



Comparison of code-oriented site classification in the Saguenay region, Québec

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ABSTRACT

Local geological and geotechnical conditions can have significant effects on the incoming seismic waves and their spatial variation. Commonly referred to as site-effects, certain conditions can significantly amplify the intensity of the seismic shaking and make it more destructive. Site effects are accounted for in national building codes by the selection of amplification factors as functions of soil category, seismic intensity and frequency. The soil type is categorized by considering representative shear-wave velocity, the number of blows in the standard penetration test, and/or undrained shear strength in the top 30 meters. Although soil categorizations based on these geotechnical parameters are more or less similar across earthquake-prone countries, there are some differences, which may result in over- or underestimation of the potential site effects. The Saguenay-Lac-Saint-Jean region (SLSJ) is located in a moderate seismicity zone in Eastern Canada; the last major earthquake in this region occurred in 1988 with a moment magnitude of 5.9. The presence of important deposits of sensitive clays in SLSJ combined with the strong impedance contrast between the unconsolidated deposits and the underlying crystalline bedrock can play an important role in the soil dynamic response. Different soil classification criteria and respective amplification factors are compared: the 2015 National Earthquake Hazards Reduction Program (NEHRP), Eurocode 8, and the 2015 National Building Code of Canada (NBCC). The advantages and disadvantages of each classification approach are discussed.

Keywords: Site-effects, National Codes, The Saguenay region, Site classification, $V_{s,30}$

INTRODUCTION

The geological conditions of near-surface deposits have a significant role in variations of observed seismic motion intensities. These variations can affect the amplitude and frequency content of seismic waves at a particular location, which has been known as site-effect [1]. Significant contribution to the observed damage during past destructive earthquakes was attributed to this phenomenon, e.g. 1985 M8.0 Mexico City, 1989 M6.9 Loma Prieta, etc. Borchardt and Glassmoyer [2] and Borchardt [3] were the first to propose the implementation of geotechnical and geological parameters as identification criteria to empirically delineate the effect of local site classes and associated spectral-frequency dependent amplification factors. Borchardt [3] characterized the local site conditions in terms of time-averaged shear-wave velocity of the top 30 meters, $\bar{V}_{s,30}$. This parameter has been generally adopted in national seismic building codes to determine potential amplification ([4-6]). The standard site classification scheme considers four to five site classes ranging from hard rock, rock with moderate fracturing and weathering, stiff or dense cohesionless soil, to soft clayey or loose sandy soil. This type of classification provides a reliable basis for mapping of local site conditions, and consequently can be adopted for seismic microzonation [7]. Generally, this approach provides a useful guidance for assessing the seismic hazard for a site associated amplification factors. However, it has been questioned, first for its non-applicability in some regions outside of the primary study area (California), and secondly the oversimplification of the site effect by considering the stiffness of the surface layers only as contributing factors [8-12].

Seismic microzonation and site categorization in eastern Canada due to the characteristic geology of overlying soft post-glacial sediments on hard crystalline bedrock cannot be compatible to regions where the soil mechanical properties of deposits increase gradually and steadily with depth [11]. In this region, geological modeling of subsurface layers plays a significant role in the determination of shear-wave velocity and thus site categorization. A number of seismic hazard studies have been carried out recently in southern Ontario and Quebec, and selected results are summarized in Table 1 [13-17]. Motazedian et al. [13] identified three main geological layers for the city of Ottawa on the basis of their distinct shear wave velocity, namely post-glacial, firm glacial and bedrock. The shear wave velocity of the post-glacial deposits, which are the surficial sediments in this region, presents gradually increasing values with depth, described as a V_s -depth profile. Rosset et al. [14] developed three different $\bar{V}_{s,30}$ models for Montreal using predictive equations for the V_s -depth profile: (1) single-layer model based on the total thickness of soft soils, (2) four-layers model based on geological and geotechnical information from borehole data, and

(3) composite model comprising all of the characteristics of the former two models. Nastev et al. [15-16] in the Ottawa and St. Lawrence Valleys, and Foulon et al. [17] in the Saguenay region have implemented similar approach to map the shear-wave velocity and the site fundamental period (T_0). Based on the definition of the $\bar{V}_{s,30}$ in national codes, this parameter can be calculated by Eq. (1) for i layers model [14],

$$\bar{V}_{s,30} = \frac{30}{\left(\sum \frac{h_i}{V_{s_i}}\right) + \frac{(30 - \sum h_i)}{V_{s_{rock}}}} \quad (1)$$

where, h_i and V_{s_i} are the thickness and shear-wave velocity of each i layer, and $V_{s_{rock}}$ is the bedrock shear-wave velocity in case of a thickness of deposits less than 30 meters. Consequently, the spatial distribution of site classes and the microzonation can be mapped over a study area. Due to the high variability of the V_s measurements and the thickness of soil layers, however, the estimated value of $\bar{V}_{s,30}$ includes a considerable uncertainty and a smoothing effect, which challenges the reliability of the averaging process. For example, considering the $V_{s_{rock}}$ as 2500m/s causes a huge difference in $\bar{V}_{s,30}$ along a site column where the total thickness of soil layers range are less than 30 meters.

The objective of this paper is to present site microzonation map of the Saguenay region based on three national codes: the 2015 NEHRP provisions [5], the Eurocode 8 [6], and the National Building Code of Canada 2015, NBCC [4]. The spatial distributions of the site classes determined with these methods are compared and discussed. At the end, the effect on the final results of shear wave velocity values of different geologic layers and different $\bar{V}_{s,30}$ site classification ranges are delineated and evaluated.

Table 1. Shear wave velocity of major Quaternary deposits and bedrock outcrops of eastern Canada region

Authors	Location	Geological unit	Average shear-wave velocity of measurements (m/s)	Velocity-depth regression relationship	Remarks
Motazedian et al 2011	City of Ottawa	post-glacial sediments	~ 150	$V_s = 123.86 + 0.88Z \pm 20.3 \text{ m/s}$	For $10 < Z < 100 \text{ m}$
		firm glacial sediments	580 ± 174	-	Till
		Bedrock	2783 ± 504	-	Pre-Cambrian Migmatic and Metasedimentary
Rosset et al 2015	Montreal	Backfill and peat	~ 155	-	-
		Sand deposits	100 to 500	$V_s = 144.8 + 36.8 Z^{0.57} \pm 54 \text{ m/s}$	-
		Leda clay	80 to 320	$V_s = 121.2 + 40.8 Z^{0.43} \pm 43 \text{ m/s}$	Sensitive marine clay
		Till	565 ± 261	-	-
		Bedrock	2300 ± 590	-	Limestone and Shale
Nastev et al 2016a-b	Ottawa and St. Lawrence Valleys	Postglacial deposits (sand)	165 ± 49 (geometric mean: 158 m/s)	$V_s = 103.1 + 31.1 Z^{0.5} \pm 52 \text{ m/s}$	Fluvial, aeolian, glaciofluvial, glaciolacustrine and deltaic sandy deposits
		Postglacial deposits (clay)	143 ± 46 (geometric mean: 137 m/s)	$V_s = 97.0 + 10.9 Z^{0.5} \pm 41.6 \text{ m/s}$	Marin and glaciolacustrine clay, highly sensitive clay in some cases accompanied by organic sediments
		Till and sub-till sediments	400 ± 152 (geometric mean: 385 m/s)	-	-
		Bedrock	2500 ± 700	-	Precambrian and intrusive rocks
Foulon et al 2018	Saguenay Region	Sandy soils	80 to 260	$V_s = 40.9 + 53.7 Z^{0.5} \pm 29.8 \text{ m/s}$	Post-glacial deposits
		Clays	80 to 250	$V_s = 79.3 + 17.3 Z^{0.5} \pm 45.3 \text{ m/s}$	Glaciomarine clay

GEOLOGY OF THE STUDY AREA

The effect of soft surface deposits and lateral heterogeneity can be evaluated for the Saguenay region using the 3D geo-model developed by Foulon et al. [17]. This model has been constructed by integrating and interpreting the surface quaternary maps [18-21] combined with subsurface data mostly based on borehole logs from various sources [22]. The Quaternary units of the Saguenay region can be integrated into 5 major groups, from bottom of the soil column: till, glaciofluvial gravel and sand, fine glaciomarine sediments (clay and silt), coarse glaciomarine sand and gravel sediments, and various loose post-glacial deposits consisting of alluvium, floodplain, organic sediments and landslide deposits [17,21]. The bedrock geology of Saguenay region makes part of the Grenville geological province and is mainly composed of crystalline Precambrian rocks [23]. The surficial geological map of the Saguenay region (Figure 1a) is based on Daigneault et al. [21]. The surface area of each exposed

stratigraphic unit present in the region is given in Table 2. It can be seen that the surficial geology in the region mainly consist of till, fine post-glacial, coarse post-glacial sediments and bedrock outcrops, with 38%, 30%, 14% and less than 8 percent respectively. Till, in the lowlands, is compact, consolidated and continuous with a thickness from a few meters to more than 10 meters, and it covers the bedrock; whereas, it is discontinuous in highlands, with a thickness decreasing to 1 meter or less [17]. Fine post-glacial sediments, which are mainly composed of clays, present the thickest and most widespread sediments in the Saguenay region. Bouchard et al. [24] proposed a hypothesis of pre-consolidation for these clays, resulting from partial erosion after their deposition; however, further studies are required for evaluating the reliability of these glaciomarine clays for infrastructural development. Figure 1b presents the total thickness of surface-deposits overlying bedrock in the Saguenay region. The thickness of these sediments is mainly in a range of less than 10 meters, but it reaches more than 100 meters in some lowlands area mainly composed of post-glacial sediments.

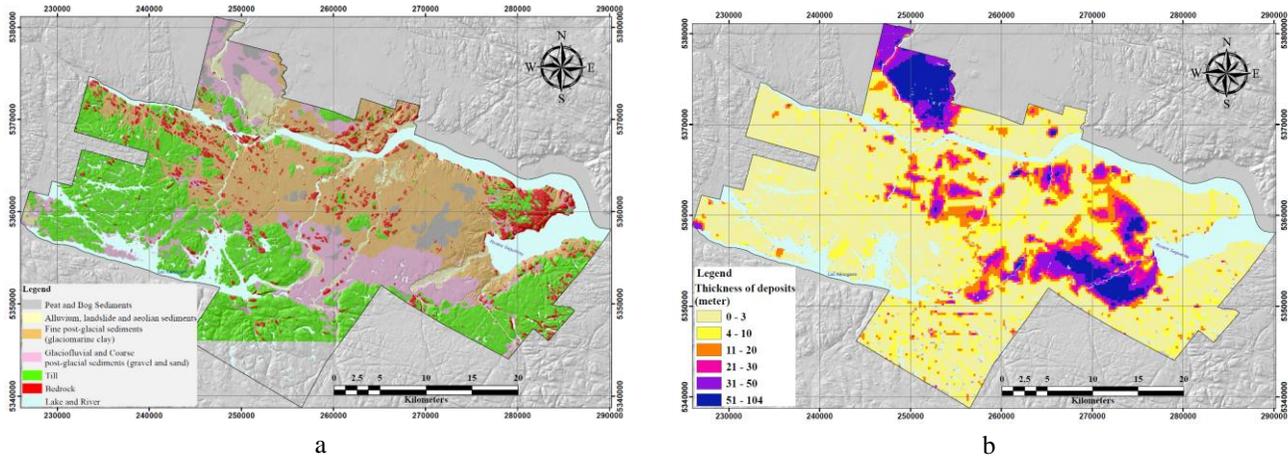


Figure 1. (a) The simplified surface geological map of Saguenay region (modified from [21]), (b) The thickness map of surface-deposits

Table 2. Major geologic units and the area of surface deposits and bedrock outcrops in Saguenay region

Geologic Unit	Area(km^2)	Area (%)
Alluvium	30	2.8
Eolian Sediments	2	0.2
Landslide deposits	28	2.6
Peat and Bog Sediments	41	3.8
Coarse post-glacial sediments (sand and gravel)	149	13.9
Fine post-glacial sediments (glaciomarine clay)	317	29.6
Glaciofluvial sediments (gravel and sand)	16	1.5
Till	407	38.0
Bedrock	81	7.6
Total	1071	100.0

SEISMIC CODE-ORIENTED SITE CLASSIFICATION

National Building Code of Canada (NBCC 2015)

Site classification based on NBCC 2015 [4] is divided into 5 categories (Table 3). Class A and Class B in this code are representative of rock, with an average shear-wave velocity more than 760 m/s for the top 30 m; the other classes are defined for soil profiles. It should be noted that for classes A and B, the thickness of the soft materials must be less than 3 meters; for thicker deposits, the time-averaged shear wave velocity is computed only for the soil above the rock. The additional site Class F includes liquefiable soils, sensitive or highly organic clays more than 3 meters in thickness, or plastic clays more than 8 m in thickness. Consequently, considering these criteria, estimating the thickness of soft soil materials plays a significant role and must be evaluated with a precision of less than 1 meter. These conditions can be applied precisely for a small area, for instance a construction site for a building, yet they are difficult to achieve for a large area such as the Saguenay region. Therefore, some generalization and approximation are required in geological modeling to conduct the seismic microzonation over the Saguenay region. In addition to $\bar{V}_{s,30}$, soil classifications can be undertaken by considering two other parameters such as standard penetration test data (N_{SPT}) and undrained shear strength (S_u). The site coefficients (amplification factors) can be evaluated

based on the site classes and the reference peak ground acceleration for a site. These factors intensify or de-amplify the seismic hazard parameters represented by 5% damped spectral response acceleration values, $S_a(T)$, for six short and long periods to determine the design spectral acceleration values.

National Earthquake Hazards Reduction Program (NEHRP, 2015)

The current 2015 *NEHRP Recommended Provisions for New Buildings and Other Structures* [5] are the source of site classifications in the U.S. [25]. The site classes in both ASCE/SEI 7-16 and NBCC are similar; however, there are some differences in additional definition. For instance, the shear-wave velocity for weathered and highly fractured Site Class B shall either be measured on site or classified as Site Class C (the thickness criteria is not clearly identified). In other words, the interpretation of the quality and continuity of rock Classes A and B in the NEHRP provisions can be dependent on the knowledge of a geotechnical engineer or geologist. Regarding ASCE/SEI 7-16, site coefficients (F_a and F_v) are based on the site shear wave velocity reference of 760m/s (referred to as B/C boundary), and they have been defined for both short and long periods. The site coefficients depend on the intensity of spectral acceleration for two periods (S_s and S_{l1}) and the local Site Class.

Eurocode 8

The Eurocode 8 consists of six parts dealing with different types of construction procedures and rules. Part 1 and part 5 (En 1998-1 and En 1998-5) include the subjects relevant to seismic and geotechnical issues. The approach for soil classification in Eurocode 8 part1 [6] is similar to NBCC and NEHRP and is based on the mechanical parameters of the ground surface. The time-averaged shear wave velocity of the top 30 meters of soil profiles is the lead parameter. It can also be substituted by the number of blows in the standard penetration test (N_{SPT}) or undrained cohesion (undrained shear strength (C_u)). In this way, five Ground Types, denoted A, B, C, D, and E, described by the stratigraphic profiles and classified quantitatively by $\bar{V}_{s,30}$ (Table 3). Two special Ground Types, S1 and S2, are similar to Class F of NBCC or NEHRP for which special studies shall be undertaken to define the required seismic action. Ground types A through D vary from Rock to loose cohesionless or soft cohesive soils. Class E denotes an essential characteristic of ground profiles where there is a sharp contrast between soft surface layers and the stiff or hard underlying formations with V_s values greater than 800 m/s.

The Soil Factors (site coefficients) have been defined for two types of spectral responses: Type 1 and Type 2. Type 1 should be used for sites where the contribution of the seismic hazard of earthquakes with surface-wave magnitude (M_s) is greater than 5.5, otherwise Type 2 is recommended. The main difference between these two spectra is the higher intensity of spectral acceleration for longer periods in Type1. Moreover, there is some modification in soil factors due to the nonlinear behavior of soil during strong ground motion with a higher magnitude.

Table 3. Site Classifications and $\bar{V}_{s,30}$ intervals between the NEHRP, NBCC Provisions and Eurocode 8

Code	Site Class and $V_{s,30}$ (m/s)				
	A	B	C	D	E
NEHRP & NBCC	>1500 ^(*)	760-1500 ^(*)	360-760	180-360	<180
Eurocode 8	>800 ^(**)	360-800	180-360	<180	^(***)

* Soft soil must be less than 3 meters.

** Surface weak materials must be less than 5 meters.

*** $V_s < 360$ m/s and $5 m < H < 20$ m

RESULTS AND DISCUSSIONS

Site classification based on NEHRP and NBCC 2015

Figure 2 presents the spatial distribution and the percentage area of site classes based on NEHRP, NBCC and Eurocode 8 site classifications. Figure 2a shows that 38.1% and 15.9 % of the study area has been delineated as rock site class A and B respectively. These two site classes cover more than the half of the map surface area and they comprise the area with bedrock outcrops and till. Classes C (dense soil and soft rock) and D (stiff soil) comprise 20.5% and 15.3% respectively; only 10.2% of the study area is classified as soft soil (Class E). In other words, due to the shallow bedrock and the effect of shear wave velocity averaging, the site classification based on the $\bar{V}_{s,30}$ results in almost 90% of the area classified as rock, dense and stiff soil with site coefficient of less than 1.00. Whereas, the impedance contrast between the crystalline bedrock and the upper layers of soft soil such as glaciomarine clays, which cover more than 30% of the region, presumably indicates the underestimation of amplification factors. The impact of averaging on the $\bar{V}_{s,30}$ regional distribution is assessed by computing the thickness of each geological unit using the 3D geo-model [17]; then the normalized total thickness is considered as the representative factor in percent (Table 4). The entire thickness of a 30-meter site-column in site classes A to D is mainly composed of bedrock, and the

portions vary from 97.5% for site class A to the 39.7% for site class D. As a result, the impact of high shear wave velocity in the bedrock for site classes C and D results in overestimating $\bar{V}_{s,30}$, especially for areas with a small thickness of various types of unconsolidated sediments over a shallow bedrock.

Table 4. The total normalized thickness (in percent) of geological units contributing to the estimation of $V_{s,30}$ based on NEHRP- NBCC 2015 classification approach

Site Class	Bedrock	Till	Glaciofluvial sediments	Clay	Sand & Gravel	Total
A	97.5%	2.5%	0.0%	0.0%	0.0%	100.0%
B	86.4%	11.0%	0.0%	1.4%	1.1%	100.0%
C	76.3%	7.4%	0.4%	8.4%	7.5%	100.0%
D	39.7%	8.6%	3.6%	28.2%	20.0%	100.0%
E	2.4%	3.5%	2.2%	69.9%	21.9%	100.0%

Site classification based on Eurocode 8

Figure 2b presents the percentage area of site classes based on Eurocode 8. It shows that 53 % of the area has been delineated as rock site class A. Similarly to the result of classification based on NEHRP and NBCC, this site class covers more than half of the study region; it comprises areas with either bedrock or till outcrops. However, the area coverage of very stiff and stiff material, namely Ground Types B and C, decreases to 7.8% and 5.0% respectively in comparison to Classes C and D of NBCC. 10.2% of the study area is covered by soft soil as Ground Type D, and 24.0% of the area has been delineated as Ground Type E, which represents a soil column underlain by rock. The normalized thickness of geological profiles is considered in the estimation of $\bar{V}_{s,30}$ given in Table 5. It can be observed that the normalized portion of bedrock thickness is limited only in the estimation of the Ground Types A and B, which corresponds to the definition of these site classes. The main geological unit in Ground Type C is sand & gravel, and in Ground Type D, it is clay. Based on the definition of Ground Type E, the determination of V_s is only based on the soft materials overlying the bedrock or very stiff soil; therefore, the effect of shallow depth bedrock has been alleviated by outlining this Ground Type.

Table 5. Total normalized thickness (in percent) of geological units contributing to the estimation of $V_{s,30}$ of site classes based on Eurocode 8 classification approach

Ground Type	Bedrock	Till	Glaciofluvial sediments	Clay	Sand & Gravel	Total
A	94.5%	4.8%	0.0%	0.4%	0.3%	100.0%
B	81.6%	7.4%	0.1%	6.2%	4.7%	100.0%
C	14.4%	11.6%	8.4%	22.6%	43.1%	100.0%
D	2.4%	3.5%	2.2%	69.9%	21.9%	100.0%
E*	-	21.5%	2.4%	51.7%	24.4%	100.0%

- V_s estimation

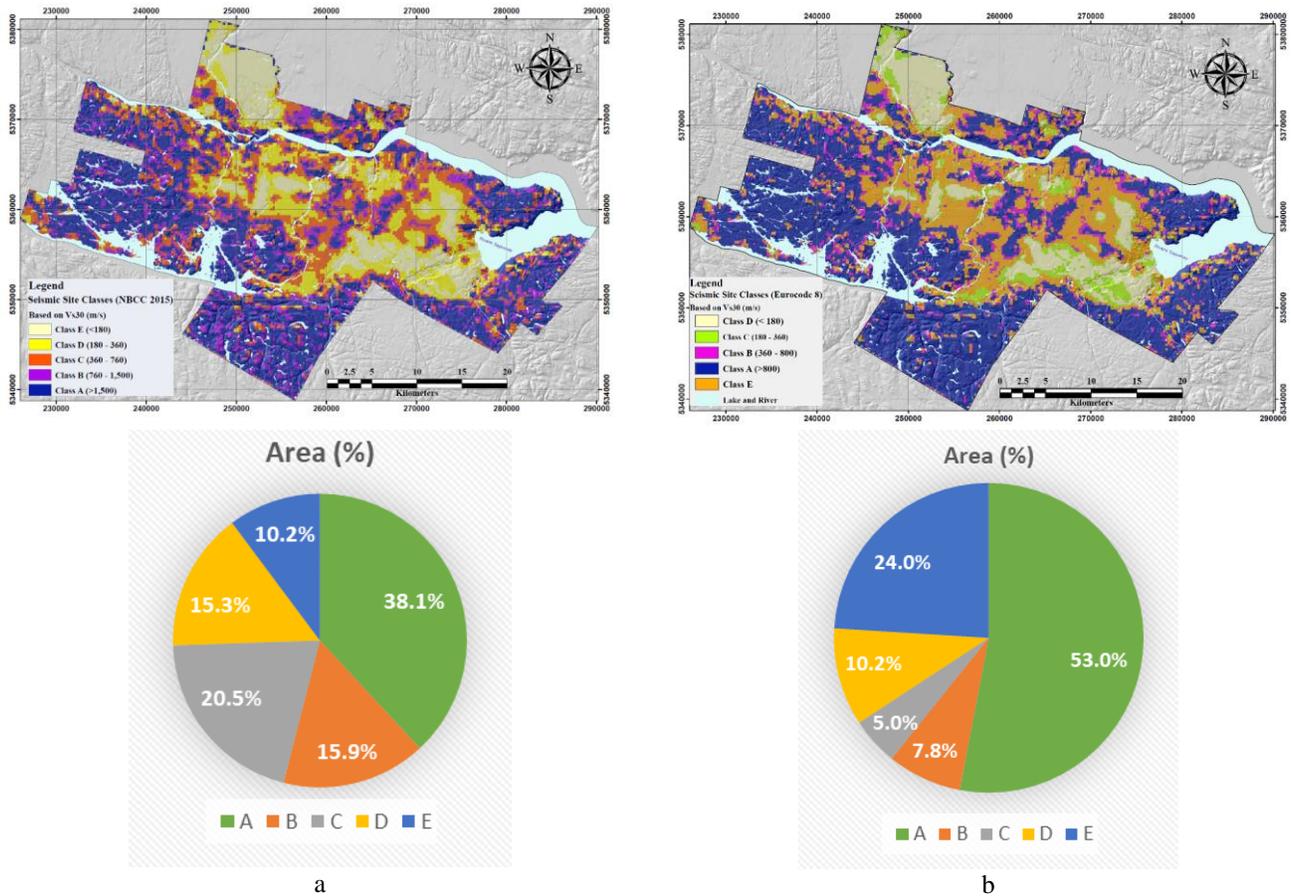


Figure 2. Relative surface area for seismic site classes in the Saguenay region: (a) NEHRP and NBCC 2015, (b) Eurocode 8

Comparison

To obtain a better insight on the differences and consistencies of the two site classification approaches that are NEHRP (or NBCC) and Eurocode 8, the percentage area covered by each site class is shown in a bar chart in Figure 3. It indicates that 53.0 % of the regional surface area is denoted as Class A (Eurocode 8, Figure 2b), that is 38.1% of Class A and 14.9% of Class B (NEHRP & NBCC). Correspondingly, the other Eurocode 8 site classes, including B, C, and D, are consistent with C, D, and E of NEHRP site classes, which are in accordance with the $\bar{V}_{s,30}$ thresholds for each site class (Figure 3). The main difference can be observed in the percentage of Ground Type E of Eurocode 8, which is mainly composed of Class C (very dense soil), and Class D (stiff soil) of NEHRP site classification. This difference in classification is a direct consequence of averaging high shear wave velocity of rock and low shear wave velocity of soil.

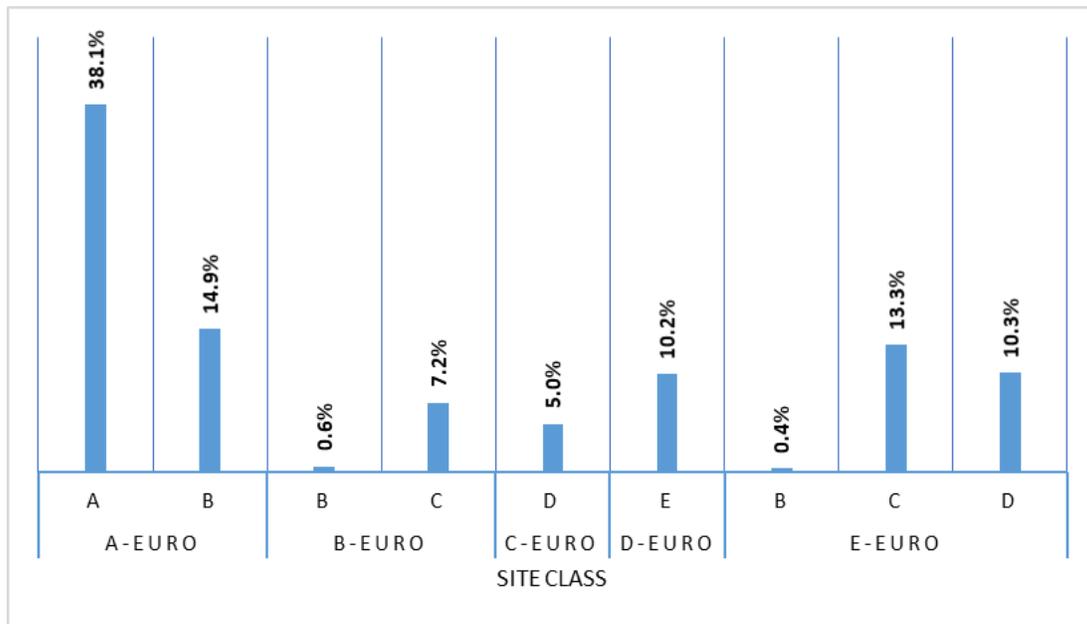


Figure 3. Comparison between Eurocode 8 and NBCC 2015, (NEHRP 2015), site classification for the Saguenay region (the percentage values are based on the area portion of each site class)

CONCLUSION

With respect to the seismic hazard parameters, NEHRP defines the site-specific design spectral acceleration parameter for two periods, namely for short period 0.2 s (S_s) and for long period of 1.0 s (S_1). Spectral response acceleration values, $S_a(T)$, has been defined in NBCC for six definite periods, while Eurocode 8 defines seismic hazard only for a single parameter which is the value of the reference peak ground acceleration (a_{gr}).

Due to the potential nonlinear behavior of soils, site coefficients are also dependent on seismic intensity. This effect is accounted for by using different amplification factors for short and long periods in NEHRP (F_a and F_v) and NBCC ($F(T)$). Whereas Eurocode 8 proposes only two types of response spectra based on the seismicity hazard level at the site.

In terms of site classification, the comparisons presented above between the three considered national codes suggest the following remarks.

- Eurocode 8 is missing the hard-rock site condition, such as the Site Class A in NBCC and NEHRP. Due to the effect of weathering on the rock-outcrop, classification of rock site in two categories can help to better predict the site effect in weathered-fractured rock sites.
- Class E of Eurocode 8 encompasses the impedance contrast between the overlying soft or loose material, and the underlying rock. The thickness of soft material in this category ranges from 5 to 20 meters, which is the case over a fairly significant area of the Saguenay region.
- Regarding NBCC and NEHRP site classifications, for a site column presenting various layers of rock and soil, an overestimation of the $\bar{V}_{s,30}$ value is caused by averaging the shear wave velocity of the rock-classified site combined with soil classes; this effect has been relatively mitigated by defining Ground Type E in Eurocode 8.
- Defining a distinct site class, which considers sharp impedance contrasts between soft soils and underlying hard rock, should result in a more consistent site classification for the characteristic geology of Eastern Canada.

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