Significance of accurate seismic site class determination in structural design

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ABSTRACT

Three cases are presented in which the seismic site class is determined using shear wave velocities and the data obtained from a deep borehole. The results show that depending on the methodology used different site classes may be obtained for the site. The significance of this discrepancy is investigated through a parametric study that comprises evaluation of seismic loads on typical steel and concrete frames with different configurations using the spectral values for major Canadian metropolitans. It is observed that a small change in the geotechnical measurements or a change in the geotechnical investigation methodology may result in a step change in the estimated seismic loads on the structure. It is shown that the accuracy of the geotechnical measurements are not sufficient to warrant such sharp changes in the structural loadings. Therefore, it is recommended that the spectral site coefficients be defined based on smooth functions of subsurface shear wave velocity. This approach will avoid sharp changes in the seismic loads, which is more consistent with the level of accuracy associated with geotechnical measurements and has a better physical justification.

RÉSUMÉ

Trois études de cas sont présentées dans lesquelles la catégorie d'emplacement est déterminée sur la base de la vitesse des ondes de cisaillement Vs, et des données provenant d'un forage profond. Les résultats montrent que différentes catégories d'emplacement peuvent être obtenues selon la méthodologie utilisée. La conséquence de cet écart est étudiée à l'aide d'une analyse paramétrique qui comprend une évaluation des charges sismiques sur des cadres typiques en acier et béton, de différentes configurations, en utilisant les valeurs spectrales de villes canadiennes d'importance.

1 INTRODUCTION

The National Building Code of Canada (NBCC 2005) adopted new seismic design provisions in 2005. Other building codes such as International Building Code (IBC) adopted similar provisions a few years earlier (IBC 2003). Heidebrecht (2003), and NBCC User's Guide (2006) provide summary of the development history of the NBCC seismic provisions and the major changes in the seismic provisions of NBCC 2005 in comparison to the previous versions of this code. These changes present the results of the researches and experiences with this respect in the past twenty years.

One of the major changes in the current provisions is the new methodology for considering the local site effects on the seismic loads. In the previous versions of the code the site conditions and soil types were qualitatively assessed and amplification factors would be assigned to the site (Heidebrecht 2003). The advantage of the new provision is the adoption of a quantitative methodology for determination of local site effects. In summary, NBCC 2005 defines six (6) different site classes (A to F) for which a qualitative description is provided in Table 4.1.8.4.A of the code (Table 1). Site class A is associated to hard rock and site class E is associated to soft soils. For site classes A through E period dependent seismic site factors (Fa ad F_{v}) are defined from which site response spectra for each of these classes can be defined. Site class F is assigned to special soil conditions which need more detail

evaluation. This table provides quantitative methodologies based on average shear wave (s-wave) velocities, standard penetration test (SPT 'N') values or undrained shear strength (s_u) within the upper 30 m of the subsurface soil below the founding level of the foundations or the top of the pile.

		Average Properties in Top 30 m				
Site class	Soil Profile Name	Shear Wave Velocity V _s (m/s)	Standard Penetration Resistance, N ₆₀	Undrained Shear Strength, s _u		
A	Hard Rock	V _s > 1500	Not Applicable			
В	Rock	760 < V _s < 1500	Not Applicable			
с	Very Dense Soil and Soft Rock	360 < V _s < 760	N ₆₀ > 50	s _u > 100 kPa		
D	Stiff Soil	180 < V _s < 360	$15 \le N_{60} \le 50$	50 < s _u ≤ 100 kPa		
Ε	Soft Soil	V _s < 180	N ₆₀ < 15	s _u < 50 kPa		
E	Soft Soil	Any profile with more than 3 m of soil with the following characteristics: ● Plastic Index PI>20 ● Moisture content w ≥ 40%, and ● Undrained shear strength su < 25 kPa				
F	Otthers	Site specific evaluation required				

Та	ble	1: \$	Seismic	site	class	definition	(NBCC	2005)
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The average quantities are calculated based on the following schemes (NBCC User's Guide, 2006):

$$\overline{V} = \frac{H}{\sum \frac{h_i}{V_{S_i}}}$$
[1]

$$\overline{N}_{60} = \frac{H}{\sum \frac{h_i}{N_{60}}}$$
[2]

$$s_u = \frac{H}{\sum \frac{h_i}{s_{u_i}}}$$
[3]

where \overline{V} , \overline{N}_{60} and s_u are the average shear wave velocity, corrected SPT 'N' values and undrained shear strength, respectively. *H* is the total layer thickness, h_i is the thickness for layer *i*, and V_{S_i} , N_{60_i} and s_{u_i} are the shear wave velocity, SPT 'N' value (corrected for energy) and undrained shear strength corresponding to layer *i*, respectively.

The preferred method for seismic site class determination is shear wave velocity measurement and the averaging scheme as provided in equation [1], which is applicable to all soil conditions (NBCC User's Guide 2006, IBC 2006, NEHRP 2003). According to NBCC User's Guide 2006 equations [2] and [3] above should be used for sand and clay sites, respectively. However, NBCC does not provide any specific comment about the evaluation of sites with mixed soil conditions using SPT or C_u methods. According to IBC 2006 and NEHRP 2003 for mixed soil conditions the following three methodologies can be used:

- Measuring average shear wave velocities and using equation [1]
- Measuring SPT 'N' values (within cohesive and cohesionless soil layers) and using averaging scheme per equation [2]
- Measuring SPT 'N' and s_u values within the cohessionless and cohesive soil layers respectively. Calculating N_{60_i} and s_{u_i} over the applicable soil layers. Finally the site class is determined based on the lower site class obtained from the above methods.

According to NBCC 2005 a quantitative evaluation is required for the assignment of seismic site class. As Table 1 implies, site classes A and B can only be determined based on shear wave velocitv measurements. For other site classes either of the three methods (\overline{V} , \overline{N}_{60} and s_u) can be used. Most of the geotechnical investigations for structures supported on shallow foundations consist of drilling and sampling boreholes with depths limited to 10 to 15 m below existing ground surface. Therefore, for proper assessment of the seismic site class either deep boreholes are required (to obtain average SPT or su values) or geophysical methods should be used to measure average shear wave velocities. Various geophysical methods are available for this purpose (Stokoe 2008), among which surface methods are attractive for the following reasons:

• they are carried out from surface without any need for installing additional boreholes,

- they provide an average of the soil properties over a distance rather than localized values,
- in most cases they are less expensive and the field works are faster than borehole geophysical methods,

This paper presents the results of three case studies in which multichannel analysis of surface waves (MASW) was combined with conventional geotechnical investigations for seismic site class assessment. A parametric study is also carried out that to evaluate the effect of site class on the structural seismic loads. It is shown that the current system of site classification suffers from several weaknesses that need to be addressed in the next generation of the seismic codes. Specifically, the determination of the seismic site class using different methods (i.e. \overline{N}_{60} or \overline{V}) may result in different site classes. Further, sharp changes in the structural seismic loads for different site classes result in difficulties in determination of proper site class for sites that marginally meet the conditions of one class or the other. Suggestions are made to address these issues.

2 OVERVIEW OF MASW METHOD

The MASW method is a seismic geophysical technique to estimate soil shear wave velocity profile (Park et. al., 1999). To carry out MASW test, several geophones are deployed along a line at certain distances from an impact source (Figure 1). The length of the geophone array (D) controls the deepest investigation depth that can be obtained from the measurements. The distance between the source and first receiver (offset) determines the contamination level of the signals. The source should produce enough energy over the desired test frequency range to allow for detection of Rayleigh waves above background noise. Common active sources are sledgehammers or heavy drop weights. The existing traffic noise can also be utilised as a passive source for investigating deep soil layers (Louie, 2001, Park 2006). Generally, using a sledgehammer the maximum investigation depth is limited to about 15 m to 20 m below the existing ground surface (bgs), however using traffic noise or heavier active sources the investigation depth can be increased to more than 30 m bgs.

Theoretically, the MASW test is based on the dispersive behaviour of Rayleigh wave (R-wave) in a layered media (Park, 1999, Rix, 2005). Dispersion of R-wave arises because different frequencies traverse the medium with different velocities. The latter is due to the fact that the penetration depth of R-wave is inversely proportional to its frequency. Thus, higher frequencies travel through shallower strata, and lower frequencies propagate mostly in the deeper layers. For practical purposes, the maximum depth of penetration can be considered to be equal to one to one third of the wavelength (KGS 2008, Stokoe 2008). Therefore each frequency carries the information associated to a specific depth of the medium that it is traversing. Field data are collected in time domain, and constitute the basis of the

calculation of phase velocity profile (dispersion curve) of the site. Subsequently, inversion of the constructed dispersion curve leads to the estimation of the shear wave velocity profile of the medium.

It is noted that in recent years the use of MASW method in geotechnical investigations gained significant attention. This is partly due to the advancement in available analysis softwares and also the easiness of the field work in compare to other shear wave velocity methods. Further, numerous works showed relatively good correlations between the obtained results from MASW test and other available methods such as Crosshole tests. For further information the reader is referred to the works carried our at Kansas Geological Survey (KGS 2008).



Figure 1: MASW general field set up.

3 CASE STUDIES

Three case studies are presented herein in which MASW method is combined with conventional borehole investigations to evaluate subsurface soil conditions. Case 1 presents s-wave velocity measurement results with SPT measurements carried out within a deep borehole (SPT - ASTM 1586). Case 2 compares the results obtained from boreholes investigated using SPT and cone penetration tests with s-wave velocity measurements. Case 3 presents an example where shallow boreholes were used in combination with MASW in a liquefiable soil condition. The case studies show that in some instances poor correlations between SPT 'N' values and shear wave velocities may exist. Therefore, the use of different methodologies may result in different site classes. Further, these examples show marginal cases in which a small change in the measurements may result in significant changes in the evaluated site amplification factors. Suggestions are made for modifying the code procedures in a way that the defined site factors are less susceptible to the small changes in the measured subsurface properties.

3.1 Case 1: MASW – SPT Comparison

The subjected site (Site A) is located in south-eastern Ontario, Canada. The site is investigated by a borehole drilled to a depth of about 31.0 mbgs employing 150 mm continuous hollow stem augers and sampled by 50 mm split-barrel sampler (SPT) at regular intervals of 0.75 m for the first 3.0 m and 1.5 m thereafter.

To obtain the V_s profile at the site, MASW test is carried out with the geophone array centered at the borehole location. The geophone array consisted of a total of 24 geophones and multi-geometry approach was used for field data collection using 2.0 m and 4.0 m geophone spacings (Nasseri-Moghaddam and Park, 2010). The active source was a 20 lb sledge hammer and a 20⁺ton track mounted excavator travelling between 10 to 15 m of the geophone array generated the background noise for passive data collection. The variation of shear wave velocity with depth as obtained from MASW is shown on Figure 2.



Figure 2: Case study 1. Comparison between measured soil mechanical properties.

The subsurface soil condition at the location of borehole consisted of a thin layer of topsoil and organic clayey silt layer (about 0.6 m thick) underlain by a clayey silt till/clayey silt deposit about 5.0 m thick, which in turn was underlain by a silty clay deposit that was encountered to the termination depth of the borehole at about 31.0 m bgs. Based on the SPT 'N' values the upper clayey silt layer showed very stiff to hard consistency, whereas the underlying silty clay material was in stiff condition along the majority of depth. Figure 2 shows the soil profile based on the borehole data and corresponding SPT 'N' values measured at each level.

The SPT 'N' values within the upper 8 m of the soil profile varies from 5 to 32 blows per 0.3 m of penetration which is well compared with measured shear wave velocities within this depth that varies from 214 m/s to 419 m/s. However, below this depth the SPT 'N' values are generally in the range from 10 to 15 blows per 0.3 m

of penetration, whereas the shear wave velocities show a much wider variation range, i.e. from 256 m/s to 548 m/s. To obtain the seismic site class, the average shear wave velocity and average SPT 'N' (\overline{V} and \overline{N}_{60}) are calculated using equations [1] and [2], which result in $\overline{V} = 373 \ m/s$ and $\overline{N}_{60} = 14$. Therefore, the site is classified as site Class C based on the shear wave velocity measurements and is classified as Site Class E based on the average SPT 'N' values. It is noted that the average SPT 'N' value of 14 marginally falls in Class E range.

This example shows that first there is not always a good correlation between the SPT 'N' values and shear wave velocities. Further, there are cases in which seismic site class determination using different methods may result in different answers.

3.2 Case 2: MASW – with shallow borehole

To evaluate the seismic site class at a site in Ottawa, Ontario (Site B) borehole and MASW investigations were carried out. Two boreholes were installed at the site. The boreholes were sampled by Standard Penetration Test (SPT) up to about 16 m bgs after which the dynamic cone penetration test (DCPT) was carried out to approximate depth of 31 m bgs. The stratigraphy at the site consisted of a thin layer of topsoil about 0.2 m thick, underlain by a layer of silty sand generally found to a depth of about 1.5 m bgs, underlain by a thick silty clay layer about 14 m thick, which was underlain by a silty sand layer encountered to the termination depth of the boreholes at about 30 m bgs. The silty clay layer consisted of a thin firm crust (SPT 'N' values of 6 and 7 blows per 0.3 m of penetration) about 1.0 m thick. SPT 'N' values measured within this deposit below the upper firm crust were from 1 to 2 blows per 0.3 m of penetration indicating soft consistency. Field vane tests (ASTM D2573) carried out at various depths within this deposit all resulted in undrained shear strengths larger than 40 kPa. The underlying silty sand layer was generally in loose to compact condition based on SPT and dynamic cone investigations.

MASW measurements were carried out along three lines across the site. Along each line the geophone array was rolled four (4) times. Thus a total of twelve (12) measurements were made across the site. The average shear wave velocities (\overline{V}) obtained from these 12 measurements varied from 176 m/s to 198 m/s with total average of 188 m/s (average of 12 measurements).

Figure 3 shows the variation of soil stratigraphy, SPT 'N' values, and total average shear wave velocity with depth at the site. The low shear wave velocities (smaller than 250 m/s) within the upper 22 m of the soil profile show good correlation with the low SPT 'N' values and Dynamic Cone test results measured within the same depth of this deposit. Within this depth V_s varies from 100 m/s to 246 m/s.

Very low shear wave velocities were measured from 2 m bgs to 11 m bgs therefore selected soil samples from

these depths were subjected to further laboratory testing (grain size analysis and Atterberg limits) to verify the soils susceptibility to liquefaction (Seed et. al., 2003). The measured total average shear wave velocities marginally meet the requirements for Site Class D and laboratory and field test results eliminate the conditions for Site Class E. Therefore a seismic Class D can be recommended for this Site.

It is noted that the average SPT 'N' values within the upper 16 m of this deposit is 1.3, therefore it is likely that if the SPT investigations were continued to 30 m depth the average SPT 'N' values within the 30 m depth could be less than 15, thus meeting site Class E requirements. It is noted that the \overline{V} measured along one of the lines was 176 m/s meeting site Class E requirements. Therefore, it is observed that depending on the investigation methods and the measurement locations a site class E or D may be recommended for this site.



Figure 3: Case study 2. Comparison between measured soil mechanical properties. It is noted that the penetration index shows the measured SPT 'N' values up to about 16 m bgs and the recorded DCPT values afterwards.

3.3 Case 3: MASW – with shallow and deep boreholes (liquefiable soil)

A site in Ottawa, Ontario, Canada (Site C) was subjected to geotechnical borehole testing along with MASW. Two shallow boreholes were installed to depths of 6.7 m and 8.2 m bgs and MASW was carried out along two lines at the site to obtain \overline{V} . Measurements were made along two lines across the site. Along each line the geophone array was rolled five (5) times. Thus, a total of ten (10) measurements were obtained across the site. The average shear wave velocities (\overline{V}) obtained from these 10 measurements varied from 173 m/s to 204 m/s with total average of 188 m/s (average of 10 measurements). Figure 4 shows the variation of shear wave velocity and the soil stratigraphy with depth.

The low shear wave velocities measured at the site to significant depths warranted more detail investigations. Therefore, one additional deep borehole was installed to the depth of 29.5 m bgs at the site. SPT samples were collected at regular intervals along the depth of the boreholes. Further, field vane tests were carried out within the soft soil deposits and Shelby tube samples were collected from various depths for further laboratory testing.

The stratigraphy at the site consisted of about 1 m of topsoil and fill material, underlain by about 2 m of sandy silt deposit, underlain by a layer of clayey silt about 7 m thick, underlain by a layer of silty clay material that was encountered to the termination depth of the deep borehole. The two shallow boreholes were terminated within the clayey silt deposit. SPT 'N' values measured within the sandy silt deposit varied from 4 to 8 blows per 0.3 m of penetration indicating loose relative density. SPT 'N' values measured within the underlying clayey silt material generally varied from 0 to 3 blows per 0.3 m of penetration indicating very soft to soft state of consistency. Localized SPT 'N' values between 8 to 12 blows per 0.3 m of penetration were measured at the top of this deposit indicating a firm crust on top of this layer. Within the underlying silty clay deposit all the split spoon samplers penetrated under the hammer weight (SPT 'N' value of 0) indicating very soft state of consistency. Very shallow groundwater (about 1.0 m bgs) was encountered in the two piezometers installed in the shallow boreholes. The stratigraphy at the site is depicted in Figure 4.



Figure 4: Case study 3. Comparison between measured soil mechanical properties.

Comparing the variation of SPT 'N' values and shear wave velocities with depth indicate a good match within the upper 24 m (Figure 4). Very low SPT 'N' values, low shear wave velocities along with high groundwater levels indicate that the subsurface soil might be prone to liquefaction. Detail liquefaction analysis including laboratory tests on representative samples was carried out for this site that confirmed the potential for liquefaction at this site (Nasseri-Moghaddam et. al., 2011). A site class F is assigned to this site due to it susceptibility to liquefaction.

4 PARAMETRIC STUDY

According to NBCC 2005 the minimum lateral earthquake force on structures (V) is calculated using the following relation:

$$V = \frac{S(T_a)M_v I_E W}{R_d R_0}$$
[4]

Where $S(T_a)$ is 5% damped spectral response acceleration, T_a is structures period, M_v is the factor to account for higher modes, I_E is importance factor, W is structures dead load ()with some modifications), and R_d and R_0 are ductility and overstrength related force modification factors, respectively. This equation implies that the effect of seismic site class on the structure's lateral loads is reflected in the factor $S(T_a)$. This effect is modified based on the type of the seismic force resisting system (SFRS) adopted for the structure through factors R_d and R_0 .





To evaluate the significance of proper seismic site class determination on the economy of the structure, a parametric study is carried out. In this study structures with different heights and SFRS are selected and the corresponding V_W ratios (base shear coefficients) are calculated using equation [4]. The calculations are carried out for structures located in major Canadian metropolitans i.e. Vancouver (high seismic hazard), Montreal and Ottawa (moderate seismic hazard), Toronto (low seismic hazard), and Calgary, and Edmonton (very low seismic hazard). For brevity only the results for Ottawa and Toronto are presented. To simplify the procedure in all the cases the factors M_v and I_E are assumed to be equal to 1. In each city four structural systems are considered as follows:

- Scenario 1: concrete structure with conventional moment resisting frame ($R_d = 1.5$ and $R_0 = 1.3$)
- Scenario 2: concrete structure with moderately ductile shear walls ($R_d = 2.0$ and $R_0 = 1.3$)
- Scenario 3: steel structure with moderately ductile moment resisting frame ($R_d = 3.5$ and $R_0 = 1.5$)
- Scenaro 4: steel structure with moderately ductile concentrically braced frame ($R_d = 3.0$ and $R_0 = 1.4$)

For each of the above Scenarios four different cases are considered corresponding to different frame heights i.e. 3.0 m, 5.0 m, 7.0 m, and 9.0 m. It is assumed that this height range covers the majority of the ongoing constructions in these cities.

Figure 5 shows the base shear coefficients for Ottawa. Plots 5a, 5b, 5c and 5d correspond to Scenarios 1 to 4, respectively. In each plot the base shear coefficients for different cases and for different seismic site classes are compared. Similar comparisons are made in Figure 6 for Toronto.

For each city the design spectra (S(T)) is constructed according to NBCC 2005. The fundamental lateral period of vibration (T_a) of the considered frames are calculated, based on the relations provided in the Code. The spectral values for each considered scenario $(S(T_a))$ are calculated and the base shear coefficients (V/W) are developed for each structural system.

These figures show that in general the base shear coefficient changes with the type of structures (SFRS), period of the structure (height) and site class. It is observed that a change from a lower site class to a higher site class can result in a change in base shear coefficient in the range from 6% to 60%, and 14% to 70% it Ottawa and Toronto, respectively.

Investigating the trends in the changes in base shear coefficients with seismic site class results in the following general observations:

- Significant changes are observed when moving from site class C to B and from E to D,
- A change from site class D to C can result in a moderate change in the base shear coefficient,





In Toronto for different structural scenarios. Plots a and b correspond to concrete structures and plots c and d correspond to steel structures. Horizontal axis shows the seismic site class.

- The effect of the changes in seismic site class on base shear coefficients is more significant for structures with longer periods (tall structures),
- Increasing the ductility of the structural system decreases the vulnerability of the base shear coefficient to the site class.

The above observations show that proper seismic site class determination can result in a considerable reduction in the seismic loads on the structure and consequently increase the economy of the structure.

5 CONCLUSIONS AND RECOMMENDATIONS

Three cases were presented in this paper in which conventional geotechnical investigations were complemented by MASW method for seismic site class determination. Parametric studies are presented that show the effect of seismic site class on the lateral loads of structures. Based on results presented herein the following conclusions are made:

- The correlations between shear wave velocities and intrusive in-situ tests such as SPT or field vane tests as presented in the building codes are not very strong. Therefore, seismic site class determination using different methods may result in different answers.
- Marginal cases may occur in seismic site class determination in which a small change in the field measurements (V_s, SPT 'N', or S_u) may result in a change in site class, resulting in a significant change in amplification factors.
- Shear wave velocity measurements provide a promising method for identifying problematic soil conditions (i.e. soft soil layers, liquefiable soils etc.) in lieu of deep soil investigations.

Since the initiation of site class concept (Borcherdt, 1992) and their adoption in the codes valuable research and practical information became available. The use of this classification system was a step forward towards better quantification of the local site effects on seismic waves. However, practical projects such as the ones

presented in this paper show that a review of these provisions is prudent at this time. Further, the advances made in seismic geophysical methods such as MASW makes the in-situ measurement of shear wave velocities at the sites easier and more practical. Therefore, it is recommended that a methodology that defines the amplification factors as continuous functions of shear wave velocity be adopted. This approach will reduce the sharp changes in the amplification factors (i.e. lateral loads applied to the structure), which is more consistent with the level of accuracy of the methodologies available for measuring soil stiffness profiles. Further, a review of the provided correlations between shear wave velocities and SPT 'N' values and S_{μ} values is recommended.

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