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Induced Seismicity in Fox Creek, AB: Amplification Function and Foundation Factors

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ABSTRACT

The increase in induced seismicity in the Fox Creek AB area has triggered the interest in site amplification for sites characterized by shallow rock. A new methodology to characterize the thin soil sites amplification is presented in this paper and is based on the characterization of the linear (initial) site fundamental period of vibration. The methodology is applicable to sites where soil having shear wave velocities smaller than 300 m/s overlay soft rock characterized by shear wave velocities between 360 and 760 m/s, typical of site C conditions. Amplification functions for hazard studies and foundation factors for engineering applications are developed and proposed to characterize the surface ground motion.

RÉSUMÉ

L’augmentation de la sismicité induite dans la région de Fox Creek AB a suscité l’intérêt pour l’amplification de sites pour des sites caractérisés par des roches peu profondes. Une nouvelle méthodologie pour caractériser l'amplification de sites de sol minces est présentée dans cet article et est basée sur la caractérisation de la période de vibration fondamentale du site linéaire (initial). La méthodologie est applicable aux sites où le sol ayant une vitesse d'onde de cisaillement inférieure à 300 m / s recouvre une roche tendre recouverte de vitesses d'onde de cisaillement comprises entre 360 et 760 m / s, caractéristiques des conditions du site C. Des fonctions d'amplification pour les études de risque et des facteurs de base pour les applications d'ingénierie sont développées et proposées pour caractériser le mouvement du sol en surface.

1 INTRODUCTION

The recent increase of small to moderate induced seismic events in some of the Western-Canadian unconventional oil and gas plays (Figure 1) has generated the interest in the characterization of the ground motion occurring when a thin soil cover rests on stiffer rock. In most of the areas experiencing induced seismicity (Figure 1), a few meters of glacial and post-glacial sediments overlap stiffer and more competent tertiary rock. Induced earthquakes are usually triggered at shallow depths by industrial activities and can generate ground motions of relatively large amplitude with short period of vibration at very small hypocentral distances. Short period amplification is relevant for small buildings and equipment foundation at grade. A thin soil cover may further amplify the ground motion in the short period range. In contrast, thin soil cover de-amplifies the ground motion in the long period range, potentially reducing the response of taller and more flexible structures such as high-rise buildings, flares, and bridges.

To improve the reliability of the seismic hazard, specific site response considerations describing the distinctive thin layer amplification characteristics are needed. After a short discussion on the relevance and the areal distribution in North-America of the subsurface conditions considered in this study, we first review the available literature on site amplification and foundation factors and after propose a new and practical site classification method based on the fundamental period of the thin soil cover site. The new site classification method is then applied to derive the surface acceleration in the Fox Creek, AB area (study area), which has experienced a number of small to moderate induced seismic events in the recent years.

2 SUBSURFACE CONDITIONS AND SEISMICITY

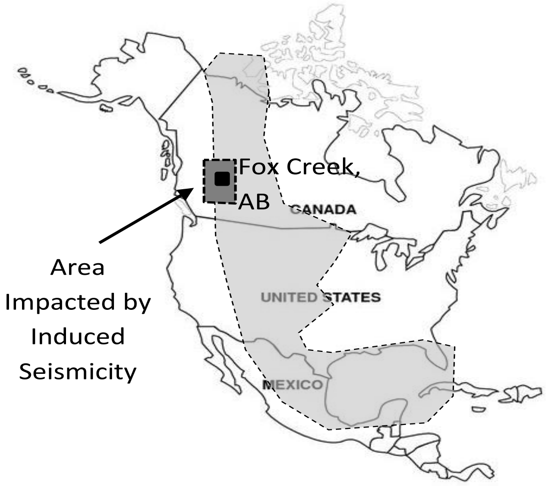
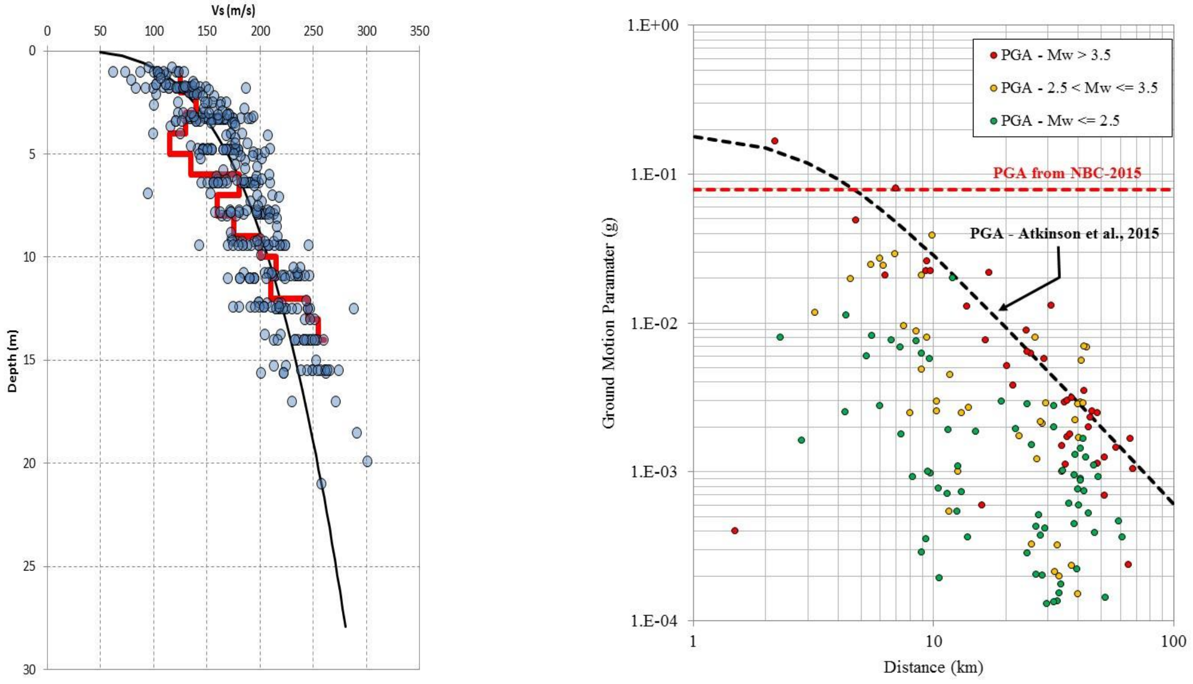


Figure 1. Study area and extent of subsurface conditions considered in this study

The area considered in this study is around the town of Fox Creek, AB (Figure 1), covers about 50 km2 and is characterized by a thin sedimentary cover, highly variable in thickness and geotechnical characteristics but generally less than 15m consists of glacial and post-glacial sediments (till) resting on tertiary clay shale rock. A total of eighty-six boreholes were found in the study area. In about 70% of the cases, boreholes hit the shale clay rock before completion at an average depth of around 9 m. The glacial till has shear wave velocities increasing with depth and ranging from 150 m/s to 250-300 m/s (Figure 2a). One downhole shear wave velocity measurement is available and substantially confirmed this trend (Figure 2a). The clay



(a) (b)

shale rock in the area can be classified according to the National Building Code of Canada (NBC - NRC, 2015) as soil class C (very dense soil and soft rock), with the average shear wave velocity v_(s,30), generally between 450 and 650m/s. Shear wave velocity measurements of clay shales are not too frequent, however the few data available in the area (Suthaker and Tweedie, 2009) confirm that the clay shale behaves as a site C type of rock, with the variability mostly driven by the presence or absence of sandstone and by the degree of overconsolidation sustained by the clays. The subsurface conditions described above are very common in North-America, east of the Rocky Mountains (Figure 1, shaded area).

The induced seismicity in the area is characterized by shallow earthquakes of short duration and short period content, with typical response of a thin soil cover having the maximum amplification occurring between 0.15 and 0.3s. Figure 2b shows the Peak Ground Accelerations (PGA) as function of the hypocentral distance and magnitude recorded by Shell stations located at different distances from the epicenter between January 1, 2015 and December 2017. Figure 2b also shows the Ground Motion Prediction Equation (GMPE) developed by Atkinson (2015) for the area and the tectonic PGA for the area given in NBC (NRC, 2015). The maximum magnitude recorded in the area was 4.3 on January 11, 2016.

3 SITE AMPLIFICATION OF THIN SOIL SITES

The effect of the soil cover on the intensity of the ground motion at the surface can be described by the site-specific, period-dependent and intensity-dependent amplification function, $A(T)$ defined as (Bazzurro and Cornell, 2004a):

$$A(T) = S_{a,s}\ (T)/S_{a,r}\ (T) \qquad [1]$$

Where T is the generic period of the oscillator, and $S_{a,s}\ (T)$ and $S_{a,r}\ (T)$ are the 5%-damped response spectra at ground surface and rock level respectively. An estimate of $A(T)$ distribution can be obtained through nonlinear dynamic analyses of the soil response. Several nonlinear and equivalent-linear models are available to estimate the distribution of $A(T)$, such as Shake (Schnabel, 1972), and Strata (Kottke and Rathje, 2009). If the thin soil cover is assumed to be undamped and uniform, an analytical expression for the amplification function is available (Kramer, 1996)

$$A(T) = 1/\left(\sqrt{cos^2 k_s H + \alpha_z sin^2 k_s H}\right) \qquad [2]$$

Where k_s is the wave number of the soil layer, defined as the ratio of the circular frequency ω and the soil shear wave velocity $v_{s,s}$, and α_z is the impedance ratio defined as

$$\alpha_z\ = \rho_s v_{s,s}/\rho_r v_{s,r} \qquad [3]$$

The amplification function $A(T)$ is the largest at the fundamental period of vibration of the soil layer T_0 which is

$$T_0 = 4H/v_{s,s} \qquad [4]$$

The analytical expression in Eq. (2) indicates that, at the fundamental period of vibration T_0 of the thin soil layer, the amplification function $A(T)$ increases as the stiffness contrast between rock and soil increases. Note that the fundamental period of vibration for thin soil layers is generally short and exceeds 0.5 seconds only when the soil thickness exceeds 20 - 25m and the shear wave velocity is less than 150m/s. Thick and soft soil deposits have longer fundamental period of vibration. It is also important to note that when the soil response is nonlinear as result of large ground motion, the shear wave velocity decreases and the fundamental period of vibration T_0 increases. Thus, the fundamental period of vibration T_0 is intensity-dependent and the typical site classification based on $v_{s,30}$ or *N* reflects low-intensity ground motion and linear response. From now on, we will use $T_{0,lin}$ to describe the linear (initial) period of vibration of the site, and $T_{0,nonlin}$ the non-linear period of vibration during the maximum intensity of the shaking.

Depending on the extent of the area where the seismic hazard is to be estimated, soil and geometry variability is of importance for the site amplification function $A(T)$. When the extent of the area is large, the degree of subsurface variability becomes large having two effects on the site amplification. Firstly, the average site amplification is reduced and smoothed. Secondly, the subsurface variability dominates over the record-to-record variability (Bazzurro and Cornell, 2004b). Therefore, the subsurface variability is a necessary qualifier when defining the ground motion hazard. In typical site-specific response studies, the amount of subsurface variability is generally less than the record-to-record variability. Bazzurro and Cornell (2004a) found that, when the typical coefficient of variation (COV) of the soil shear wave velocity is less than 0.2 and the geometry of the soil layers does not vary too much, the variability of the amplification function $A(T)$ mostly depends on the record-to-record variability, best represented by the spectral acceleration at rock level, $S_{a,r}(T)$, whereas the soil variability is of secondary importance.

The foundation factors *F(T)* given in design codes are provided in terms of either the mean or any other meaningful statistics of the amplification function $A(T)$, calculated over vibration period ranges of engineering interest. In essence, *F(T)* is a discrete form of the continuous amplification function $A(T)$ to be used for engineering design. Borcherdt (1992) was the first to use the average shear wave velocity $v_{s,30}$ of a site as a continuous measure of site conditions and developed frequency-dependent foundation factors that are continuous functions of $v_{s,30}$ determined with respect to the Franciscan rock formation in California. The shear wave velocity in the Franciscan rock is less than 1100 m/s. Borcherdt (1992) determined foundation factors by averaging the amplification function $A(T)$ over the period range 0.1–0.5 s for the short period range, and over the period range 0.4–2.0 s for the mid period range.

Since the fundamental work of Borcherdt (1992), foundation factors *F(T)* have been traditionally correlated to the average properties of the top 30 m of soil, preferably characterized either in terms of the average shear wave velocity $v_{s,30}$, or as the SPT blow-count *N*. In its most recent version, NBC (NRC, 2015) adopts the original approach of Borcherdt (1992) included in NEHRP (2003) and slightly modified by Finn and Wightman (2003) for Canadian applications, and specifies foundation factors *F(T)* for five site classes, ranging from Class A, hard rock, to Class E, soft soil. Humar (2015) describes how *F(T)* in NBC 2015 are derived for 6 different vibration periods (0.2, 0.5, 1.0, 2.0, 5.0 and 10.0s) and what $v_{s,30}$ values were used to determine them for each site class. In addition, for the same site class and period of vibration, different values of the foundation factor *F(T)* are provided for different PGAs, recognizing that response non-linearity caused by strong ground motion has the effect of reducing the soil amplification.

4 AMPLIFICATION FUNCTION AND FOUNDATION FACTORS OF A THIN TILL COVER ON SITE C ROCK

We derived a new set of non-linear amplification functions by studying the correlation between $A(T)$ and the linear fundamental period $T_{0,lin}$ of the thin soil cover, considering different values of the 5%-damped spectral acceleration at rock level, $S_{a,r}(T)$. The rock conditions considered in this study are typical soft rock or hard soil conditions (site class C according to NBC – 2015). The linear shear wave velocity $v_{s,r}$ of the soft rock is considered uniformly distributed ranging between a minimum of 360 and a maximum of 760 m/s and with a damping ratio of 1%. Considering a combination of different linear soil shear velocities $v_{s,s}$ and soil thicknesses *H*, five soil classes are associated to ranges of the fundamental period of vibration $T_{0,lin}$ (Table 1). Note that a certain fundamental period of vibration $T_{0,lin}$ can be the result of multiple combinations of $v_{s,s}$ and *H*. For instance, a site with the pair $v_{s,s}$ = 110 m/s and *H* = 4m and a site with the pair $v_{s,s}$ =240 m/s and *H*=9m have both a fundamental period of vibration $T_{0,lin}$ of 0.15s and would both be classified in Soil Class 2. For the application of proposed methodology, it is important that the COV of the fundamental period of vibration $T_{0,lin}$ remains below 0.2.

The nonlinearity of the response as result of the ground motion intensity was taken into account by using the stiffness and damping degradation model of Vucetic and Dobry (1991) for plasticity index (PI) of 15, which closely matches the PI normally observed in glacial till sediments. The uncertain correlation between the amplification function $A(T)$ and the linear fundamental period $T_{0,lin}$ was modelled by randomization of the subsurface layering according to the approach proposed by Toro (1995) and implemented in Strata (Kottke and Rathje, 2009). The randomness of the soil thickness *H* was modelled with a uniform distribution with the truncation limits shown in Table 1.

Table 1 – Soil Classes

Soil Class	$T_{0,lin}$ (s)	$v_{s,s}$ (m/s)	*H* (m)
1	$T_{0,lin}$ < = 0.1	120 - 250	3 - 6.5
2	0.1 < $T_{0,lin}$ <= 0.2	100 - 250	3 - 9
3	0.2 < $T_{0,lin}$ <= 0.4	100 - 250	4 - 15.5
4	0.4 < $T_{0,lin}$ <= 0.6	100 - 250	6.5 - 27
5	0.6 < $T_{0,lin}$ <= 0.8	100 - 200	11.5 - 27

A Monte Carlo (MC) simulation was executed to model the population of the amplification function $A(T)$. For each of the five soil classes, twenty realizations of the soil cover were used to calculate the response to twenty-five different synthetic earthquakes derived from Random Vibration Theory (RVT), for a total of five hundred realizations of the amplification function $A(T)$. The twenty-five synthetic earthquakes represent a random sample of different distances (minimum 3.5 km and maximum 147 km), magnitudes (minimum 4.9 and maximum 8.1) and depths (minimum 2 km and maximum 7 km) to provide a range of PGA and PGV representative of the record-to-record variability. The model allows non-linear response and softening by utilizing a linear-equivalent degradation scheme of the stiffness and damping (Kottke and Rathje, 2008).

The calculated values of the amplification function $A(T)$ were correlated against $T_{0,lin}$ for the period of vibrations T_{osc} considered by NBC (NRC, 2015), 0.2s, 0.5s, 1s, and 2s. The results of the MC simulation are in Figure 3 for T_{osc} = 0.2s and for T_{osc} = 0.5s. The amplification function $A(T)$ is calculated as the ratio between the 5%-damped surface response spectrum $S_{a,s}$ (T) and the outcropping 5%-damped response spectra of rock $S_{a,r}$ (T) as in Eq, (1). We use the outcropping 5%-damped response spectra of rock $S_{a,r}$ (T) to mimic the design process where the available outcropping 5%-damped response spectra of the reference rock conditions $S_{a,r}$ (T) is multiplied by foundation factors to generate the design surface ground motion.

Figure 3 indicates that $A_{T_{osc}}$ increases from unity at very low $T_{0,lin}$ to its maximum around T_{osc}. For fundamental periods of vibration larger than $T_{0,lin}$, $A_{T_{osc}}$ decreases from its maximum to values that become lower than unity when $T_{0,lin}$ >>T_{osc}. Since the shape of the regression of $A_{T_{osc}}$ resembles the damped response of a homogeneous soil layer on damped elastic rock, we used the following model for the regression of $A_{T_{osc}}$:

$$A_{T_{osc}}=\frac{1}{\left|cos\left(\frac{T_{0,lin}\cdot b}{a}\right)+i\cdot c\cdot sin\left(\frac{T_{0,lin}\cdot b}{a}\right)\right|} \qquad [5]$$

Where | | indicates the absolute value, a, b, and c are the regression parameters, and *i* is the imaginary unit. The proposed model captures all the features of the thin layer amplification, as it is equal to unity at very low $T_{0,lin}$, reaches a maximum around T_{osc}, and decreases asymptotically to zero for $T_{0,lin}$ >>T_{osc}. Another important observation is that the magnitude of $A_{T_{osc}}$ depends on the intensity of the ground shaking. $A_{T_{osc}}$ are therefore sorted according to the intensity of the ground motion at rock level $S_{a,r}(T_{osc})$. Figure 3 shows that, as $S_{a,r}(T_{osc})$ increases, $A_{T_{osc}}$ decreases, with the lager decrease for $T_{0,lin}$ >>T_{osc}. It can also be observed that the variability of $A_{T_{osc}}$ around $T_{0,lin}$= T_{osc} is smaller than at other fundamental periods of vibrations. The reason is that around $T_{0,lin}$= T_{osc} the variability of $A_{T_{osc}}$ depends only on the shear wave velocity of rock, $v_{s,r}$ and soil $v_{s,s}$, and damping. At any other fundamental period $T_{0,lin}$, the variability of $A_{T_{osc}}$ depends not only on $v_{s,r}$ and $v_{s,s}$ but also on the soil thickness *H*. Finally, it is interesting to note that $T_{0,nonlin}$ can be much larger than $T_{0,lin}$, depending on the intensity of the ground shaking $S_{a,r}(T_{osc})$. As consequence, the regression $A_{T_{osc}}(T_{0,lin})$ has the effect of squeezing the data and artificially increasing the variability at any $T_{0,lin}$.

The regression models from Eq. 5 are shown in Figure 4 for $A_{T_{osc}}$ at 0.2s, 0.5s, 1s, and 2s. The values of the regression parameters for each $A_{T_{osc}}$ are given in Table 2. The $A_{T_{osc}}$ values are sorted according to the intensity of the 5%-damped rock response spectrum $S_{a,r}$ (T_{osc}) into four groups. Note that the boundaries between the four groups are not the same, due to the fact that the seismic energy decreases with the increase of the period of vibration. For instance, a site with a $T_{0,lin}$=0.2s transmits virtually no energy from rock to surface at $T \gg T_{0,lin}$, therefore the regression A_{2s} is zero at $T \gg T_{0,lin}$,. The regression amplification functions can be incorporated in GMPEs for the Fox Creek area. From the $A_{T_{osc}}$ regression, the foundation factors $F(T_{osc})$ for different intensity of the ground motion at rock level $S_{a,r}$ (T) are derived as the arithmetic mean of the sample population for each soil class (see Table 1) and each intensity class. The sample population consisted of arithmetically spaced $A_{T_{osc}}$ values. The proposed foundation factors F(T_{osc}) are in Table 2.

5 APPLICATION OF FOUNDATION FACTORS FOR FOX CREEK INDUCED SEISMICITY

The foundation factors $F(T_{osc})$ in Table 2 are used to derive the design spectral accelerations according to NBC (NRC, 2015) for the Fox Creek area. The design spectral acceleration is the quantity that it is used in Canada for seismic structural design using the pseudo-static approach of NBC (NRC, 2015). Two locations in the study area are considered for this exercise, at each location, boreholes are available. The average $v_{s,s}$ of the thin till layer was estimated from the SPT blow-count *N*. The thickness *H* was the refusal depth of the boreholes. The $T_{0,lin}$ of each site was determined using Eq. 4. The first site is located 8 km north of the town of Fox Creek and is representative of very shallow soft rock conditions (depth to rock about 5m) with $T_{0,lin}$ equal to 0.14s. The second site is in the town of Fox Creek, has a depth to rock of about 18 m and $T_{0,lin}$ is equal to 0.38s.

The outcropping 5%-damped response spectrum of rock $S_{a,r}$ for the reference site C conditions due to induced seismicity is currently not available for Fox Creek. Work is in progress to develop the response spectrum of rock $S_{a,r}$ (personal communication with E. Yenier, 2017) for the 2,475 years return period. Therefore, we use an early development of the outcropping 5%-damped response spectra of rock $S_{a,r}$ for the reference site C conditions for the 2,475 years return period, which was published in Atkinson et al. (2015). Some modifications were made to the original work of Atkinson et al. (2105) to account for the missing values of $S_{a,r}$ at 0.2s and 2s (Table 3). This is necessary to apply the method proposed in this paper as it requires the values of $S_{a,r}$ at the T_{osc} of interest to derive the foundation factors $F(T_{osc})$. This is one of the major differences with the NBC (NRC, 2015), which instead only requires the peak ground acceleration PGA to define the intensity of the amplification. $S_{a,r}$ in Atkinson et al. (2015) predicts quite large ground shaking at short vibration periods, and therefore large nonlinearity is expected. The design spectral accelerations using the natural seismic hazard in the area are also considered for comparison purposes to assess the effect of moderate shaking and moderate response nonlinearity.

The foundation factors $F(T_{osc})$ for the Fox Creek area derived in this study are shown in Figure 5 for the seismic hazard from Atkinson et al. (2015 – Figure 5a) and from the NBC (NRC, 2015 - Figure 5b) and compared to the foundation factors $F_{NBC}(T_{osc})$ from NBC (NRC, 2015) for site

D conditions ($180\frac{m}{s} < v_{s,30} \leq 360m/s$). The relative difference d shown in Figure 5 is calculated as

$$d = (F(T_{osc}) - F_{NBC}(T_{osc}))/F_{NBC}(T_{osc}) \quad [6]$$

Therefore, a positive difference implies that NBC (2015) underestimates the amplification and vice-versa. The first observation is that NBC (NRC, 2015) can severely underestimate the short period foundation factor $F(0.2s)$ and the corresponding base shear for structures having their fundamental period around this range, for instance a 2-storey timber frame. The underestimate is as high as 45% for low intensity ground motion (Figure 5b) and decreases to around 20% for larger intensity ground motion (Figure 5a). This is explained with the nonlinearity of the response that has the effect of flattening the amplification around unity. Also, the shorter the fundamental period of the site $T_{0,lin}$, the larger the underestimate of the short period foundation factor $F(0.2s)$. The NBC (NRC, 2015) foundation factors $F(0.5s)$ overestimate the response for sites with very short $T_{0,lin}$, the larger the intensity of ground shaking, the lesser the overestimate. In contrast, for longer $T_{0,lin}$, the NBC (NRC, 2015) foundation factors $F(0.5s)$ underestimate the response. For longer periods of vibrations, the NBC (NRC, 2015) foundation factors $F(T_{osc})$ always overestimate the response, with the overestimate ranging between 10-30% at $F(1s)$ and 20-30% at $F(2s)$. Therefore, the vulnerability of structures having fundamental periods larger than 0.5 s (for instance steel moment frames) would be overestimated if the NBC (NRC,2015) foundation factors $F(T_{osc})$ are used. Finally, the foundation factors $F(T_{osc})$ for the subsurface conditions prevalent in the Fox Creek area never exceed 2 and are less than 1.5 for large ground motion in the short period range. This may be the case for other sites having similar geotechnical conditions.

6 CONCLUSIONS

The increase in hazard caused by induced seismicity in the Fox Creek AB area and the observation that existing methodologies to characterize the amplification of thin soil sites are insufficient have motivated the work presented in this paper. A new methodology to characterize the thin soil sites amplification is presented in this paper and is based on the characterization of the linear (initial) site fundamental period of vibration $T_{0,lin}$. The methodology is applicable to sites where soil having shear wave velocities smaller than 270 m/s overlay soft rock characterized by shear wave velocities between 360 and 760 m/s, which corresponds to site C conditions according to NBC (NRC, 2015). The methodology is valid for sites where the variability in shear wave velocity and depth of rock is less than 20%. The results of the work presented herein consist of amplification functions to be used in conjunction with GMPEs and foundation factors to be used for engineering design. The maximum amplification calculated for these subsurface conditions occurs at very short periods and ranges between 1.5 and 1.8 for weak ground motion and is less than 1.5 for strong ground motion.

The advantages of the presented methodology are:

- Amplification functions and foundation factors can be readily derived from available soil investigation and the 5%-damped spectral acceleration at rock level, $S_{a,r}(T)$; in addition, they do not require any advanced soil testing nor numerical analysis;
- It takes into consideration the spectral characteristics of the site response, amplifying and de-amplifying the response according to the local site characteristics;
- It takes into account the profound impact of nonlinearity associated to large ground motion;
- It is compatible with the seismic provisions and the seismic hazard in NBC (NRC, 2015) therefore allowing calculation of base shear force and overturning moment as directed by the code; and
- Although it has been developed for the Fox Creek AB area, it is quite general as amplification functions and foundation factors can be adopted for the site response of large portions of Midwestern North-America characterized by similar geological conditions.

7 REFERENCES

Atkinson, G., 2015. Ground-Motion Prediction Equation for Small-to-Moderate Events at Short Hypocentral Distances, with Application to Induced-Seismicity Hazards. Bulletin of the Seismological Society of America, Vol. 105, No. 2A, pp. 981–992, April 2015, doi: 10.1785/0120140142

Atkinson, G, Ghofrani, H., Assatourians, K., 2015. Impact of Induced Seismicity on the Evaluation of the Seismic Hazard. 11th Canadian Conference on Earthquake Engineering, Victoria, BC, Canada.

Bazzurro, P. and Cornell, A.C., 2004a. Ground-Motion Amplification in Nonlinear Soil Sites with Uncertain Properties. Bulletin of the Seismological Society of America, Vol. 94, No. 6, pp. 2090–2109, December 2004.

Bazzurro, P. and Cornell, A.C., 2004b. Nonlinear Soil-Site Effects in Probabilistic Seismic-Hazard Analysis. Bulletin of the Seismological Society of America, Vol. 94, No. 6, pp. 2110–2123, December 2004

Borcherdt, R.D. 1992. Simplified site classes and empirical amplification factors for site-dependent code provisions. In Proceedings of the NCEER, SEAOC, BSSC Workshop on Site Response During Earthquakes and Seismic Code Provisions, 18–20 Nov. 1992, University of Southern California, Los Angeles, Calif. Edited by G.R. Martin.

Braganza, S., Atkinson, G.M., Ghofrani, H., Hassani, Chouinard, L.B., Rosset, P., Motazedian, D. and Hunter,J., 2016. Modeling Site Amplification in Eastern Canada on a Regional Scale.

Seismological Research Letters Volume 87, Number 4 July/August 2016.

Finn, W.D.L., Wightman, A., 2003. Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada. Can. J. Civ. Eng. 30: 272–278 (2003).

Finn, W.D.L., Ruz, F., 2015. Amplification Effects of Thin Soft Surface Layers: A Study for NBCC 2015. In A. Ansal, M. Sakr (eds.), Perspectives on Earthquake Geotechnical Engineering, Geotechnical, Geological and Earthquake Engineering 37, Springer International Publishing Switzerland 2015.

Gallipoli M.R., Mucciarelli M., 2009. Comparison of site classification from VS30, VS10, and HVSR in Italy. Bull Seismol Soc Am 99:340–351.

Ghofrani, H, Atkinson, G.M., 2014. Site condition evaluation using horizontal-to-vertical response spectral ratios of earthquakes in the NGA-West2 and Japanese databases Soil Dynamics and Earthquake Engineering 67(2014)30–43.

Humar, J., 2015. Background to some of the seismic design provisions of the 2015 National Building Code of Canada. Canadian Journal of Civil Engineering, 2015, 42(11): 940-952, 10.1139/cjce-2014-0385

Kramer, S. L. (1996). Geotechnical Earthquake Engineering, Prentice-Hall, Inc., Upper Saddle River, New Jersey, 653.

Kottke, A.R, Rathje, E.M.,2009. Technical Manual for Strata. PEER Report 2008/10 Pacific Earthquake Engineering Research Center College of Engineering University of California, Berkeley February 2009

Luzi, L., Puglia, R., Pacor, F., Gallipoli, M.R., Bindi, D., Mucciarelli, M., 2011. Proposal for a soil classification based on parameters alternative or complementary to Vs,30. Bull Earthquake Eng (2011) 9:1877–1898.

Manandhara, S., Chob, H.I., and Kim, D.S.,2017. Site Classification System and Site Coefficients for Shallow Bedrock Sites in Korea. Journal of Earthquake Engineering, DOI: 10.1080/13632469.2016.1277570

National Earthquake Hazards Reduction Program (NEHRP), 2003. NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 450). Building Seismic Safety Council National Institute of Building Sciences, Washington, D.C.

NRC, 2015. National building code of Canada. National Research Council of Canada, Ottawa.

Seyhana, E., and Stewart, J.P., Semi-Empirical Nonlinear Site Amplification from NGA-West2 Data and Simulations. Earthquake Spectra, Volume 30, No. 3, pages 1241–1256, August 2014.

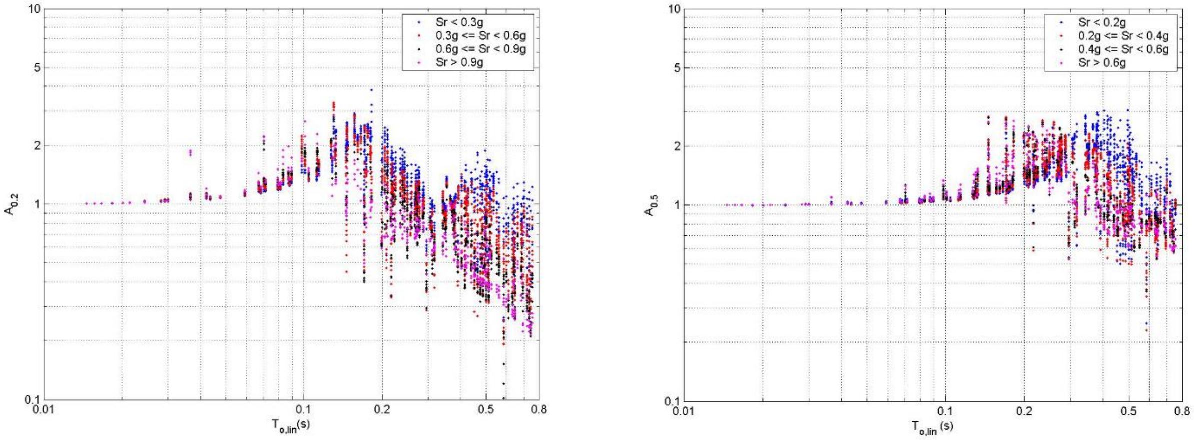
Steidl J.H., 2000. Site response in southern California for probabilistic seismic hazard analysis. Bull Seismol Soc Am 90(6B):S149–S169

Suthaker, N., Tweedie,R., 2009. Comparison of shear-wave velocity measurements by crosshole, downhole and seismic cone penetration test methods. GeoHalifax 2009.

Toro, G. R. (1995). Probablistic models of site velocity profiles for generic and site-specific ground-motion amplification studies. Upton, New york: Brookhaven National Laboratory.

Vucetic, M. & Dobry, R. (1991). Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering, 117:1, 87-107.

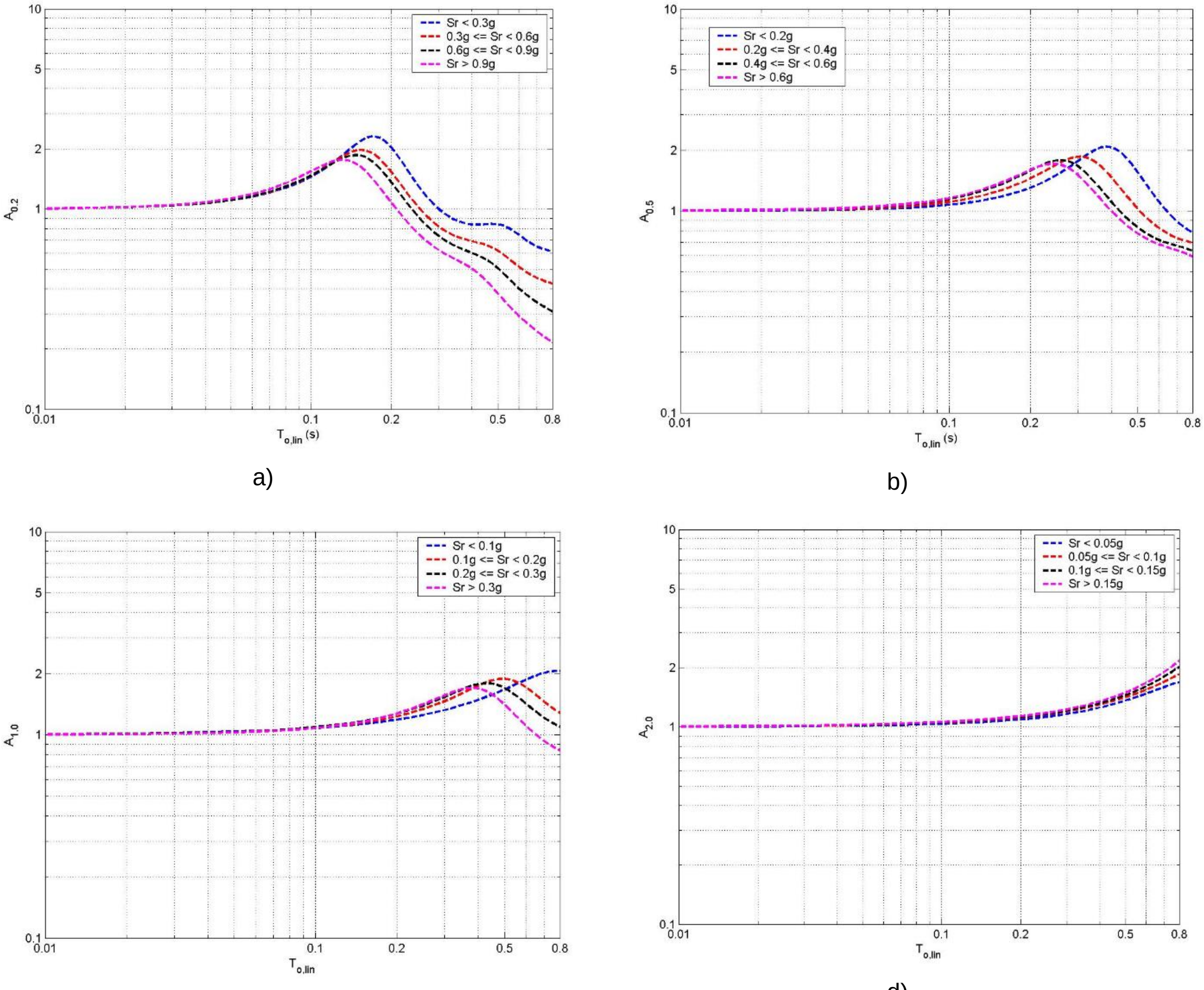
Yenier, E., 2017. Personal communication on Probabilistic Seismic Hazard Analysis from Induced Sesimicity. Nanometrics Inc., Ottawa, ON.



(a)

(b)

Figure 3. Regression of $A_{0.2s}$ on $T_{0,lin}$ (a) and $A_{0.5s}$ on $T_{0,lin}$ (a)



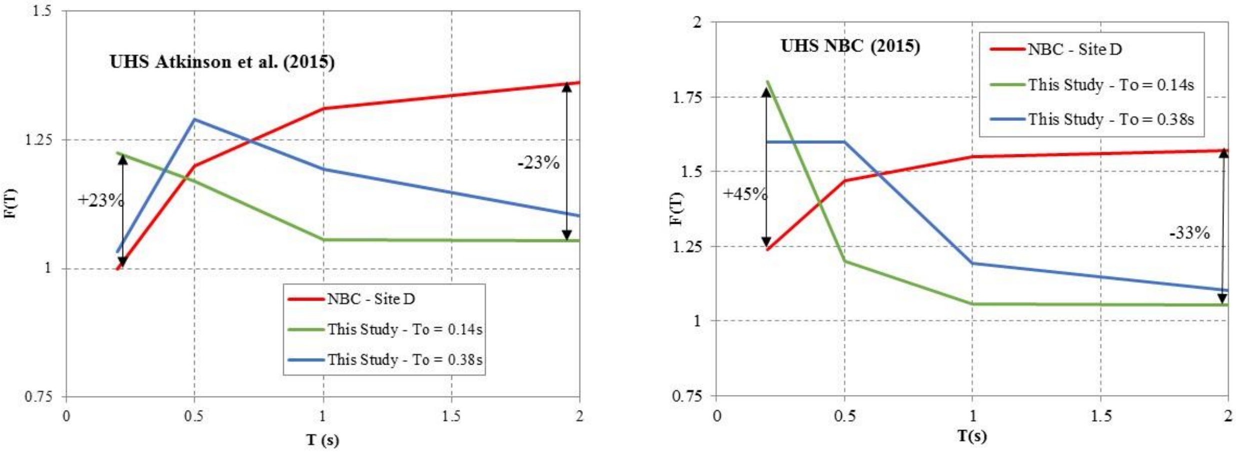
a)

b)

c)

d)

Figure 4. Results of the linear regression analysis of $A_{T_{osc}}$ at 0.2s (a), 0.5s (b), 1s (c), and 2s (d).



a) b)

Figure 5 – Foundation factors $F(T_{osc})$ for the two sites considered in this study – a) $S_{a,r}$ from Atkinson et al. (2015) and b) $S_{a,r}$ from NBC (NRC, 2015)

Table 2 – Coefficients of regression *a* and *b* and foundation factors $F(T_{osc})$

	$A_{0.2s}$		$F(0.2s)$				
Intensity Motion	*a*	*b*	Class 1	Class 2	Class 3	Class 4	Class 5
$S_{a,r}$ <= 0.3g	55	0.28	1.2	1.8	1.6	1.4	1.3
0.3g < $S_{a,r}$<=0.6g	50	0.33	1.2	1.6	1.4	1.2	1.2
0.6g < $S_{a,r}$ <=0.9g	48	0.35	1.2	1.2	1.0	0.9	0.8
0.9g < $S_{a,r}$	43	0.37	1.2	1.2	1.0	0.9	0.8
	$A_{0.5s}$		$F(0.5s)$				
	a	*b*	Class 1	Class 2	Class 3	Class 4	Class 5
$S_{a,r}$<= 0.2g	125	0.3	1.0	1.2	1.6	1.5	1.4
0.2g < $S_{a,r}$<=0.4g	100	0.35	1.0	1.2	1.5	1.4	1.3
0.4g < $S_{a,r}$<=0.6g	85	0.37	1.0	1.2	1.3	1.2	1.2
0.6g < $S_{a,r}$	80	0.39	1.0	1.3	1.3	1.2	1.2
	A_{1s}		$F(1s)$				
	a	*b*	Class 1	Class 2	Class 3	Class 4	Class 5
$S_{a,r}$<= 0.1g	250	0.4	1.0	1.1	1.2	1.4	1.4
0.1g < $S_{a,r}$<=0.2g	60	0.38	1.0	1.0	1.3	1.5	1.5
0.2g < $S_{a,r}$<=0.3g	140	0.4	1.0	1.0	1.2	1.3	1.3
0.3g < $S_{a,r}$	125	0.4	1.0	1.1	1.3	1.4	1.4
	A_{2s}		$F(2s)$				
	a	*b*	Class 1	Class 2	Class 3	Class 4	Class 5
$S_{a,r}$<= 0.05g	300	0.42	1.0	1.1	1.1	1.2	1.2
0.05g < $S_{a,r}$<=0.1g	350	0.35	1.0	1.0	1.1	1.2	1.3
0.1g < $S_{a,r}$<=0.15g	350	0.28	1.0	1.0	1.1	1.1	1.2
0.15g < $S_{a,r}$	350	0.24	1.0	1.0	1.1	1.2	1.3

Table 3 - 5%-damped response spectra for the reference site C in g

	PGA	$S_{a,r}(02s)$	$S_{a,r}(0.5s)$	$S_{a,r}(1s)$	$S_{a,r}(2s)$
Atkinson et al. (2015)	0.3	0.7*	0.55	0.03	0.015*
NBC (2015)	0.08	0.14	0.09	0.05	0.025

*Values assumed