bedrock then the following equation, which represent the resonance amplification (Shearer and Orcutt, 1987), is more applicable.

$$A_{res} = \frac{\rho_{rock} Vs_{rock}}{\rho_{soil} Vs_{soil}} \qquad (2)$$

Numerous studies done in recent years using numerical modelling have shown the importance of 3D effects, including work by Bard and Bouchon (1980a, 1980b, 1985), Kawase (1996), Olsen (2000) and Semblat et al. (2005). These studies have demonstrated the importance of basin geometry and material properties. However, there have been much fewer field experiments designed to actively gather and analyze ground motions over basins.

Cornou and Bard (2003) showed that the amplification recorded over an alpine valley in Grenoble, France was significantly higher than expected from 1-D modelling, particularly at and above the fundamental frequency of the basin. Hence, they argued that all amplification exceeding the expected value was likely due to the 2- and 3-D effects of the basin. Using Shearer and Orcutt's equation (see equation 1) for the rock and soil at our site, for the Ottawa region we would expect to see around 5 times amplification of the soil site over the adjacent rock site due to impedance. However, as the soil to bedrock contrast is quite large in the Ottawa region, the equation for resonance (equation 2) is likely more appropriate, which predicts we'll see approximately 25 times amplification of the soil site over the rock for this basin.

Experiments on the Texcoco basin in Mexico City (Stephenson et al., 2006) and the Parkway basin in New Zealand (Chávez-García et al., 2002) used an array of seismograph stations to show how the direction of the seismic waves crossing the basin were controlled by the basin geometry, rather than the azimuth of the earthquake. It was noted that this was easier to accomplish on the larger basins, as the reverberations from either side of the basin quickly overwhelmed the recordings, making any directional analysis much more difficult if not impossible (Stephenson et al., 2006). For the current study, only data from a station pair is available: a soil site located approximately at the centre of the basin and a nearby bedrock site, used as a reference. Hence, we begin by examining the particle motion for indications of the origin of the long duration soil recordings.

3. Setting

The Orleans basin is located along the south-western edge of the west Quebec seismic zone in the east end of the city of Ottawa. It was instrumented with a pair of identical weak motion seismometers, one instrument being located over the deepest portion of the basin (ORHO, installed in 2007), while the other is located on a nearby rock site (ORIO, installed in 2008). Both stations were closed in the fall of 2013 (see Figure 1).

The basin is roughly an elongated bowl-shaped (see region filled in red in Fig.1a), with steep sides and oriented SW to NE, with a shallow extension to the east (Motazedian et al., 2011). The basin is in-filled with 83 m of sensitive clay, which has been found to have a shear wave velocity (Vs) of less than 180 m/s (Hunter et al., 2007). Fig. 1b shows shear wave velocities in the top 30 m from a borehole located near the soil seismograph site average ~110m/s, but the Vs increases with depth to approximately 300 m/s near the bottom of the layer. In some places the clay is underlain by a thin layer of glacial till, approximately 10 metres thick at the soil seismograph site, which has a mean shear wave interval velocity estimated to be 580 m/s. These rather low velocities are in contrast with the high velocity of the underlying Paleozoic sediments and Precambrian rock, which have a Vs of ~ 2700 m/s (Motazedian et al., 2011). A horizontal versus spectral ratio (HVSR) reading was taken with a Tromino instrument 600 m from the seismograph site, which showed a fundamental frequency of ~0.78 Hz (see Figure 2).

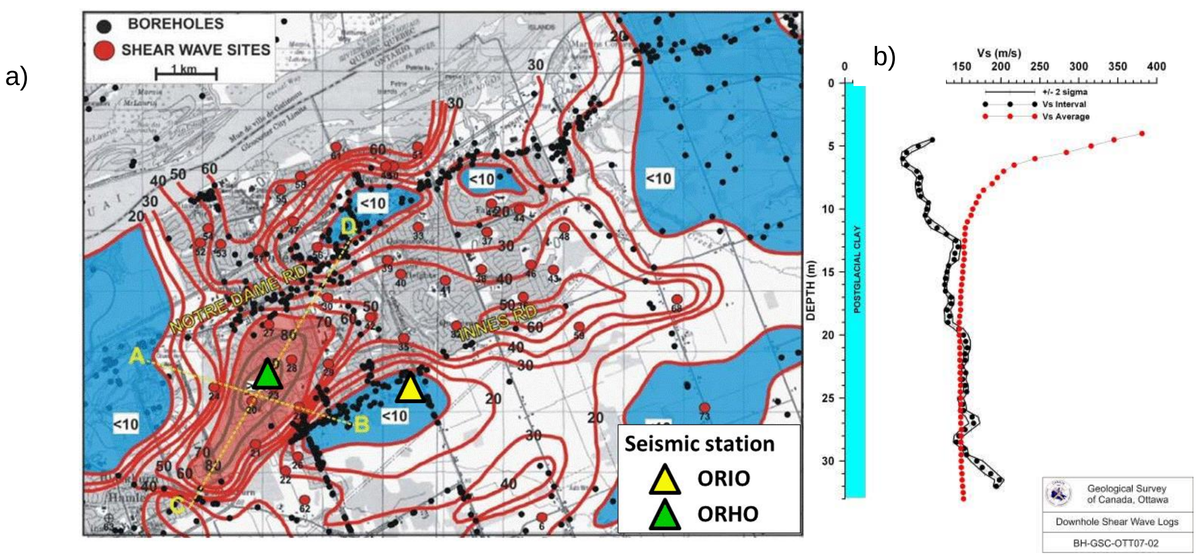

Fig. 1 – a) Map of Orleans basin with blue areas corresponding to bedrock or <10m of soil, and red contour lines showing 10 m intervals for soil depth (after Motazedian and Hunter, 2008). Approximate locations of seismic stations added as triangles. b) Shear wave data (Vs in m/s) collected down to 30 m at a borehole located within the basin. 1m Vs interval data shown in black line; 0.5 m Vs average data shown in red; geological profile in blue.

4. Observed soil amplifications

The data from 11 local earthquakes (see Table 1) recorded on the seismograph station pair were examined to identify the events with the highest signal to noise ratio. The amplification spectral ratio between soil and rock recordings were calculated for these events using 60 s of data (from the onset of shear) to determine the amplitude and frequency content of the soil site as compared to the rock site. The data was selected to ensure that the signal was well above the noise for the entire duration used, and included the shear, and in the case of the soil recordings, surface wave portions of the recording.

From equations 1 and 2, the expected amplification of the soil site due to impedance is around 5 times and 25 times, respectively, that of the nearby rock site. However, the actual amplifications recorded on the horizontals for local, weak motion earthquakes are often 40 times or more, particularly at the fundamental frequency of ~0.8 Hz. The geological information from Section 3 was used to create a soil profile, which was entered into a one-dimensional (1D) ground response analysis program to estimate the expected one-dimensional amplification at this site. Results are plotted in Figure 2, along with the HSVR data, and the amplification recorded from actual earthquake data. (Note that the HSVR and modelled 1D amplification were multiplied by 10 to make it easier to compare the frequency content to the earthquake records).

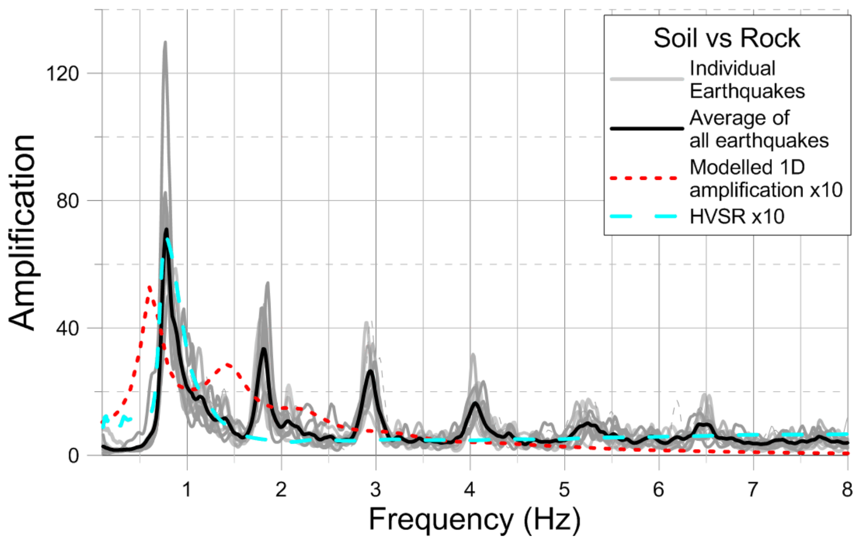

Fig. 2 – Transfer functions calculated from earthquake recordings of 11 earthquakes (in gray) as recorded on the horizontal components of ORHO (soil site) versus ORIO (rock site) using 60 s of data starting at the onset of the shear, as well as the average of those readings (in black). Dashed red line shows the modelled 1D amplification multiplied by 10. Dashed blue line shows the recorded HVSR multiplied by 10, using 30 minutes of recorded noise 600 m from the ORHO.

Table 1: List of earthquakes used to calculate the amplifications in Fig. 2

	Date.time (UT)	Mag (m_N)	Dist. (km)	Azim	Location
1	20131020.1040	3.6	150	96°	Barry's Bay, ON
2	20130530.0534	3.7	71	117°	Ladysmith, QC
3	20130517.1353	4.1	71	117°	Ladysmith, QC
4	20130517.1343	5.2	71	116°	Ladysmith, QC
5	20130116.0053	3.5	68	186°	Val-des-Bois, QC
6	20121212.1746	4.4	494	240°	La Malbaie, QC
7	20121106.0905	4.2	76	258°	Hawkesbury, ON
8	20121010.0419	4.5	177	262°	Vercheres, QC
9	20120204.0917	3.6	173	152°	Maniwaki, QC
10	20120122.0559	3.6	102	201°	L'Annonciation, QC
11	20110316.1736	4.3	78	260°	Hawkesbury, ON

Like Cornou and Bard (2003), we found no significant amplification below the fundamental frequency (f_0) of the basin (~0.8 Hz). Amplification tends to be highest at f_0, with additional peaks at various higher frequencies (probably higher modes), generally of lower amplitude with the increase in frequency (see Figure 2). Note, however, that the 1D modelled results are much, much lower in amplitude (were multiplied by 10 in Fig. 2 in order to easily compare the data with the earthquake recordings), with a maximum of approximately 5 times amplification at f_0. According to Cornou and Bard (2003), the additional amplification must therefore be due to 2- and 3D effects from the basin.

Also, the frequency at which the modelling assigns f_0 (and the following 1st harmonic) is slightly lower than the recordings, although this could be due to any of the assumptions used in the modelling, including the Vs, bulk unit density and thickness of layers, as well as the damping ratio and modulus reduction curves used.

5. Seismic particle motions

In order to determine if any of the additional seismic energy recorded over the basin is being converted by the basin edge, we examined the horizontal particle motion recorded on the soil site. For motion controlled by the earthquake source, we would expect the motion to be in close agreement with the azimuth of the earthquake from the station. However, if the waves are a result of being converted or generated at the basin edge, then the azimuth of the particle motion should be reasonably consistent from earthquake to earthquake, regardless of the direction of the source.

To examine this, the direction and amplitude of particle motion was calculated along the time-series. As the events being investigated are local, weak motion events, they are rich in high frequency. This makes the direction of the particle motion chaotic and difficult to interpret. Hence, the direction data was then binned in 10° azimuth bins and 2 second time-slice bins with 20% overlap, and plotted along with the time series underneath, much like a spectrogram. The values for both the bins and overlap were selected after testing various values. It was found that these values allowed for enough data to be collected within each bin while not smearing the end results. It was noted that for signals with a lower frequency content (e.g. regional or teleseismic data), the time-slice and/or the overlap should be increased to give better results. A second plot weighted by amplitude was also produced. This was done for both the soil and the reference rock site, and the results compared.

We repeat the procedure outlined above for the data bandpass filtered from 0.3 Hz to 5 Hz, which helps reduce the random chatter of the higher frequencies, as well as the bias created for low amplitude data from the low frequency; and then again for several narrow bandpass filters. The frequencies chosen were the ones that showed the highest amplifications in the calculated transfer functions for the earthquakes examined (see Figure 2), and likely represent the fundamental frequency (f_0) and the three higher harmonics (1st, 2nd and 3rd): 0.8 Hz ±0.3 Hz, 1.8 Hz ±0.3 Hz, 2.9 Hz ±0.3 Hz, and 4.1 Hz ±0.5 Hz.

Converting the data to displacement before plotting the results did not generally improve the resolution of the results. In fact, for the smaller events and unfiltered data, the quality of the displacement plots was significantly poorer. Hence, velocity plots were used for most of the analysis.

It was noted that when plotting just noise, the plots mostly showed random patterns. However, occasionally a preferred azimuth could also be detected. This tended to occur more on the soil site than the rock, and was not always consistent across the different frequency bands. As the stations are located within the residential area, it is probable that these occasional patterns were due to local noise, or perhaps a more distant background low frequency signal. However, the pattern from the noise is quickly overcome when an actual earthquake signal is present. Hence, as long as there is good signal to noise ratio, this background noise should not influence the results.

No pattern was obvious on the unfiltered data due to the high frequency scatter. However, preferred azimuths appear in the filtered data (see Figure 3). The amplitude-weighted data help to bring out details in some of the more energetic arrivals (i.e. the S wave arrival, and some later energy bursts). This technique performed best on earthquakes with magnitudes of around M3.5 and greater within the west Quebec seismic zone.

As expected, on the rock site (ORIO) the plot of azimuths clearly shows a direction along the azimuth/backazimuth for the P arrivals (at around 10s in Figure 3) while the S arrivals (at around 20s) appear perpendicular to it. In general, there is no further strong azimuthal preference after the S arrival (see Figure 3).

In contrast, azimuthal plots for the soil site (ORHO) show P-wave arrivals that almost never align with that of the earthquake, and in some cases are shifted a full 90°, as seen for the P phase arrival in Figure 4 at around 16s. For the S wave arrivals (early high amplitude arrivals 25-32s) in Fig. 4, the direction of motion occurs at the earthquake azimuth (at 24-28s) and then drifts or migrates towards perpendicular directions (28-36s), possibly due to the arrival of surface waves combining with the shear wave. This drifting causes the arrival to be smeared over several azimuthal bins, making the actual angle of arrival difficult to determine. This occurred even within the P phase of some events, generally the more distant ones where there is more time before the arrival of the shear phase. When the same data is filtered around the fundamental frequency (see Figure 5), the initial P phase arrival is clearer, but S wave arrivals appear weaker, with the rolling of the particle motion from one azimuth to another appearing more pronounced and of longer duration.

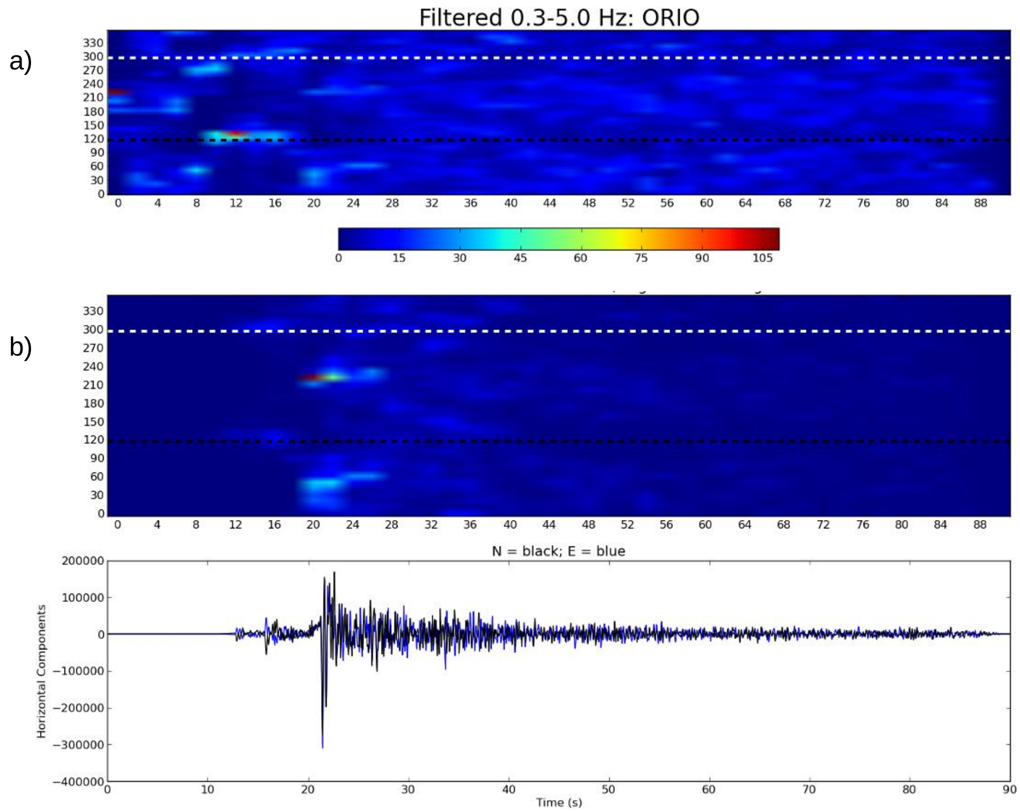

Fig. 3 - Particle motion analysis versus time for the bedrock site ORIO, showing the azimuth (black horizontal dashed line) and the backazimuth (white dashed line) for the 2013/05/17 m_N 5.2 Ladysmith, QC earthquake: a) broadband filtered from 0.3 – 5.0 Hz; and b) same filter but number of counts in bin multiplied by the amplitude; the two horizontal components (north-south = black; east-west = blue) are shown below at the same time scale for reference.

The data filtered around a narrow frequency band tend to have much cleaner arrivals and much less variation of azimuths along the time series. Often filters centred around the 1st and 2nd harmonics show the clearest particle motions associated with arrivals for most events. The filter centred around f_0 often showed the azimuth of the particle motion rolling back and forth, as see in Figure 5, except for the 2012/10/10 M4.5 Vercheres earthquake where, for the soil site, the particle motions analysed with this filter had a nearly constant direction of motion for both the P and S wave arrivals. The P wave showed azimuths just slightly shifted from the direction of the earthquake, and the S wave arrivals showed orientations perpendicular to that of the P wave. Note, however, that this result was not typical for any of the other earthquakes analysed.

Note that the recorded azimuths for one particular earthquake and arriving phase did not always match between the different frequency bands. That is to say the particle motion recorded for the P phase when using a filter around the fundamental frequency could be different than that recorded when filtering around the 1st or 2nd harmonic.

Even events from the same epicentral region (similar backazimuth and distance to source) do not show consistent results. Figure 6 shows three events from the same azimuth: M4.3 2011/03/16 Hawkesbury, M4.5 2012/10/10 Vercheres, and M4.2 2012/11/06 Hawkesbury. Although there is some consistency for the P arrival on all three events, the first Hawkesbury event has a completely different azimuth for the S phases. The second Hawkesbury event and the Vercheres event are more consistent with each other, despite being at different epicentral distances.

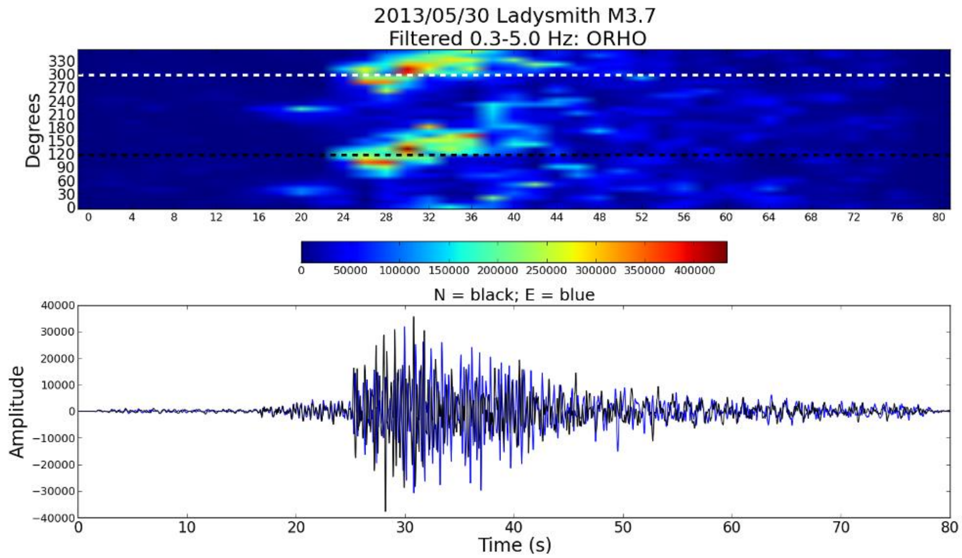

Fig. 4 - Particle motion with respect to time for the soil site ORHO (dashed black line representing the event azimuth; backazimuth in white) for the 2013/05/30 m_N 3.7 Ladysmith, QC earthquake. The data is filtered from 0.3-5.0 Hz and weighted by amplitude.

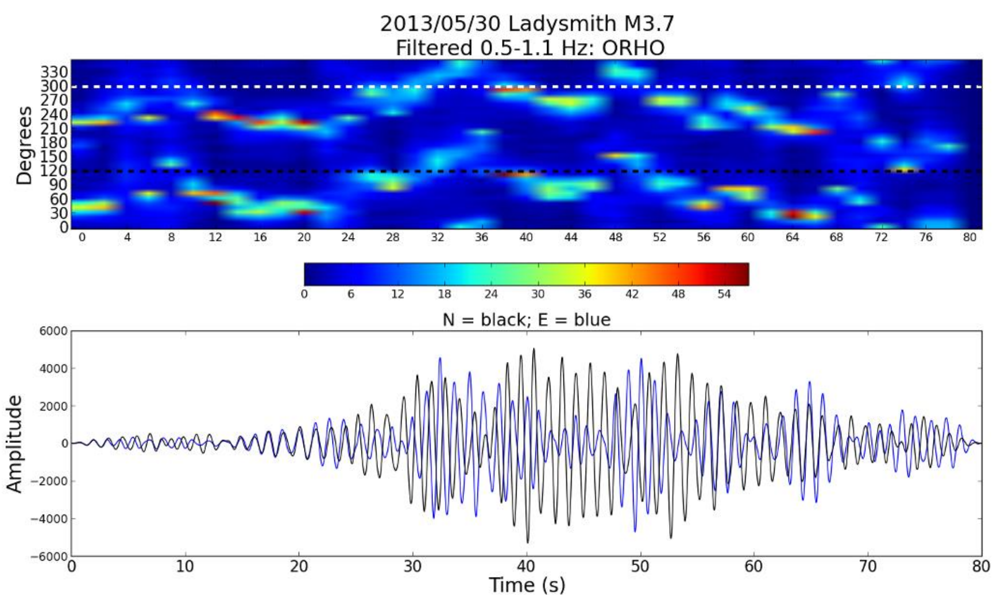

Fig. 5 - Particle motion analysis with respect to time for the soil site ORHO (event azimuth in black, backazimuth in white) for the 2013/05/30 m_N 3.7 Ladysmith, QC earthquake, with data filtered around the fundamental frequency (0.8 ± 0.3 Hz) of the basin.

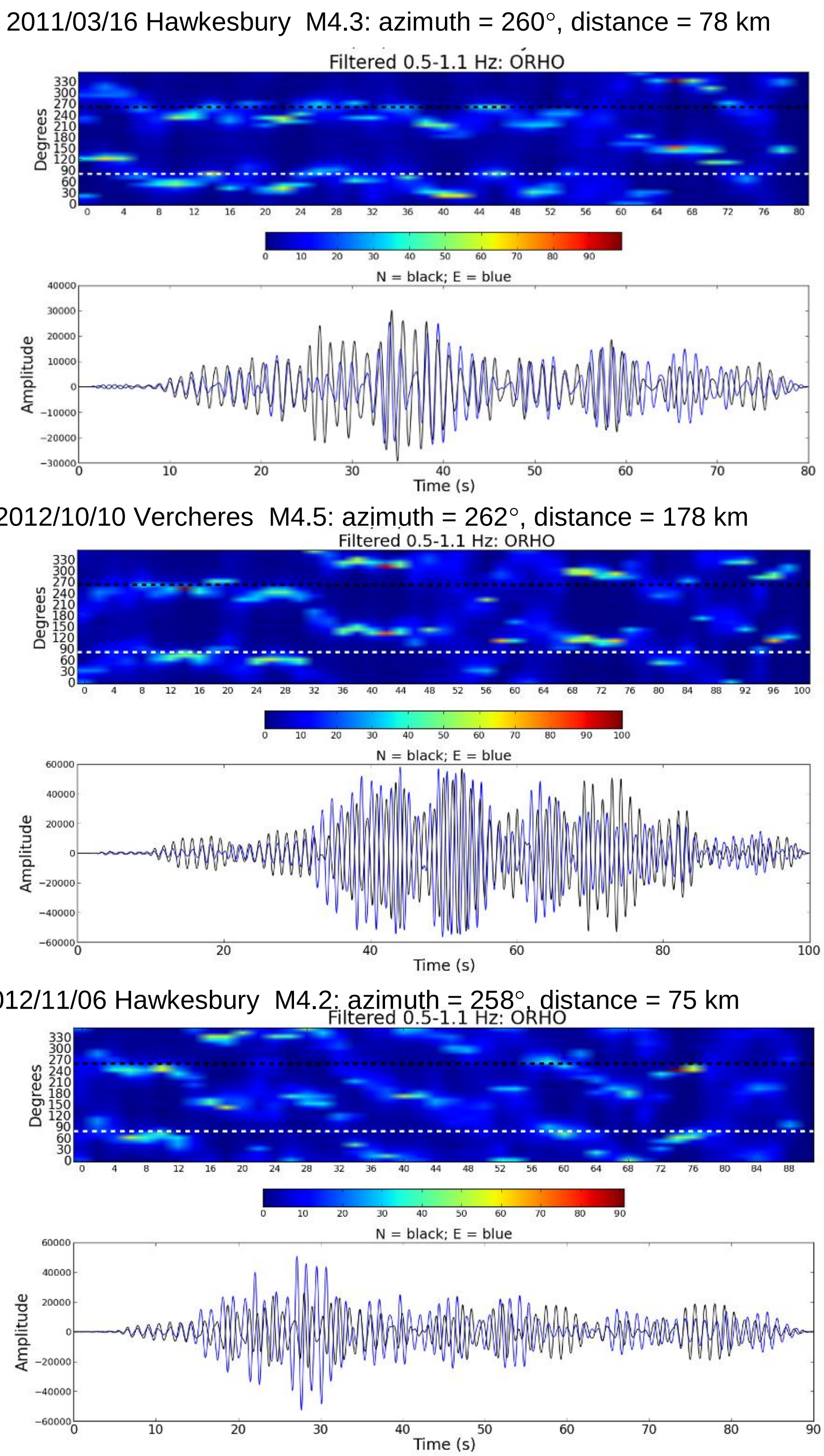

Fig. 6 - Particle motion analysis on soil site ORHO for three earthquakes from similar azimuths, narrowband filtered around the fundamental frequency from 0.5 – 1.1 Hz.

6. Interpretation

The soil profile at the site shows a varying shear wave velocity at depth (see Figure 1b). Hence, the value of Vs to be used in equations 1 or 2 is not straightforward. However, even using a range of possible Vs values, the expected amplification due to impedance and resonance is still well below that of what is actually recorded. Hence, it is probable that 2- and 3-D effects play a role in the recorded site effects. The amplification is greatest at the fundamental frequency, with additional amplification peaks at the higher harmonics. No significant amplification was noted below the fundamental frequency.

The particle motions for the P and S phase are as predicted on the nearby rock site. However, over the basin, the P and S arrivals are seemingly random. The reason for this is unclear, but as both ORIO and ORHO are processed in the same manner, processing errors can be ruled out. A systems error, such as the components being accidently mis-named or switched, was also ruled out as the calculated predominant angles are not off by a consistent angle. This was confirmed by Dr. Allison Bent of Natural Resources Canada (email communication, 2014), who had found no issues with this station during her checks of the network stations. Hence, the variation in the arrival azimuths must be due to the presence of the 3D geometry from the basin.

The azimuths of the particle motion do not seem to be related to the earthquake itself. There is no relation or systematic offset from the direction of the earthquake to the recorded incoming phases. As events similar in magnitude, azimuth and distance produced different resulting plots, frequency content, radiation pattern and/or other source parametres could play a role in the final effect of the basin on the redirecting of the energy, as evidenced by the events shown in Figure 6. However, lack of data (number of events, and information on their focal mechanisms) does not allow us to come to any definite conclusion.

The reduction of the drifting effect in the narrow band filtered data versus the more broadly filtered data suggests that the wandering and smearing of arrivals may be due to waves of various frequencies each being affected differently by the basin.

The occasional variation of particle motion azimuth for a phase from a particular earthquake filtered at different narrow bandpasses, also suggest that the initial frequency content of the earthquake may play a role in how the basin affects the final ground motion at the soil site. Plots from more distant events often showed the migrating of direction of motion occurring several seconds into the P phase already.

7. Discussion

The initial focus of this study was to determine whether the basin played a role in the recorded ground motions. Although it was determined that the amplification appears to be well over what would normally be calculated for just impedance (1-D) alone, the examination of the particle motions could not constrain any preferred orientations of surface waves that would be related to the basin geometry. However, it should be noted that the shape of the basin is somewhat complicated and small in size, which may play a role in the lack of obvious relation between the ground motions, with possible reflections at basin edges from multiple directions.

The particle motion of the soil site recording also did not seem to be related to the azimuth of the earthquake, unlike the nearby rock site that clearly showed expected particle motions for both the P and S phases. Hence, although not predictable or repeatable, the basin is nonetheless affecting the resulting direction of the particle motions.

Filtering the data at several narrow band frequencies helped to isolate the motions of various frequencies, but did not help determine any pattern to the data with respect to either the earthquake location or local geometry.

As only one station is available, the difference between the azimuth and backazimuth cannot be sorted out using this method of displaying the recorded motion. This is not a problem on the rock site on which the motions are oriented as expected, or even on the soil site when the angle is not too far removed from the original (as the wave is unlikely to be travelling from the far end of the basin back to the source). However, at more extreme deviations, it becomes impossible to decipher which angle is the azimuth of the motion, which only further confuses any interpretation of a possible pattern. The installation of an array would eliminate this ambiguity and allow one to track the coherent energy across the basin.

Two other basins have also been instrumented with station pairs, and one has since been upgraded to a six-station array (see Crane et al., 2015). In the future, the data from these basins will also be analyzed and compared with the results from Orleans. However, neither basin has been instrumented as long as the Orleans basin was, and it will therefore take time to collect a significant number of events with sufficient signal to noise with which to do this type of analysis.

8. Acknowledgements

The authors would like to thank the reviewer for the helpful comments and suggestions, and also to acknowledge the Canadian Hazards Information Service, Natural Resources Canada for collecting and making available the data from ORIO and ORHO as part of the Canadian National Seismograph Network.

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