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DYNAMIC RESPONSE PREDICTIONS OF SOIL PROFILES IN MONTREAL

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ABSTRACT: The short and long period ground motion amplification factors in the National Building Code of Canada are defined in relation to the 2010 NBCC soil sites classes A, B, C, D and E. The factors are derived from field data on ground motions recorded during earthquakes and equivalent linear and nonlinear analyses, and represent average responses for a wide variety of soils and ground motions. For sites of Eastern North America, very few strong ground motion records are available in order to determine empirically amplification factors for site soil classes. Recently, NGA-East has compiled data and performed Equivalent linear dynamic analyses of one-dimensional soil columns in order to update these factors. Using a similar approach, database for soil profiles in Montreal at 26 sites were analyzed using DeepSoil using the equivalent linear 1D analysis both for natural and synthetic rock input motions that match the response spectra for Montreal. The results for amplification factors of peak ground acceleration on rock (corresponding to structural period of 0.01 s) are compared to the current factors of the NBCC (2010), and to the latest factors derived by NGA-East. The results also indicate a large degree of scatter which may have an effect on overall hazards.

1. Introduction

The region of Montreal has a significant urban seismic risk, estimated to be the 2nd largest in Canada (Lamontagne, 2009); however, very few strong events have been recorded. One of the most significant recent event is the 1988 Saguenay earthquake (M 5.7) which was located in the Charlevoix seismic zone, about 350 km north of the city. Some evidence of liquefaction was found at sites in the vicinity (~ 26 km) of the epicenter (Tuttle et al., 1990), as well as structural damage at sites as far as Montreal. In the latter case, the most important damages were at the site of the Montreal East city hall, which was located on a deep soft clay deposit that amplified ground motions. In this study, results from the most recent site investigations on the island of Montreal are used to characterize shear wave velocity profiles and to compute amplification factors using DEEPSOIL (Hashash and Park, 2001). For this purpose, amplification is defined as the ratio of the observed peak ground acceleration at the ground surface to the peak ground acceleration at the rock interface.

Soft soil zones are mainly located in the downtown area and along the south east shore of the island (Rosset and Chouinard, 2009). These are thick marine deposits overlying stiff glacial deposits or hard rock.

The site amplification factors of NBCC (2010) are derived for NEHRP site class (Finn and Wightman, 2003). In this application, the equivalent linear 1D model (Idriss and Sun, 1992) is used to estimate: (1) amplification factors (at structural periods of T=0.01 s) from the ratio of the peak acceleration at the ground surface $a_{max,surface}$ in response to the peak ground acceleration on rock $a_{max,rock}$ for soil profiles in Montreal, (2) the short period amplification factor F_a from the ratio of the spectral value on ground surface $Sa_{\text{ground surface}}(T=0.20s)$ to the spectral value on rock $Sa_{\text{rock}}(T=0.20s)$, and (3) the long period amplification factor F_v from the ratio of the spectral value on ground surface $Sa_{\text{ground surface}}(T=1.0s)$ to the spectral value on rock $Sa_{\text{rock}}(T=1.0s)$. The results illustrate the period dependence of amplification factors for site classes D and C.

2. Rock Motion for Equivalent Linear 1D Dynamic Analysis

For estimating the dynamic response of soil profiles, a suite of input ground motions is obtained which is consistent with the seismic hazard spectrum. Probabilistic seismic hazard analysis suggests that ground motions for Montreal may be selected for moment magnitudes M6 at fault distances from 10 to 30 km and for M7 at 15 to 100 km, which make largest contribution to the seismic hazard for NBCC (2010) at a probability of exceedance of 2% over 50 years. Atkinson (2009) developed synthetic accelerograms (www.seismotoolbox.ca) for Montreal for NEHRP class A (Vs_{30} > 1500 m/s) of hard rock site condition. The synthetic records are for a range of earthquake magnitudes and distances contributing most to seismic hazards at the 2 % in 50 years level. For each magnitude, the simulated records are for two epicentral distances (in accordance with the suggestion of Halchuk et al. (2007): M6 at 10 to 15 km (M6 set 1), and 20-30 km (M6 set 2) and M7 at 15 to 25 km (M7 set 1), and 50 to 100 km (M7 set 2) total of 20 ground input motions were selected for 1D site response analyses. Fifteen of the records are natural ground motions recorded on rock that approximate the hazard spectrum for Montreal and five are from the synthetic ground motions at rock sites by Atkinson (2009). Equivalent linear 1D dynamic analysis were performed by using rock motions of low to moderate shaking levels (e. g., 0.05 - 0.53 g). The set of 10 natural rock input motions (Figure 1) were selected for the 1D analyses from a suit of Western North American (WNA) ground motions to ensure that a wide band of predominant structural periods ranging from 0.1 to 1.5 s are available to adequately excite the 1D shallow to deep soil profiles with short to long site fundamental periods between 0.08 s to 0.67 s). The figure also shows that the records are representative of the range of values expected for the hazard spectrum for Montreal.

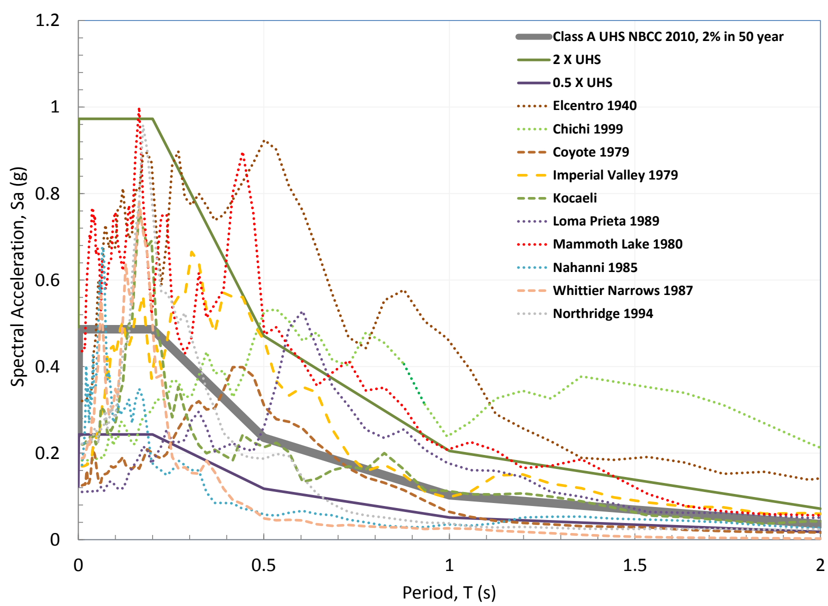


Fig. 1 – Response spectra (damping ratio of 5%) of natural ground motion recorded on hard rock condition.

Figure 2 shows a set of 5 natural ground motions (Figure 2a) on rock for the Saguenay 1988 earthquake and provide input ground motions that have a high energy content at smaller periods to adequately excite the shallow soil columns in the Montreal Island with fundamental frequency between 3-20 Hz.

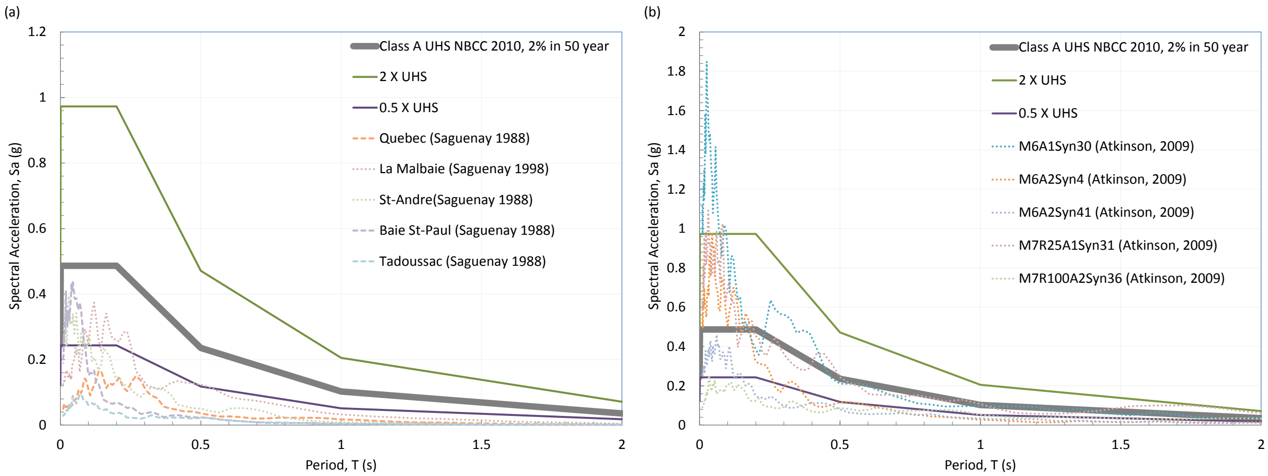


Fig. 2 – 2a) Response spectra (damping ratio of 5%) of the 1988 Saguenay accelerograms recorded on rock; 2b) synthetic accelerograms for class A hard rock condition (Atkinson, 2009).

Figure 2b shows the set of 5 synthetic input motions selected from the synthetic ground motions of Atkinson (2009). These were selected to cover the short periods of the uniform hazard spectra (UHS) which are important for amplification at sites with shallow soil deposits. The suite of ground motions selected cover a wide range of structural periods of interest (0.01 to 1.5 s) for amplification of either shallow or deep soft soil profiles.

3. Soil Profiles for Equivalent Linear 1D Dynamic Analysis

The surface geology of Montreal is an interlayered deposit with clay, silt and dense sand overlying till or rock and is the result of several alternating periods of glaciation followed by the emergence of the Champlain Sea and channelling by the St. Lawrence River and its tributaries (Prest and Hode-Keyser 1977). Bedrock material is generally limestone. In this study, equivalent linear 1D analysis of ground response is first performed for a set of 26 sites (Figure 3a) with covering a range of soft soil deposits from depths of 3 to 35 m (Figure 3b). Schematic diagram for soil profiles at each of the 26 sites (Figure 3) is shown in Figure 4. The diagram shows the type of soils and corresponding thickness.

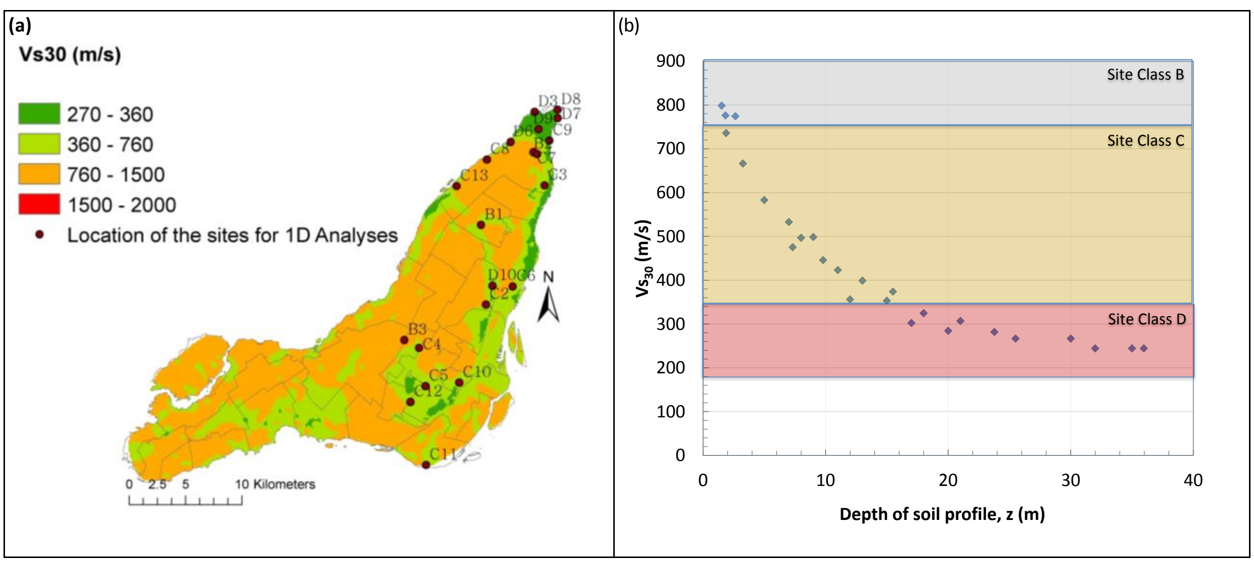


Fig. 3 – 3a) Locations of sites on the Island of Montreal where borehole information are available for Equivalent 1D site response analysis; 3b) Variation of soil profile depths of 26 sites with Vs_{30} (m/s) (average shear wave velocity of top 30 m soil).

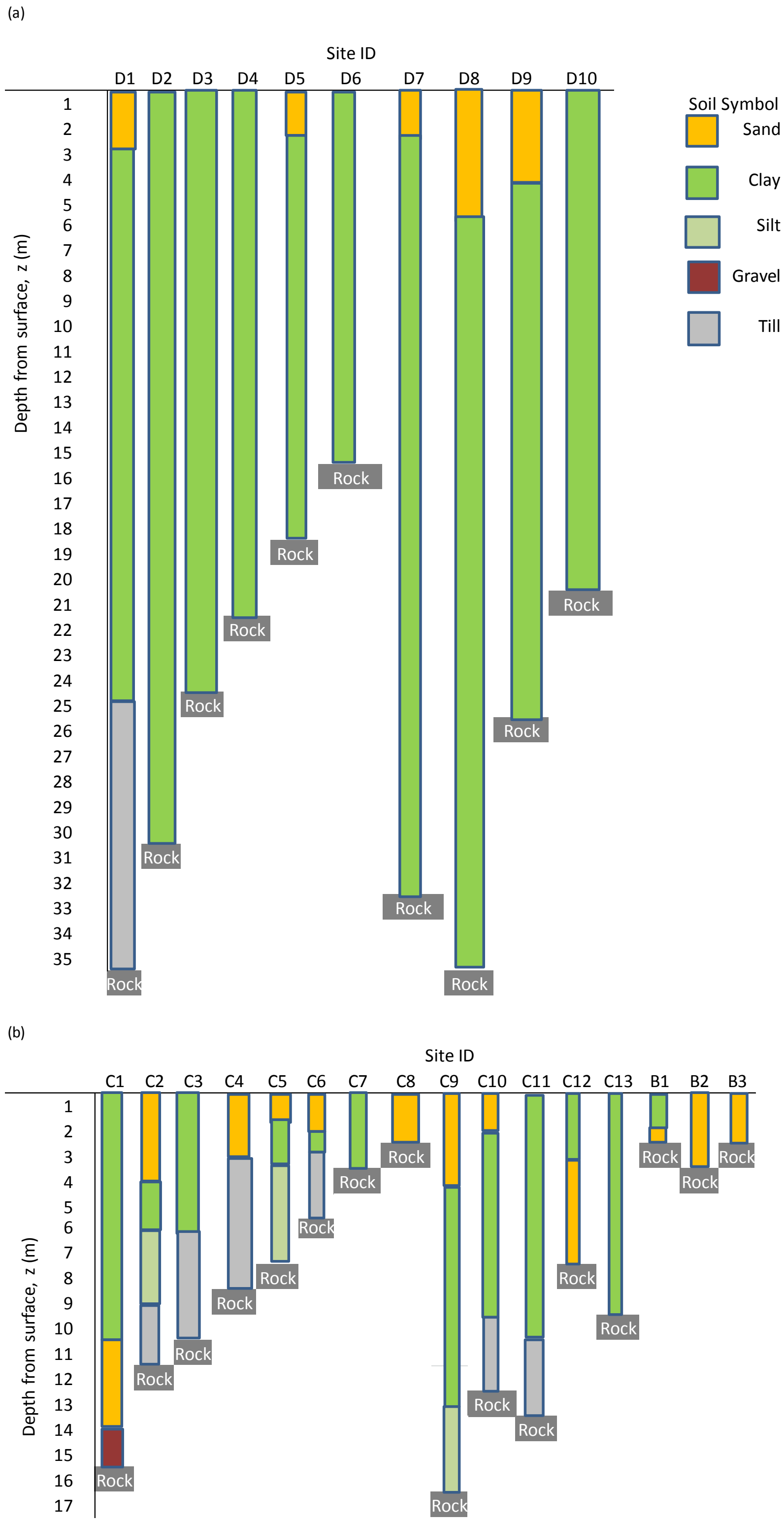


Fig. 4 – 4a) Schematic diagram on type and thickness of soils in the soil deposit at the sites of class D shown on the map in Figure 3a, 4b) soil profiles at the sites of class C and B show on the map in Figure 3a.

The 26 sites cover a range of V_{s30} from 240 to 800 m/s (Figure 3b) which correspond to site classes B, C and D. The 1D analysis requires shear wave velocity profiles. Shear wave velocity models for different soil types are listed in Table 1.

Table 1– V_s versus depth equations for sand, clay and silt in Montreal.

Soil Type	Vs=f(z), m/s	Unit Weight (kN/m^3)
Sand	Vs = $145+37z^{0.57} \pm 54$ (Chouinard and Rosset , 2011)	20 (Prest and Hode-Keyser, 1977)
Clay	Vs = $121+ 41z^{0.43} \pm 43$ (Chouinard and Rosset, 2011)	16.50 (Rassmussen, 2012)
Silt	Vs = $162 + 24z \pm 54$ (Talukder et al., 2013)	16.5 (Rassmussen, 2012)
Glacial Till (Stiff soil)	565 (Talukder et al., 2013)	21.2 (Prest and Hode-Keyser, 1977)
Glacial Till (Boulders)	1000 (Rosset and Chouinard, 2009)	24 (Prest and Hode-Keyser, 1977)
Bedrock	2350 (Talukder et al., 2013)	27.3 (Rosset and Chouinard, 2009)

At present, there are no laboratory test results available for the shear modulus degradation and damping curves for the tills of Montreal. For the purposes of this article, the shear modulus reduction and damping ratio curves were selected as indicated in Table 2 for the three main types of soils.

Table 2 – The sources of soil properties used for the 1D modeling of dynamic site response study.

Soil Type	Sear Modulus reduction curve and Damping ratio curve
Clay	Rasmussen (2012)
Silt	Sun et al. (1988)
sand	Seed and Idriss (1970)
Till	Seed et al. (1986)

All analyses were conducted using the program DEEPSOIL (Hashash and Park, 2001). In this study, equivalent linear 1D analyses were performed in total stress condition. Therefore, water table data was not required as input to DEEPSOIL. Ground input motions on rock were scaled incrementally to 0.10 g, 0.25 g, 0.50 g, 0.75 g, 1.0 g and 1.25 g.

4. Results and Discussion

The following equations were used to calculate the amplification factors of rock motions at different periods:

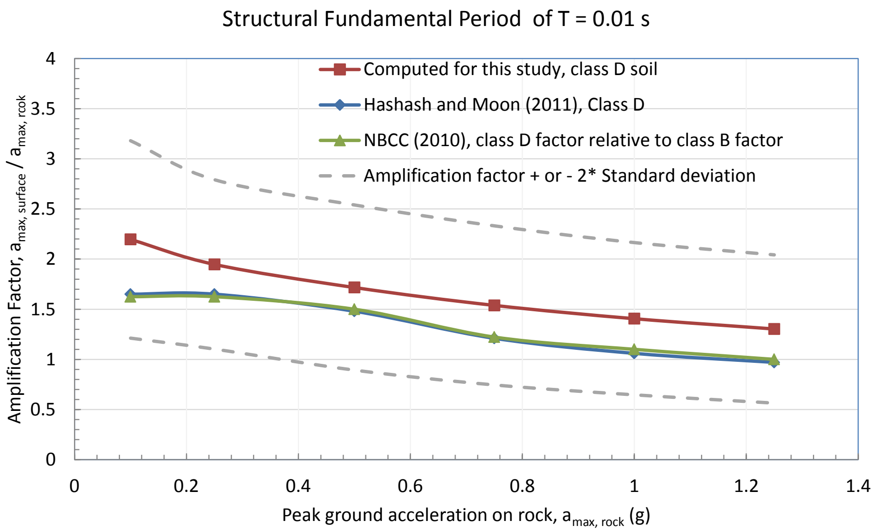
$$\frac{a_{max,surface}}{a_{max,rock}} = \frac{Sa_{ground\ surface}(T = 0.01\,s)}{Sa_{rock}(T = 0.01\,s)} \tag{1}$$

$$F_a = \frac{Sa_{ground\ surface}(T = 0.20\,s)}{Sa_{rock}(T = 0.20\,s)} \tag{2}$$

$$F_v = \frac{Sa_{\text{ground surface}}(T = 1.0\ s)}{Sa_{\text{rock}}(T = 1.0\ s)} \tag{3}$$

Damping was assumed to be of 5 % for computation of spectral acceleration values in this study. Figure 5a shows that for class D sites, the mean amplification factor varies from 2.25 at T= 0.01 s for a rock PGA = 0.1 g to a value of 1.4 for a rock PGA= 1.25 g. The reduction in amplification is due to the nonlinear stress-strain response of the soil, resulting from reduced effective shear moduli and increased damping (Finn et al., 2004; Motazedian et al., 2011). Figure 5b shows that for class C sites, the mean amplification factor F_a at T=0.01 s is 2.1 for a PGA =0.10 g and decreases to 1.45 for PGA = 1.25 g.

(a)



(b)

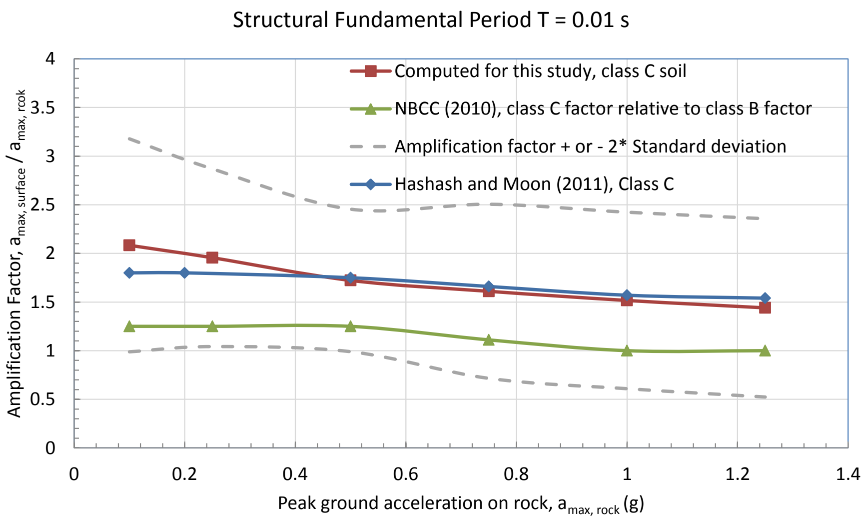
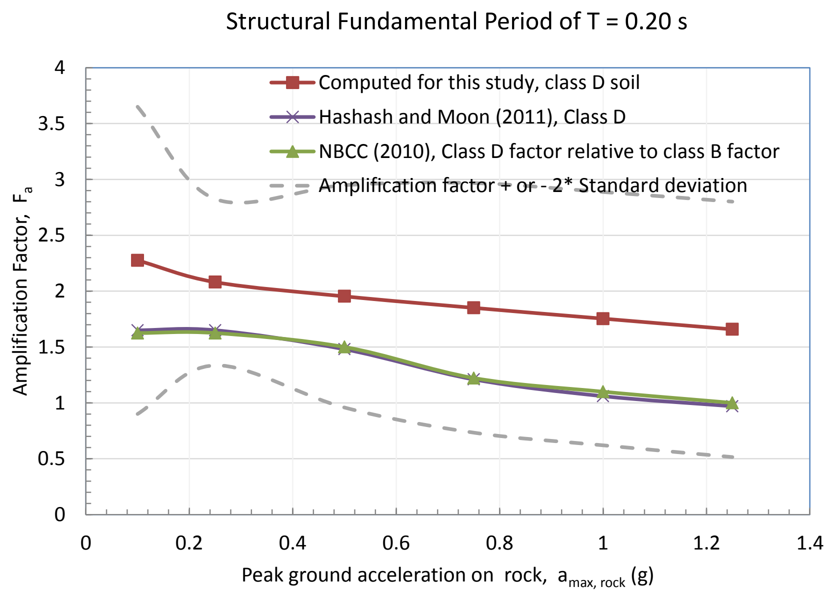


Fig. 5 – 5a) the variation of Amplification factor $a_{max,\ rock}/a_{max,\ surface}$ with rock PGA computed in this study for class D and, 5b) for class C for period of T= 0.01 s.

Figure 5b compares well with the amplification factors for Class C presented in Hashash and Moon (2011). But, both Figures 5a and 5b suggest that the difference between the results of this paper and the amplification factors for rock PGA suggested in NBCC (2010) soil is significant. One finds in Figure 5 that the amplification ($a_{max,surface}/a_{max,\ rock}$) values presented in Hashash and Moon (2011), and the 2010 NBCC are within the range of ± 2 standard deviations on the mean amplification values computed in this study for the rock PGA ranging from 0.10 to 1.25 g at T = 0.01 s. Figure 6 shows that the computed values of the factor F_a at structural period of T= 0.20 s for site classes C and D are compared with the results of Hashash and Moon (2011) and with the F_a values suggested in the 2010 NBCC

(a)



(b)

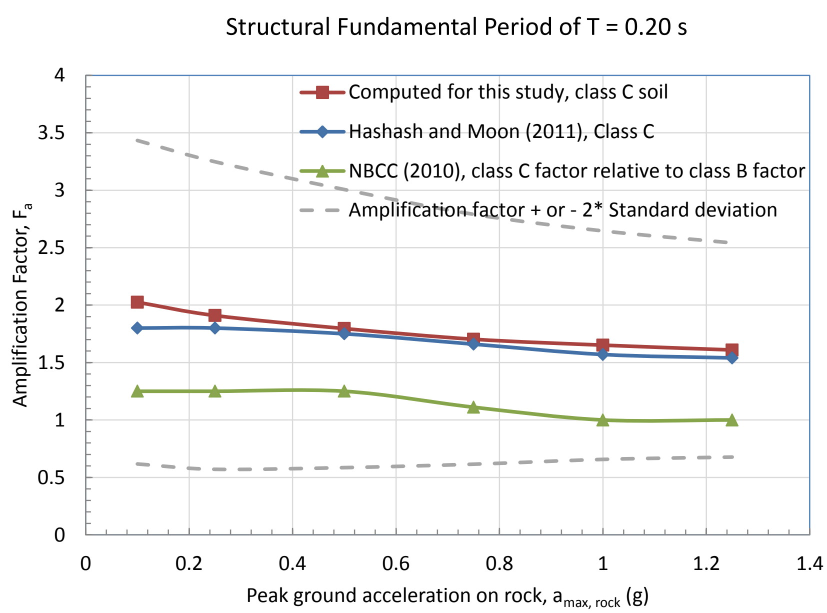
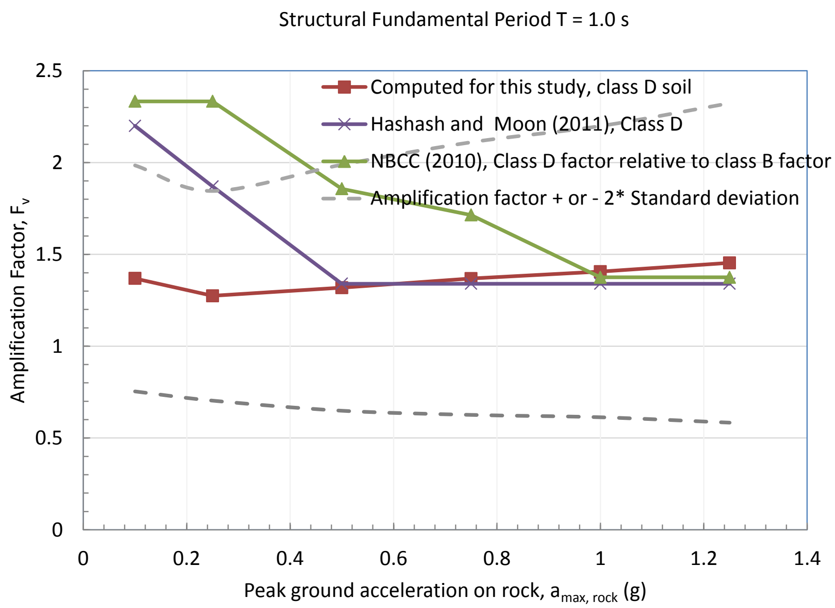


Fig. 6 – 6a) the variation of Amplification factor F_a with rock PGA computed in this study for class D and, 6b) for class C for period of T=0.20 s.

The agreement between the results of this paper and that of Hashash and Moon (2011) is better for class C soil (Figure 6b) than for class D soil shown in Figure 6a. Figure 6 shows that the disagreement between the results of this paper and the F_a values suggested in the 2010 NBCC is significant, and the mean F_a

values obtained in this study are about 1.5 times higher than the F_a values in the 2010 NBCC at all rock PGA levels for both the site classes D and C. One finds in Figure 6 that the F_a values presented in Hashash and Moon (2011), and the 2010 NBCC are within the range of ± 2 standard deviations on the mean F_a values computed in this study for the rock PGA ranging from 0.10 to 1.25 g at T = 0.20 s. Figure7b shows, the agreement between the values of F_v computed in the study and the suggested F_v values in the 2010 NBCC is well for class C than for class D shown in Figure 7a. The agreement between the results of this paper and that of Hashash and Moon (2011) is better for class C soil (Figure7b) than for class D soil shown in Figure 7a. The biggest discrepancy between the computed F_v values and the amplifications presented in the 2010 NBCC can be seen for T =1.0 s in Figure 7a.

(a)



(b)

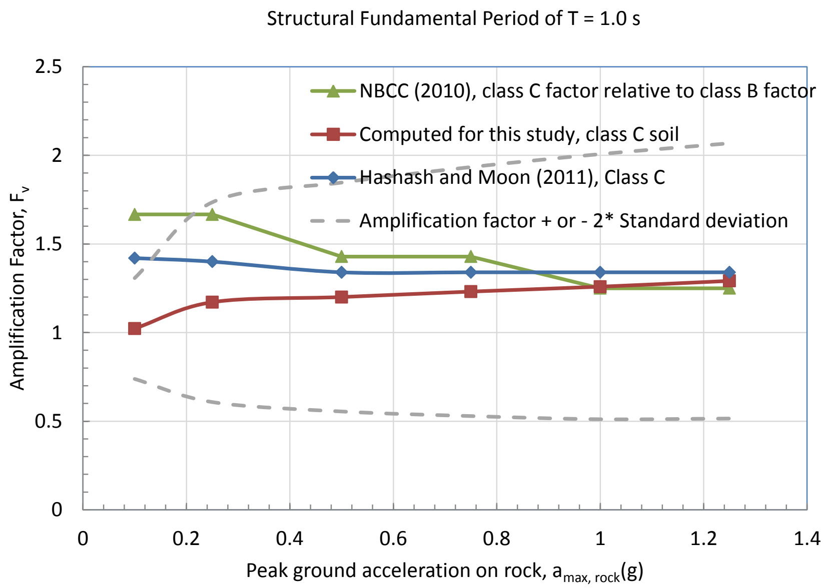


Fig. 7 – 7a) the variation of Amplification factor F_v with rock PGA computed in this study for class D and, 7b) for class C for period of T=1.0 s.

This biggest discrepancy may be due to nonlinear effects of soft soils that decrease the amplification effects as well as shift the energy to longer periods, relative to the weak-motion case (Motazedian et al,. 2011) . At long period of T = 1.0 s, the amplification factors suggested by Hashash and (2011) are primarily for Eastern North America, and about 1.5 times higher than the F_v values computed in this study at shaking levels from 0.1 g to 0.5 g. The F_v values presented in Hashash and Moon (2011), and the 2010 NBCC fall just outside the ± 2 standard deviation on the mean F_v values computed in this study for shaking levels from 0.1 g to 0.25 g. By comparing the period dependent amplification factors in Figure 5, 6, and 7, it is found that the variation in ground motion amplification from rock to surface largely depends on the frequency content of different input rock motions shown in Figure 1 and 2, and V_{s30} of soil profiles. In contrast to the computed values of amplification factor of F_v for long structural periods (T > 0.2 s) shown in Figure 7, the amplifications shown in Figures 5 and 6 at shorter periods (T = 0.01 s and T = 0.20 s) are higher. This indicate that the soft and stiff Montreal soil profiles can be in resonance when they are excited by the earthquake motions used in the study where most of the motions have medium level of frequency content (T = 0.01 s to 0.20 s). As noted from the comparison of the amplifications presented in Figures 5, and 6 for all periods of interest (T = 0.01 s, 0.20 s and 1.0 s), the amplifications generally decrease as the PGA on rock increases. The decrease in amplification with increasing intensity of shaking may be due to the nonlinear stress-strain response of the soil at high shaking level, resulting from reduced effective shear modulus and increased soil damping (Finn et al., 2004). Nonlinear effects of soft soils are expected to decrease the amplification effects as well as shift the energy to longer periods, relative to the weak-motion case (Motazedian et al., 2011). It can also be noticed by comparing the computed amplifications values in Figures 5, 6 and 7, the amplifications computed for longer period (T=1.0 s in Figure 7) are lower than those computed for shorter periods of T = 0.01 s and T = 0.2 s. This may have happened due to relatively higher damping of seismic wave energy through larger shear strain in the deep soil columns (with long period of vibration) with depths of 20 to 33 m. It can be seen from the computed amplifications presented in Figures 5 through 7 that regardless of low or high rock shaking levels, all soil classes amplify the response (all lines are above the 1:1 line).

The 2010 NBCC suggests amplification factor F_a (foundation factor for T = 0.20 s) for the Montreal area, for the design ground motion of 0.64 g (1:2475 year return period). Thus according to the 2010 NBCC, at T= 0.20 s, the amplification factor F_a for class D soil in Montreal is 1.40 times higher than class B and 1.5 times higher than class A. In this study, the computed mean amplification factor F_a was computed relative to the ground motions on rock (class A). For class D, the computed F_a at a design ground motion of 0.64 g is of 1.80 ± 0.5, which is more conservative than the value from NBCC (2010) code. The 2010 NBCC also suggests long period amplification factor F_v (foundation factor for T = 1.0 s) for the Montreal area, for the design ground motion of 0.14 g (1:2475 year return period). Thus according to the 2010 NBCC , at T= 1.0 s, the amplification factor F_v for class D soil in Montreal is approximately of 2.70 times higher than class A and 2.35 times higher than class B. In this study, the computed mean amplification factor F_v was computed relative to the ground motions on rock (class A). For class D, the computed F_v at a design ground motion of 0.14 g is approximately of 1.40 ± 0.5, which is less conservative than the value of 2.70 from the 2010 NBCC code.

5. References

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