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Investigation of Soil Amplification Factors for the Ottawa Area.

Part I - Fa

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ABSTRACT: One-dimensional soil modelling using the finite element method was carried out based on a the region-specific shear wave velocity-depth profile, damping and shear modulus reduction curves for Leda clay and seismicity features in Eastern Canada, specifically the Ottawa area, in order to investigate soil amplification factors and compare them with those of the Fraser Delta, an example from Western Canada. The model-based soil amplification factors were calculated for both study areas, and the ratios of amplification factors for the Ottawa area to those of the Fraser Delta were considered as representative for high frequency correction amplification factors.

1. Introduction

The soil amplification factors given for different soil categories, different levels of shaking intensity and frequencies in the 2010 National Building Code of Canada (NBCC, 2010) were based on two main studies for the development of intensity and frequency-dependent foundation (amplification) factors: 1) the Borcherdt approach (1994), and 2) the National Earthquake Hazard Reduction Program (NEHRP, 1994) approach. In both approaches the time-averaged shear wave velocity in the top 30 metres (Vs_{30}) is used as representative of the site condition. Vs_{30} is defined as $Vs_{30} = 30/(\sum h_i/Vs_i)$, where, Vs_i and h_i denote the shear wave velocity and the thickness of the i^{th} layer to a depth of 30 m. Borcherdt correlated the amplification factors for low and high frequency ranges to Vs_{30} values and obtained two functional forms for high (5 Hz or 0.2 s) and low frequency (1 Hz or 1 s) ranges given by $F_v = (1050/ Vs_{30})^{mv}$ and $F_a = (1050/ Vs_{30})^{ma}$, F_v and F_a are the amplification factors for low and high frequency ranges, respectively: 1050 m/s is the average shear wave velocity for bedrock (Franciscan bedrock in California), m_a and m_v are coefficients obtained from the best fit to the observed data in F_a and F_v equations. In the NEHRP approach, F_v and F_a were defined for frequency ranges of 0.5 to 2.5 Hz and 2 to 10 Hz, respectively, and for a specific shaking intensity. F_v and F_a were derived using real or mapped input ground motion data from the records of Loma Prieta earthquake.

The Canadian Committee on Earthquake Engineering (CANCEE) adopted the NEHRP provisions for site classification in the 2005 and 2010 NBCCs. The NBCC F_v and F_a are similar to those of the NEHRP approach with minor modifications: site class C is the reference site with an amplification factor of 1 in the 2005 and 2010 NBCCs, whereas the reference site is site class B in the NEHRP method (1994). In NBCC (2005 and 2010) and Finn and Wightman (2003), the foundation factors are given for F_a of spectral accelerations (indicated as S_1). Table 1 shows different site classes for F_a based on the NEHRP approach for the 2005 and 2010 NBCCs. For site class F, site-specific investigation and dynamic site response analysis are required. It should be added that for 2015 NBCC it is proposed to change Fv and F_a with values for each spectral period at 0.2 s, 0.5 s, 1.0 s, and 2.0 s (Gail Atkinson and John Adams, personal communication).

Table 1. Values of F_a as a function of site class and spectral accelerations at 0.2 s period (NRC, 2005). (1) Site-specific investigation and dynamic site response analysis are required.

Site Class	Values of F_a (NRC, 2005)				
	$S_a(0.2)<=0.25$	$S_a(0.2)=0.50$	$S_a(0.2)=0.75$	$S_a(0.2)=1.00$	$S_a(0.2)=1.25$
A	0.7	0.7	0.8	0.8	0.8
B	0.8	0.8	0.9	1.0	1.0
C	1.0	1.0	1.0	1.0	1.0
D	1.3	1.2	1.1	1.1	1.0
E	2.1	1.4	1.1	0.9	0.9
F	(1)	(1)	(1)	(1)	(1)

It should be noted that the amplification factors provided in the 2005 and 2010 NBCCs by Finn and Wightman (2003) were based on studies for a typical soil layer with a gradational velocity increase with depth in western North America with shear wave velocities (Vs) of a few hundred m/s over the typical bedrock formation with Vs ~1,050 m/s. Cities in Eastern Canada, such as Ottawa, are mainly located on loose postglacial sediments withVs~150 m/s) overlying a very hard bedrock with Vs ~2,700 m/s). The typical shear wave velocity contrast between the bedrock and the soil of Eastern Canada is ~20, which is much higher than the contrast of 3 to 5 in California or some of Western Canada. It should be added that there is trend that Vs_{30} may not be a good index parameter for Eastern Canada, and the site amplification factors should be based on fundamental site period.

The high shear wave velocity contrast has an influence on seismic soil amplification factors and, consequently, on seismic hazard and risk evaluations in Eastern Canada. Furthermore, sparse earthquake recordings in the linear range of soil behaviour from the Ottawa region show that the soil amplification is large (>40) relative to the typical amplification factors being used in geotechnical practice (Crow, 2010; Hunter et al., 2010; Khaheshi Banab, 2010; Khaheshi Banab and Motazedian, 2010; Motazedian et al., 2011). This unusually high soil amplification, which is mainly due to the linear behaviour and the low level of damping in postglacial sediments (Leda clay) at low strain levels, is a serious concern for the Ottawa region. Certainly, nonlinearity of soil behaviour would decrease the level of seismic soil amplification for strong ground motion.

In collaboration with the Geological Survey of Canada (GSC), we have conducted pilot research on seismic soil amplification factors for the Ottawa area. In our analysis, we evaluated the seismic soil amplification factors for a typical soil and bedrock profile in the Ottawa area using a simplified two-layer soil model and the seismic amplification for weak motion recordings and simulated strong motion time series. For the sake of comparison, we also evaluated the seismic soil amplification factors for a typical soil and bedrock profile in Fraser River Delta, British Columbia, Canada.

2. Local geology and geological characteristics of the Ottawa area

The Ottawa area is situated within the Ottawa-Bonnechere Graben System. This late Mesozoic feature was produced by block faulting of the Paleozoic formations and is expressed topographically by the Ottawa Valley. As a consequence of the block faulting, the Paleozoic formations generally lie flat, but can be locally deformed at steeply dipping faults and fault zones. Precambrian and Paleozoic bedrock is exposed over about 20% of the Ottawa area. Very little weathering of bedrock is evident, due to late-stage Pleistocene glacial scouring; and, most outcrops indicate hard rock.

Detailed bedrock and surficial geology maps are available for the Ottawa area (Belanger, 1998). The base of the Late Quaternary sequence in the area generally consists of a till that, in places, may include sand and/or gravel (Gadd, 1986). Glacial till and glacially derived sediments, covering 15% of the area, overlie bedrock and are relatively thin (1 to 4 m), but can thicken locally in narrow bedrock topographic lows. Glacial till is overlain by a glaciomarine-marine sequence, deposited in the Champlain Sea. The glaciomarine and pro-delta silt, clayey silt, silty clay and clay deposits in the Ottawa Valley region are informally known as Leda clay. Typically, they are composed of glacially ground, non-clay minerals held together in a loose structural framework (see Torrance, 1988).

In the Ottawa area, Leda clay outcrops over 65% of the city. The problematic geotechnical characteristics of these soils have been studied by many researchers including Eden and Crawford (1957), Karrow (1961),Bozozuk (1963), Crawford (1963), Quigley and Thomson (1966), Pusch (1970), Gillott (1971), Selvadurai et al. (1980) and Morin et al.(1983). Leda clay can be sensitive clay with thixotropic properties, meaning it may liquefy when disturbed during earthquake shaking.

The three-dimensional (3D) configuration of soil and rock can be obtained from the GSC website: http://gsc.nrcan.gc.ca/urbgeo/natcap/index_e.php or the Carleton University website: http://http-server.carleton.ca/~dariush/Microzonation/main.html. From these data and prior knowledge of the shear wave velocity characteristics of the rock and soils in the area, a generalized surficial geology map of the city has been developed (see Hunter et al., 2010; Motazedian et al., 2011). The mapping consists of three basic outcrop units: bedrock, glacial till, and late glacial/postglacial sediments. A map of the National Capital Region representing the distribution of seismic site categories across the city based on the average shear wave velocity down to a depth of 30 m (Vs_{30}) has been published (Motazedian et al., 2011, Hunter et al, 2012).

3. Finite element soil modelling

In this investigation, soil modelling was performed using the Open System for Earthquake Engineering Simulation (OpenSees, Mazzoni et al. 2010). OpenSees was created by the Pacific Earthquake Engineering Research Center (PEER) and uses finite element (FE) applications for simulating the responses of structural and geotechnical systems subjected to earthquakes. In the application of OpenSees, the shear modulus reduction curve is used to construct the backbone curve, the cyclic behaviour of the soil and, consequently, unloading-reloading criteria. The nonlinear behaviour of soil has been simulated using an advanced elasto-plastic constitutive model proposed by Parra (1996) and Yang (2000). OpenSees is similar to equivalent linear (SHAKE) programs with backbone curve informing nonlinear behaviour. However, FE modelling is a full solution to wave equation/propagation from base calculated at node points.

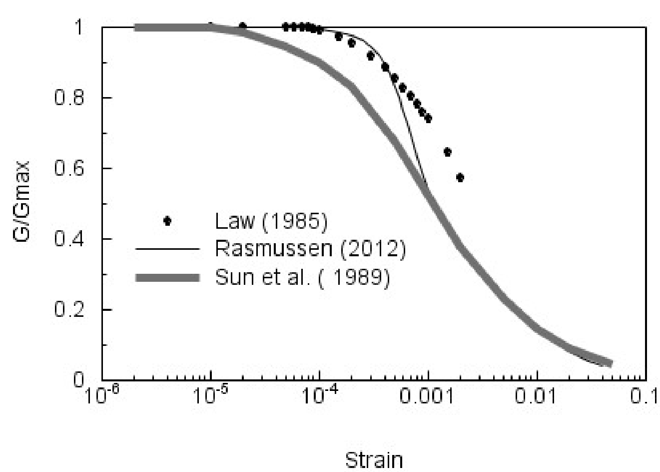

Figure 1. Shear modulus reduction curves from Law (1985) and Rasmussen (2012) for Leda clay and from Seed and Sun (1989) for a typical soil in Western Canada.

In soil modelling using OpenSees, the soil was modelled as 3D eight-node brick elements; however, the nodes at the base were fixed against vertical and lateral directions, as we are interested in one-dimensional (1D) site response analysis.

One of the main input parameters in soil modelling is soil damping. Different approaches have been introduced to model soil damping. One conventional approach is correlation of the damping ratio (D) to the shear modulus reduction (G/G_{max}). The estimations of the variation of shear modulus (G) and the damping ratio (D) of soils are the key issues for nonlinear soil. Many researchers have carried out studies to describe and characterize factors that are significant in the determination of these parameters (Stokoe et al., 2004; Darendeli, 2001; Sun et al., 1988; Seed and Idriss, 1970). These studies show that the most important parameters affecting the shear modulus reduction are the level of shear strain, the confining stress and the plasticity index. Laboratory results of resonant column tests and torsional shear tests are routinely used to obtain and correlate the shear modulus reduction and the damping ratio relationships.

The available damping and shear modulus reduction data for Leda clay in Eastern Canada are very limited. Figure 1 shows the two available shear modulus reduction curves for Leda clay in Eastern Canada: 1) Rasmussen (2012) who investigated damping and shear modulus reduction based on monotonic direct simple shear tests on Leda clay samples from the Champlain Sea basin in Eastern Canada; and, 2) Law (1985) who examined damping and shear modulus reduction based on in situ and laboratory tests on Champlain Sea clay under and outside an earth dyke using the resonant column and cyclic triaxial methods.

Needless to mention that there are many damping and shear modulus reduction data available for western North America. The main purpose of this pilot investigation is to address the differences in soil amplification using Leda clay curve for eastern Canada versus one of the popular curves for Western North America, including Western Canada. Thus, we evaluated seismic soil amplification factors just using damping and shear modulus reduction data of clayey soil from Seed and Sun (1989) for the site response analysis for Western Canada and Rasmussen (2012) for Eastern Canada. It is obvious that the Law (1985) shear modulus reduction curve was not complete compared to that of Rasmussen (2012) and it is not used due to its limited data.

4. Site response analysis for the weak motions

Many studies (Crow, 2010; Hunter et al., 2010; Khaheshi Banab and Motazedian, 2010; Motazedian et al., 2011) have shown that soil amplification is unusually large at low strain levels. The combined effects of shear wave velocity contrast, level of shaking, shear modulus reduction and damping are the subjects of ongoing soil modelling research (e.g. Crow et al, 2013).

As an example, Figure 2 illustrates the seismic soil amplification (thin black line) based on recordings from the Ladysmith, Quebec, May 7, 2013, M_W4.6 earthquake, at two nearby soil and rock seismic stations (in Kinburn basin) at a distance of about 44 km from the epicentre. Modelling was carried out for the soil seismic stations, and the finite element (FE) modelling results are shown in Figure 2 (thick gray line). The FE modelling produced reasonable locations associated with the fundamental frequency and higher soil modes, but did not provide the right peak values. There are a few reasons for these difference: 1) two-dimensional (2D) and 3D effects of subsurface topography, such as focussing and defocussing; and, 2) the 2D and 3D heterogeneity of geotechnical properties that

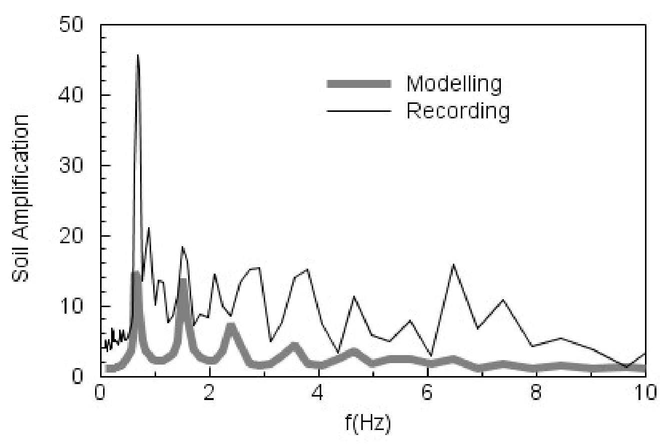

Figure 2. Ladysmith May 7, 2013 earthquake, M_W4.6, R44 km. Soil amplification factors based on the ratio of the Fourier spectrum on soil to the Fourier spectrum on rock for the combined horizontal components (thin black line), results of soil modelling using OpenSees (thick gray line)

cannot be modelled in 1D FE modelling based on one existing borehole. Our research team at Carleton University and Geological Survey of Canada is currently doing 2D and 3D basin modelling using different methods for soft sediments in Ottawa area, which is beyond the goal and the scope of this paper.

For the Ottawa area, the shear wave velocity / depth profile of Leda clay was based on Vs = 0.88*Z + 123.86, where Z is the thickness of Leda clay, based on comprehensive studies done by Hunter et al. (2010) and Motazedian et al. (2011). In addition, the average shear wave velocity for glacial till and bedrock are 580 m/s and 2700 m/s for glacial till and bedrock, respectively.

5. Site response analysis method for estimation of F_a

To comply with the 2010 NBCC, the selected input time series for FE modelling were the simulated strong motion recordings produced by Atkinson (2009) for engineering applications and the new (2015) NBCC. The simulated earthquakes are available to the public (http://www.seismotoolbox.ca). Atkinson (2009) calibrated the stochastic model (Motazedian and Atkinson, 2005) by using information derived from past large events and from seismographic recordings of small-to-moderate earthquakes. Calibrated stochastic ground motion models used to produce a range of magnitudes and distances contributing to hazard at 2% in 50 years.

To differentiate the disparity of the seismicity parameters for the two different seismic regions, different key input assumptions were considered for Eastern Canada versus Western Canada: the stress drop, the regional attenuation, the fault sizes, etc. (see Atkinson 2009). The key simulation parameters, in particular those that are varied from eastern North America to western North American, are listed in Atkinson (2009). For eastern North America, the simulated acceleration times series were for moment magnitudes of **M**6 at fault distances from 10 to 30 km and **M**7 at 15 to 100 km, based on the seismic hazard de-aggregations (Adams and Atkinson 2003; Halchuk et al. 2007). For cities in Eastern Canada in regions of moderate-to-high seismicity, an **M**6 event in the 10 to 30 km distance range matches the short-period end of the uniform hazard spectra (UHS), and an **M**7 event at a somewhat larger distance (but within the same range) matches the long-period end of the UHS.

Hypothetical sites with a soil thickness of 1 to 30 m and an incremental thickness of 1 m were considered. Each site was subjected to input time histories with different levels of shaking. The input time series were scaled to match the $S_a(0.2\ s)$ values at 0.25, 0.50, 0.75, 1.00, and 1.25 g for F_a. Other major geotechnical properties of the geological units and selected input time series for Eastern Canada in the FE modelling were a soil unit weight (density) of 1700 kN/m^3, a bedrock shear wave velocity of 2700 ± 680 m/s and a bedrock unit weight (density) of 2500 kN/m^3. For the Ottawa area, more than 1800 soil modelling scenarios were performed using the above-mentioned region-specific input time series at different distances, different soil thicknesses (from 1 m to 30 m) and the modulus curve from Rasmussen (2012).

For Western Canada, the simulated acceleration time series were available for **M**6.5 at 10 to 15 km, **M**6.5 at 20 to 30 km, **M**7.5 at 15 to 25 km, and **M**7.5 at 50 to 100 km, reflecting the greater contribution to hazard from larger events in B.C. and for **M**9 at 112 km for a megathrust event on the Cascadia subduction zone. In this investigation, we used the above-mentioned simulated time series for site class A and input time series in the FE modelling. Other major geotechnical properties of the geological units and selected input time series for Western Canada (e.g. Fraser River Delta) in the FE modelling were: a soil shear wave velocity (Vs) of 90.9+35.8*Z**(0.433) (after Hunter et al. 1998), a soil unit weight (density) of 1700 kN/m^3, soil thicknesses from 0 to 30 m, a bedrock shear wave velocity of 1800 m/s and a bedrock unit weight (density) of 2500 kN/m^3. The same procedures were performed for 2250 scenarios for the Fraser River Delta using different region-specific input time series scaled to match different values of S_a, different soil thicknesses and the modulus curve from Seed and Sun (1989).

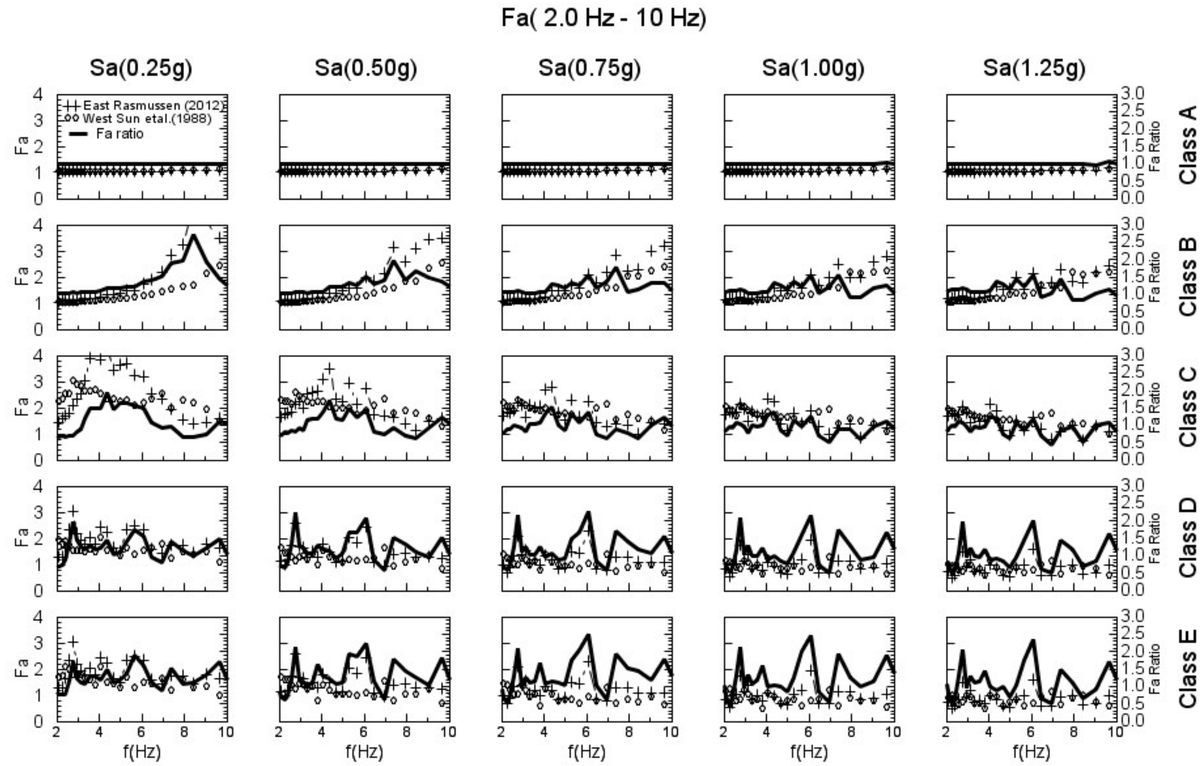

Figure 3. Soil amplification curves for the Ottawa region (+ symbols) to soil amplification curves for the Fraser River Delta (circle symbols) at the same range of frequencies (2 to 10 Hz for F_a) for the same S_a values (0.25, 0.50, 0.75, 1.00 and 1.25 g) and the same site classes. Solid line shows the ratio of Ottawa's Soil amplification curves to those of Fraser River Delta.

Amplification curves were obtained for each case using two different approaches. The first approach was based on Fourier analysis, in which the ratio of the Fourier spectra of the response on the ground level, which was the output of FE modelling, to that of input motion was taken as the amplification ratio. The second approach was based on response spectra, in which the 5% damping response spectra of the time history on the ground level produced by FE modelling to that of the input motion was obtained as the amplification ratio. For the sake of brevity, just the amplification curves based on Fourier analysis are discussed here.

Figure 3 presents a set of curves that show the soil amplification curves for F_a (2.0 Hz to 10 Hz) of OpenSees output to OpenSees input time series (+ symbols for Ottawa and circle symbols for the Fraser River Delta. As seen for site class A, as shown in the first row of Figure 3, the amplification curves for S_a values of 0.25, 0.50, 0.75, 1.00 and 1.25 g (left to right) are very close to unity. However, for site class B (second row of Figure 3), the amplification curves increased at high frequencies, as site class B is essentially a thin layer (from 2 to 4 m) with a high fundamental frequency which mainly amplifies the frequencies at and above the fundamental frequency.

As the soil thickness increased in our soil modelling from 5 to 10 m (site class C), the amplification curve moved to lower frequencies, representing the thickness of the soil and its fundamental frequencies and higher modes, as shown in the third row of Figure 3. The fourth and fifth rows of Figure 3 show amplification curve for site class D (with soil thickness from 11 to 23 m) and site class E (with soil thickness from 24 to 30 m), respectively. It is clear as the soil thickness increased, the soil amplification curves increased and moved towards lower frequencies, as expected. It should be noted that these amplification curves are based on 1D soil modelling and do not provide the soil amplification curves anticipated from real earthquake recordings for many different reasons including: 1) 2D and 3D site effects (such as focussing and defocussing) are not captured in 1D modelling; 2) the lateral heterogeneity of soil is not modelled in 1D modeling; 3) the sublayers in a real site are not modelled in this 1D modelling; 4) the surface topography that is present in many sites is not modelled; and, 5) the obtained soil amplification curves are based on theoretical models and have been simplified based on many assumptions in order to solve the complicated equations. In summary, it is not really expected that 1D modelling can provide the soil amplification curves close to real ones.

In this study, however, we were not interested in providing direct soil amplification curves based on 1D modelling for the Ottawa region: rather we were interested in finding the ratio of soil amplification curves for the Ottawa area to those of the Fraser River Delta using the same modelling techniques, including region-specific soil and bedrock features and seismicity as previously described. Solid lines in Figure 3 show the ratios of soil amplification curves for the Ottawa region to the soil amplification curves for the Fraser River Delta at the same range of frequencies (2 to 10 Hz for F_a) for the same S_a values (0.25, 0.50, 0.75, 1.00 and 1.25 g) and the same site classes.

As previously mentioned, the amplification factors provided in the NBCC were based on studies for a typical soil layer over the typical bedrock formation in western North America. These amplification factors are used in practice for Western Canada, including the Fraser River Delta. It is reasonable to assume that the soil amplification factors for the Fraser River Delta are closer to the amplification factors provided in the NBCC than those for the Ottawa area. Thus, we used the ratio of F_a factors for the Ottawa region to the F_a factors for the Fraser River Delta, as shown in Table 2, as the correction factors for the Ottawa area.

As expected, the F_a factors for site classes A and B for the Ottawa area were equal to those of the Fraser River Delta, because the contributions of soil thickness from 1 to 4 m to F_a are negligible, regardless of the difference between soil types in Ottawa and the Fraser River Delta. The same was true for site class C, but there was a 10% increase in F_a for low levels of shaking, when the soil behaved linearly. However, when the thickness of soil was increased for both the Ottawa area and the Fraser River Delta, the effects of the soil differences became more prominent. The F_a values for site class D increased by 40% in linear soil ($S_a(0.2)<=0.25$) and by 20% for very nonlinear soil ($S_a(0.2)=1.25$). This is typical behaviour of F_a values in all building codes: as the level of shaking increases, the damping reduces the soil amplification factors. For site class E, due to the large thickness of the soil, the F_a values increased by 50% for all levels of shaking for the Ottawa region compared to those of the Fraser River Delta.

Table 2. Ratios of F_a for the Ottawa region to F_a for the Fraser River Delta. F_a for Ottawa based on Rasmussen (2012), F_a for the Fraser River Delta based on Sun et al. (1988).

Site Class	Ratio of F_a for Ottawa to F_a for Fraser River Delta				
	$S_a(0.2)<=0.25$	$S_a(0.2)=0.50$	$S_a(0.2)=0.75$	$S_a(0.2)=1.00$	$S_a(0.2)=1.25$
A	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
B	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
C	**1.1**	**1.0**	**1.0**	**1.0**	**1.0**
D	**1.4**	**1.3**	**1.3**	**1.2**	**1.2**
E	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

6. Discussion and conclusion

Site amplification is a concern in geotechnical practices in the Ottawa area, as about 65% of Ottawa is located on loose postglacial sediments with very low shear wave velocities (Vs < 150 m/s). In addition, these soft soil deposits overlie hard bedrock with a very high shear wave velocity (Vs > 2300 m/s). This large contrast in shear wave velocities exhibits the high potential of the soil profiles to trap incident seismic waves. A rough calculation can verify wave trapping using a density of the loose soil sediments is 1600 kN/m^3, an average shear wave velocity of 150 m/s and a density and average shear wave velocity of the hard bedrock of 2500 kN/m^3 and 2700 m/s, respectively, Using reflected ($E_R = (Z_2 - Z_1)^2 / (Z_1 + Z_2)^2$) and transmitted energy coefficients ($E_T = (4 Z_1 Z_2) / (Z_1 + Z_2)^2$) equations, the reflected energy coefficient (E_R) of 0.87 is obtained. Z_1 and Z_2 stand for the acoustic impedance of the soil and the underlying bedrock, respectively. This coefficient means that the most of the travelled seismic wave (85% of the total energy) in the upper layer (soft soil) is reflected and trapped.

In addition to the surficial geology of the city, the sparse earthquake recordings in the Ottawa area show large amplification factors for the recorded weak motions. For instance, for an earthquake near Cochrane,

Ontario (magnitude of 4.2) on Dec. 7, 2006, very large amplification factors were reported near the fundamental frequency (f_0) of the site (ORHO station). Using this earthquake and the spectral ratio method, the maximum amplification factor was determined to be 143 at 0.78 Hz; however, at higher frequencies, this factor was more than 20 for the horizontal components (Motazedian et al., 2007). Pugin et al. (2007) obtained high amplification values for the same site using the horizontal/vertical (H/V) ratio method (Nakamura technique). They achieved the maximum amplification ratio of 75 at the fundamental frequency of the site. Similarly, Adams (2007) obtained high amplification values for the Blackburn site. However, these were weak motion soil amplifications, and the soft soil behaved linearly in this range: we are interested in soil amplification factors for stronger levels of motion.
The amplification factors provided in the NBCC are based on studies for a typical soil layer (with shear wave velocities of a few hundred meters per second) over the typical bedrock formation in western North America. Motazedian and Atkinson (2005) provided a calibrated stochastic finite-fault simulation model that predicts observed crustal earthquake ground motions in California, and Atkinson (2005) showed that the California model appears to be reasonable for B.C. when differences in site conditions are considered. In this study, we used simulated time series for bedrock (Atkinson 2009) as the input time series in FE modelling. Soil amplification factors were obtained based on region-specific seismic and geotechnical parameters for the Ottawa area in Eastern Canada and the Fraser River Delta in Western Canada.

It should be emphasized that soil modelling techniques do not provide F_a values close to those of earthquake recordings and those given by the 2010 NBCC, due to complicated 2D and 3D subsurface and surface topography, 2D and 3D heterogeneity of soil properties (density, shear wave velocity, damping, etc.) and the simplicity of available theoretical modelling techniques. Thus, as a pilot investigation, we assumed that the obtained ratios of F_a for the Ottawa area in Eastern Canada to the Fraser River Delta in Western Canada, based on soil modelling, could approximately represent the effect of the differences in geotechnical and seismicity properties on soil amplification factors. With this assumption, and assuming that the Rasmussen (2012) damping and shear modulus reduction curves are reasonable representatives of Leda, we multiplied the obtained ratios in Table 2 by the F_a values in Table 1 (NBBC, 2010), and obtained the F_a values for the Ottawa area, shown in Table 3. It should be reiterated that the F_a factors for site classes A, B and C were the same or close to those of the 2010 NBCC. However, the F_a values for site classes D and E increased up to 40% and 50%, respectively.

Table 3. Suggested F_a for Ottawa. Values of F_a for the Ottawa area are based on the ratio of F_a for Ottawa to F_a for Fraser River Delta. (1) Site-specific investigation and dynamic site response analysis are required. Values in brackets are values from Table 2.

Site Class	Suggested F_a for Ottawa area				
	$S_a(0.2)$<=0.25	$S_a(0.2)$=0.50	$S_a(0.2)$=0.75	$S_a(0.2)$=1.00	$S_a(0.2)$=1.25
A	**0.7***(1.0)*	**0.7***(1.0)*	**0.8***(1.0)*	**0.8***(1.0)*	**0.8***(1.0)*
B	**0.8***(1.0)*	**0.8***(1.0)*	**0.9***(1.0)*	**1.0***(1.0)*	**1.0***(1.0)*
C	**1.1***(1.1)*	**1.0***(1.0)*	**1.0***(1.0)*	**1.0***(1.0)*	**1.0***(1.0)*
D	**1.8***(1.4)*	**1.6***(1.3)*	**1.4***(1.3)*	**1.3***(1.2)*	**1.2***(1.2)*
E	**3.2***(1.5)*	**2.1***(1.5)*	**1.7***(1.5)*	**1.4***(1.5)*	**1.4***(1.5)*
F	(1)	(1)	(1)	(1)	(1)

As for 2015 NBCC it is proposed to change F_a and F_v (averaged over 0.1 s to 0.5 and 0.4 s to 2 s, respectively) with soil amplification factors at 0.2 s, 0.5 s, 1.0 s, and 2.0 s (Gail Atkinson and John Adams, personal communication), the results of soil amplification modelling in this research can be easily transferred to the proposed periods.

7. Acknowledgment

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