SITE-SPECIFIC RESPONSE ANALYSIS FOR THREE SITES IN THE METRO VANCOUVER REGION OF BC USING THE NBCC 2020 SEISMIC HAZARD

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ABSTRACT

The new 6th Generation seismic hazard model has been developed by the Geological Survey of Canada to provide updated seismic hazard values for the 2020 National Building Code of Canada (NBCC). The new hazard model generally involves a significant increase to the hazard values compared to the current 2015 NBCC values. For example, the peak ground acceleration for firm ground (Site Class C) in Vancouver will increase by 40%. For design purposes, the near-surface foundation level seismic hazard is of particular interest. As the firm-ground conditions are often located at depth, it is critical to assess the amplification or deamplification effects of the soils above firm ground. The near-surface seismic hazard primarily depends on the ground conditions, including the depth to firm-ground from the ground surface. With this background, a non-linear 1D site-specific seismic hazard assessment was performed for three different sites in the Lower Mainland region of British Columbia with varying depths to firm ground. The input motions were scaled to match the 2020 NBCC acceleration response spectrum for 1 in 2475yr hazard. Analyses were also undertaken based on the 2015 NBCC motions for comparison purposes. The fundamental period of the soil profile was considered in selecting the periods of interest for motion scaling. The site-specific response spectrum was compared to the 2020 NBCC Site Class E response spectrum. The results indicated significant deamplification of the hazard, particularly for deep soil profiles. This study indicated that the near-surface hazard obtained from the site-specific nonlinear ground response analyses is generally lower than the generic values of NBCC 2020 at periods outside the fundamental period of the soil column. Additionally, while there was a significant increase from the NBCC 2015 to the NBCC 2020 firm-ground seismic hazards, the near-surface site-specific hazard was similar for the sites considered in this study.

ABSTRAIT

Le nouveau modèle d'aléa sismique de 6e génération a été développé par la Commission géologique du Canada pour fournir des valeurs d'aléa sismique mises à jour pour le Code national du bâtiment du Canada (CNBC) 2020. Le nouveau modèle de danger implique généralement une augmentation significative des valeurs de danger par rapport aux valeurs actuelles du CNBC de 2015. Par exemple, l'accélération maximale du sol pour un sol ferme (site de classe C) à Vancouver augmentera de 40 %. À des fins de conception, l'aléa sismique au niveau de la fondation près de la surface présente un intérêt particulier. Comme les conditions de sol ferme sont souvent situées en profondeur, il est essentiel d'évaluer les effets d'amplification ou de désamplification des sols au-dessus du sol ferme. L'aléa sismique près de la surface dépend principalement des conditions du sol, y compris la profondeur du sol ferme à partir de la surface du sol. Dans ce contexte, une évaluation non linéaire 1D des risques sismiques spécifiques au site a été réalisée pour trois sites différents dans la région du Lower Mainland de la Colombie-Britannique avec des profondeurs variables jusqu'au sol ferme. Les mouvements d'entrée ont été mis à l'échelle pour correspondre au spectre de réponse d'accélération du NBCC de 2020 pour un danger de 1 sur 2475 ans. Des analyses ont également été entreprises sur la base des requêtes du CNBC de 2015 à des fins de comparaison. La période fondamentale du profil du sol a été considérée dans la sélection des périodes d'intérêt pour la mise à l'échelle du mouvement. Le spectre de réponse spécifique au site a été comparé au spectre de réponse de classe E du site NBCC 2020. Les résultats ont indiqué une désamplification significative de l'aléa, en particulier pour les profils de sols profonds. Les résultats de cette étude ont indiqué que le danger près de la surface obtenu à partir des analyses de réponse du sol non linéaires spécifiques au site est généralement inférieur aux valeurs génériques du NBCC 2020 à des périodes en dehors de la période fondamentale de la colonne de sol. De plus, bien qu'il y ait eu une forte augmentation entre les risques sismiques de sol ferme du CNBC 2015 et ceux du CNBC 2020, les risques spécifiques au site près de la surface étaient similaires pour les sites pris en compte dans cette étude.

1 INTRODUCTION

Soft soil deposits tend to alter earthquake ground motions as they travel from firm ground or bedrock, located at depth, to foundation level, typically near the ground surface. Motions are either amplified or deamplified depending on several factors, including the predominant period of the motion and the fundamental period of the soil profile. The latter depends on the shear wave velocity of the soil and the thickness of the soil profile above the firm ground or bedrock. During strong ground motions, the response of soft soils will be nonlinear as shear modulus is reduced and damping is increased. This can reduce the amplification of strong ground motion or even lead to a deamplification compared to a bedrock site (Beresnev & Wen, 1996).

The National Building Code of Canada 2015 (NBCC 2015) captured the amplification/deamplification effects of local soil conditions by providing site factors, which could be applied to the reference Site Class C (firm ground) Uniform Hazard Spectrum that can be obtained from the Earthquakes Canada website using the site coordinates. The site factors were primarily based on the Peak Ground Acceleration (PGA) and on V_{s30}, a site characterization parameter calculated based on the shear wave velocity in the top 30 m of the soil profile. The new NBCC 2020 removes the need for users to look up amplification factors as the amplification functions are directly embedded within the seismic hazard model (Kolaj, Adams, & Halchuk, 2020). Seismic hazard is computed directly for various site conditions and provided to the users for their specific Site Class and/or V_{s30}.

As the NBCC 2015 and NBCC 2020 seismic hazard models both rely on averaging parameters such as V_{s30}, they do not consider the complexities of the local soil conditions at a given site, including the effects of dynamic soil properties and the duration of the ground motion or its frequency content (Finn & Wightman, 2003). One way of addressing such limitations in the models would be to incorporate an additional parameter for the estimation of site amplification, such as the site period, as it explicitly accounts for both shear wave velocity and profile depth (Kamai, Abrahamson, & Silva, 2016; Kolaj, Adams, & Halchuk, 2020).

Rather than using the generic seismic hazard values from Earthquakes Canada website, NBCC 2015 and NBCC 2020 allow practitioners to perform site-specific response analyses to assess the amplification/deamplification at a site, which has been traditionally undertaken using a one-dimensional (1D) equivalent-linear approach using the software SHAKE2000. Due to the limitations of the equivalent-linear approach in simulating the soil earthquake motions propagation, particularly for soft soil at relatively large shear strains, it had been common practice recently to rely on a non-linear total stress approach using the software D-MOD2000 or more commonly DEEPSOIL (Hashash, et al., 2017). DEEPSOIL solves the equation of seismic wave propagation in the time domain while considering the nonlinearity of the cyclic behavior of the soil based on a constitutive model.

With the development of the 6th Generation seismic hazard model by the Geological Survey of Canada that was adopted by the NBCC 2020, it is of interest to assess the seismic response of key local (Metro Vancouver) sites using the new hazard values given that the new hazard model generally involves a significant increase in the hazard values compared to the 2015 NBCC hazard. For example, the Vancouver's peak ground acceleration for firm ground (Site Class C) has increased by 40%. For design purposes, the near-surface foundation level seismic hazard is of particular interest. As the firm-ground conditions are often located at depth, it is critical to assess the amplification or deamplification effects of the soils above firm ground.

With this background, this study presents the results of nonlinear site-specific response analyses performed for three soft soil sites in the Metro Vancouver Region of British Columbia using seismic records scaled to the previous NBCC 2015 and current NBCC 2020 firm ground (Site Class C) uniform hazard spectra. The obtained site-specific response spectra near the ground surface were then compared to the generic response spectra for site classes D and E.

2 SOIL PROFILES

2.1 Site Descriptions

Three sites in the Metro Vancouver Region of British Columbia with varying depths to firm ground were considered in the study. The shear wave velocity data was obtained from publicly available Seismic Cone Penetration Testing (SCPT), cross-hole shear wave velocity measurements, and data obtained from the Geological Survey of Canada open files. The selected sites are located as follows:

- Site 1: The George Massey Tunnel, Delta, BC (49°07'33.6"N 123°04'48.0"W).
- Site 2: South of the Oak Street Bridge, Richmond, BC (49°12'00.0"N 123°07'12.0"W).
- Site 3: The North Shore Wastewater Treatment Plant, North Vancouver, BC (49°19'12.5"N 123°08'12.6"W).

The soil profiles at Sites 1 and 2 consist of Fraser River deltaic deposits of interbedded silts and sands overlying a thick layer of silt which extends to firm ground. Firm ground was considered at 200 m for Site 1 and 55 m for Site 2. This is based on measured shear wave velocity at these depths corresponding to about 450 m/s (i.e., firm ground as per the NBCC 2015 commentary). The soil profile at Site 3 generally consists of granular soils interbedded with silt layers. Firm ground was encountered at a depth of 88 m. The shear wave velocity, V_{s30}, values calculated for the three sites are presented in Table 1. The shear wave velocity profiles considered in the analyses are presented in Figure 1. It is noticed that the three sites have similar shear wave velocity values with the key difference being the depth to firm ground and soil types (primarily granular soils for Site 3, and interbedded sand and silt and silt for Sites 1 and 2).

Table 1. Soil profiles considered

Sites	Firm Ground Depth (m)	V_{s30} (m/s)	Site Class
1	200	180	E
2	55	177	E
3	88	194	D

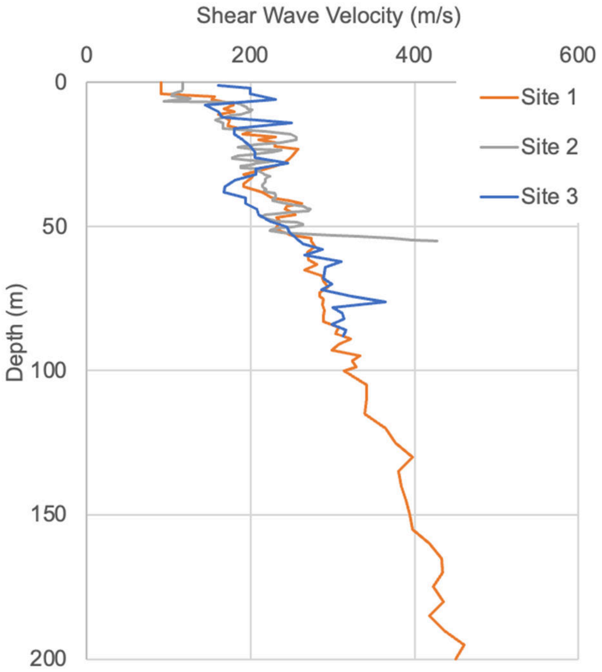

Figure 1. Shear wave velocity profiles considered in this study.

2.2 Soil Properties

The soils at each site were characterized using borehole logs and CPT results. Unit weights and plasticity index were assigned based on experience with nearby soils in the areas of the sites.

For the sand layers, friction angle was calculated according to Robertson and Campanella (1983), and shear strength was calculated using Mohr-Coulomb. The shear strength of the silt layers was computed using Robertson and Cabal (2015). We note that soil shear strength is one of the inputs required for non-linear site-response analyses.

3 METHODOLOGY

3.1 Numerical Modeling Procedure

Total stress nonlinear ground response analyses were performed using the Generalized Quadratic/Hyperbolic (GQ/H) model in DEEPSOIL v7.03 (Hashash, et al., 2017). The GQ/H model allows the shear strength of the soil at failure (i.e. large shear strain) to be defined while still providing the ability to represent small-strain stiffness nonlinearity.

The soil profiles for each site were divided into sublayers such that the maximum propagable frequency was 30 Hz. Input modulus reduction and damping curves were defined for each layer based on Darendeli (2001). The elastic half-space was defined using a shear wave velocity of 450 m/s, a unit weight of 22 kN/m^3 and a damping ratio of 2% to represent the firm ground conditions below the base of the soil profiles.

3.2 Input Seismic Motions

This study used 22 (6 inslab, 6 crustal and 8 subduction) earthquake ground motion records. These motions were previously developed for the George Massey Tunnel Replacement project in Delta, British Columbia and had been spectrally-matched to the NBCC 2015 Site Class C target spectrum (Monroy, Hull, & Atukorala, 2016). The seed motions were obtained from the UC Berkeley Pacific Earthquake Engineering Research (PEER) Center, Consortium of Organizations for Strong-Motion Observations Systems (COSMOS) and the University of Chile and S2GM databases.

As part of this study, these motions were linearly scaled to the 2475-year return period NBCC 2020 X_{450} target spectrum according to Tremblay et al. (2015). The crustal and inslab spectra were matched to periods of less than 1 second and 2 seconds, respectively. The subduction earthquakes were matched to periods greater than 2 seconds. The matching was performed such that the average spectrum from each source does not fall by more than 10% below the target spectrum within the period ranges of interest.

The ground motions used in this study are presented in Table 2.

Table 2. Input seismic motions used in this study

Earthquake Name	Magnitude	Recording Station	Comp
El Salvador (2001-01-13)	7.6	Ciudadela Don Bosco (DB-7157)	180 270
Miyagi-Oki (2005-08-16)	7.2	MYG006	NS EW
Nisqually, WA (2001-02-28)	6.8	7032-1416	050 320
Chile (2005-06-13)	7.8	Iquique Idiem	L T
Hector Mine (1999-10-16)	7.1	Joshua Tree RSN1794	090 360
Landers (1992-6-28)	7.3	Morongo Valley Hall RSN3756	000 090
SMART1Taiwan (1986-11-14)	7.3	O06 RSN580	EW NS
Tokachi-oki (2003-09-26)	8.0	HKD107	EW NS

Tokachi-oki (2003-09-26)	8.0	HKD181	EW NS
Tohoku (2011-03-11)	9.0	YMT008	EW NS
Tohoku (2011-03-11)	9.0	IWT022	EW NS

4 RESULTS AND DISCUSSION

The near-surface design spectra obtained from the nonlinear site-specific response analyses are presented in Figures 2 to 4 for the three sites considered in this study. The figures also include the generic design spectra obtained from the Earthquakes Canada website (i.e. the design spectrum that would have been considered if a site-specific analysis had not been performed) for comparison purposes.

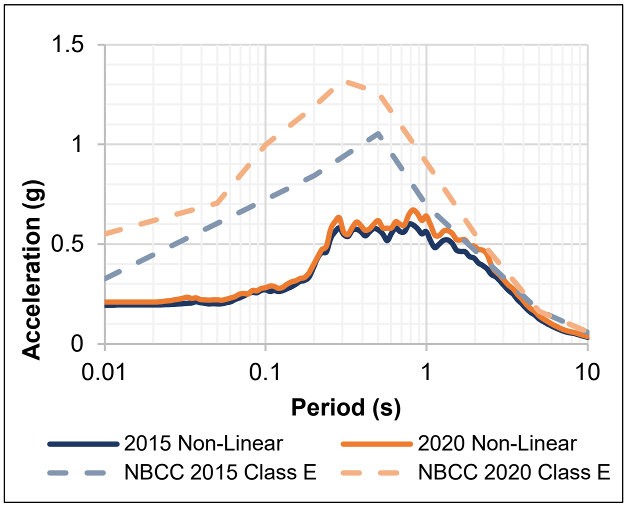

Figure 2. Near-surface Site 1 spectra

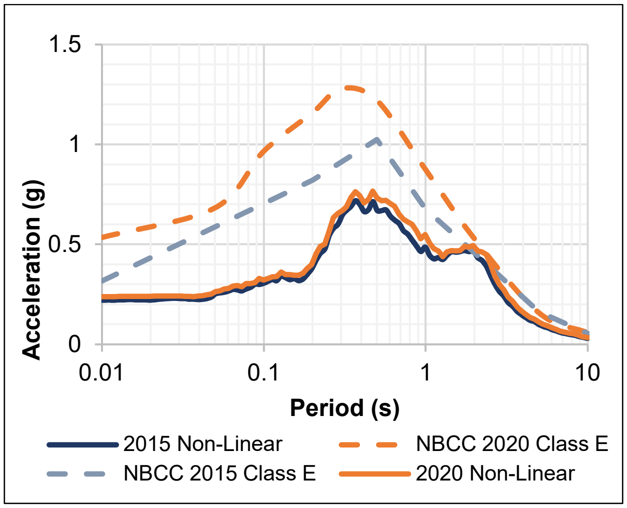

Figure 3. Near-surface Site 2 spectra

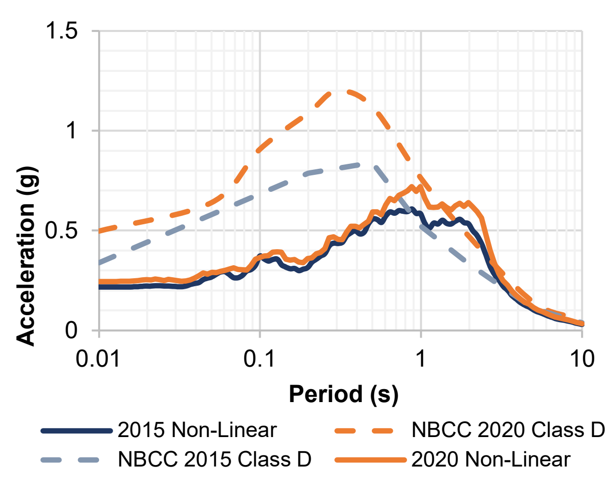

Figure 4. Near-surface Site 3 spectra

A summary of the percent difference between generic code-specified spectral acceleration values obtained from the Earthquake Canada website and the site-specific spectral acceleration values at periods of 0.1s, 0.2s, 0.5s, 1.0s, 2.0s, 5.0s, and 10.0s is presented in Table 3. The table also provides the estimated fundamental period of each of the three sites.

Table 3. Spectral acceleration percent difference with positive values indicates generic code values are higher than site-specific hazard values.

Period (s)	Site 1		Site 2		Site 3	
	2015	2020	2015	2020	2015	2020
0.01	39	61	30	56	36	51
0.1	61	71	56	67	46	60
0.2	54	66	54	66	60	67
0.5	44	49	35	40	34	47
1	17	26	28	37	-12	6
2	6	7	-2	6	-62	-37
5	23	11	38	29	6	19
10	39	37	44	42	19	37
Natural Site Period (s)	2.8		1.1		1.5	

At the three sites considered, the results indicate that the NBCC generic design spectra have significantly higher hazard values when compared to site-specific analysis at periods outside the fundamental period of the soil column. This is likely because the code values are based on generic analyses that do not consider the nonlinear dynamic behaviour of the site, including the fundamental period. The difference become particularly apparent for deep soft soil profiles that are expected to manifest significant deamplification (eg. Site 1 in this study). In these scenarios, undertaking site-specific analyses that captures the nonlinearity of the soft soil response is key to understanding the seismic behaviour of a site. As shear modulus and damping are strain-dependent, the large strains associated with higher accelerations reduce the effective shear modulus and increase damping. This results in deamplification of the input ground motions.

Figures 2 to 4 also show that the near-surface hazard values obtained from the site-specific analyses for both NBCC 2020 and NBCC 2015 hazards were very similar despite the significant increase (about 40% for PGA for Vancouver) in firm ground spectral acceleration values between the two versions of the code.

It is also interesting to note that deamplification of strong ground motions increases with firm ground depth; spectral acceleration values at Site 1 (200 m to firm ground) were lower than at Site 2 (55 m to firm ground). This may be explained by increased damping due to greater thicknesses of soft soils above firm ground.

The maximum shear strain profiles obtained for the three sites are shown in Figure 5. All shear strains were below 1%. The observed increased shear strains at certain depths were typically associated with the presence of a soft to firm fine-grained soil layer. Given that this study was based on non-linear analyses, the non-linear performance of these fine-grained soil deposits was adequately captured by the model.

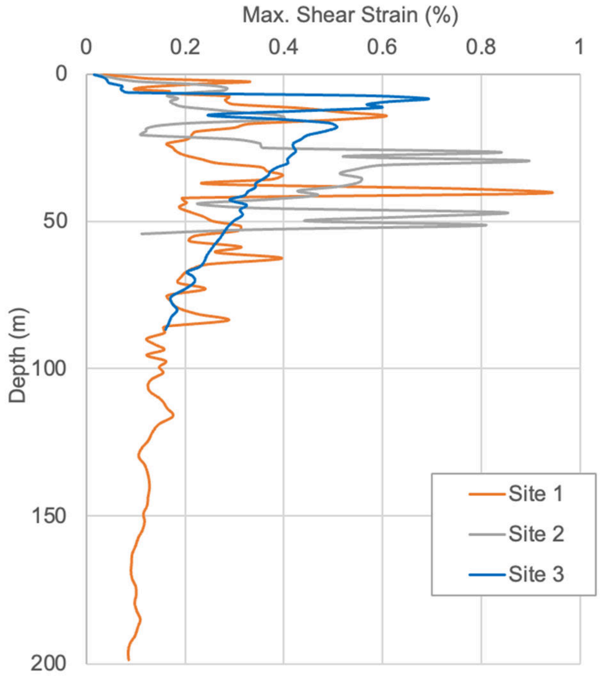

Figure 5. Maximum shear strain profiles for the 3 sites.

5 CONCLUSION

Non-linear 1D site-specific analyses were performed for three sites in the Metro Vancouver region using the new 6th generation firm ground hazard that was adopted in the NBCC 2020. The analyses were also performed using the NBCC 2015 hazard values for comparison purposes. The sites had similar Vs_{30} values. However, the selected sites had significantly different depths to firm ground, fundamental periods and soil characteristics, which are factors generally not considered in the generic hazard values typically obtained from the Earthquake Canada website and using site factors that depend on the seismic site class.

The results of this study indicated that the near-surface hazard values obtained from the 1D nonlinear site-specific ground response analyses are generally lower than the generic hazard values of NBCC 2020 obtained from the Earthquakes Canada website for periods outside the fundamental period of the soil column for the sites considered in this study. Additionally, while there was a significant increase in the firm-ground hazard from the NBCC 2015 to the NBCC 2020, the near-surface hazard values obtained from site-specific analyses were similar. This is likely due to the site-specific analyses capturing the increased nonlinearity of soft soil response due to the higher NBCC 2020 input accelerations and therefore predicting increased deamplification. The above results highlight the benefits of conducting site-specific ground-response analyses particularly for sites with deep soil profiles such as the sites considered in this study.

6 REFERENCES

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