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A comparison of different methods for the estimation of NBCC 2005 seismic hazard site classification: A case study from the Toronto-York Spadina Subway extension project

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ABSTRACT

With recent changes to the National Building Code of Canada (NBCC) in 2005 there has been an increasing demand for site classification based on dynamic shear wave velocity measurements of soil and rock. There are three seismic methods typically used for the NBCC seismic site classification; multichannel analysis of surface waves, vertical seismic profiling, and crosshole seismic testing. Typically only one of these methods is done at a site. The decision is usually based on site conditions, borehole accessibility, and cost considerations. In this paper we present a comparison of the three seismic methods and standard penetration tests completed at two sites to support the Toronto-York Spadina Subway Extension. The comparison of the four methods provides insight into the limitations and applicability of the different methods for NBCC seismic site classification.

RÉSUMÉ

Avec les changements récents du Code de Construction National du Canada (NBCC) de 2005, il y a eu une demande croissante pour la classification de site fondée sur les mesures dynamiques des vitesses des ondes de cisaillements du sol et des roches. Il y a trois méthodes sismiques typiquement utilisé pour la classification des sites sismiques d'après le NBCC; l'analyse modale des ondes de surface, le profil sismique vertical, et les mesures de diagraphies sismiques de trou à trou. Typiquement seulement une de ces méthodes est effectuée à un site. La décision est d'ordinaire fondée sur les conditions du site, l'accès au trou de forage, et les considérations de coût. Dans ce papier nous présentons une comparaison des trois méthodes sismiques et des essais de pénétration standard réalisés à deux sites pour le Projet d'Extension de la ligne de métro de Toronto-York Spadina. La comparaison de ces trois méthodes permet d'entrevoir les limitations et la validité d'application de ces méthodes différentes pour la classification de site sismique d'après le NBCC.

1 INTRODUCTION

Site classification of the seismic response of soils is critical for seismic hazard assessment of underground structures and engineering foundation design. Its determination is based primarily on the average shear-wave velocity measurement in the upper 30 metres (V_{s30}) as outlined in the National Building Code of Canada (NBCC 2005). At small strain, the shear wave velocity (V_s) of soil is a key parameter for determining the dynamic property of soils. Seismic site response can also be estimated using typical geotechnical field measurements such as the average standard Penetration Test (SPT – N values) or the average undrained shear strength (S_u) however their use is limited to cohesionless or cohesive soils within the upper 30 metres.

Table 4.1.8.4.A. of the 2005 NBCC, reproduced in Table 1, summarizes the new seismic site response classification system and provides a means of more directly quantifying the soil column shear stiffness in the upper 30 metres using measurements of the shear wave velocity, V_s .

Shear-wave velocity is becoming a more important parameter in the design of underground structures and foundation design for site specific conditions and can be determined using various intrusive or non-intrusive seismic methods. There are many geophysical methods for determining in-situ shear-wave velocity and obtaining a 1-D profile of V_s versus depth. In this paper three of the most commonly used geophysical techniques were carried out during the geotechnical investigation at two sites selected along the proposed Toronto-York Spadina Subway Extension (TYSSE). These techniques include crosshole seismic, vertical seismic profiling (VSP) and multichannel analysis of surface wave (MASW).

Results of the Standard Penetration test (SPT) carried out at the same two locations have been used to calculate the average standard penetration resistance (N_{60}). Mean shear-wave velocity and mean corrected standard penetration resistance within the upper 30 metres were investigated at the two study areas.

Site Class	Soil Profile Name	Average Properties in Top 30 m as per Appendix A		
		Soil Shear Wave Average Velocity, V_s (m/s)	Standard Penetration Resistance, N_{60}	Soil Undrained Shear Strength, s_u
A	Hard Rock	$V_s > 1500$	Not applicable	Not applicable
B	Rock	$760 < V_s < 1500$	Not applicable	Not applicable
C	Very Dense Soil and Soft Rock	$360 < V_s < 760$	$N_{60} > 50$	$s_u > 100\text{kPa}$
D	Stiff Soil	$180 < V_s < 360$	$15 < N_{60} < 50$	$50 < s_u < 100\text{kPa}$
E	Soft Soil	$V_s < 180$	$N_{60} < 15$	$s_u < 50\text{kPa}$
E		Any profile with more than 3 m of soil with the following characteristics: - Plastic index $PI > 20$ - Moisture content $w \geq 40\%$, and - Undrained shear strength $s_u < 25\text{ kPa}$		
F	(1) Others	Site Specific Evaluation Required		

Notes to Table 4.1.8.4.A.:

(1) Other soils include:

- (a) Liquefiable soils, quick and highly sensitive clays, collapsible and weakly cemented soils, and other soils susceptible to failure or collapse under seismic loading,
- (b) peat and/or highly organic clays greater than 3 m in thickness
- (c) highly plastic clays ($PI > 75$) more than 8 m thick, and
- (d) soft to medium stiff clays more than 30 m thick.

Table 1: Site classification for seismic site response, Table 4.1.8.4.A of 2005 NBCC

This paper presents, compares, and discusses the results of the seismic surveys and standard penetration tests at the two TYSSE sites, and provides site classification comparison using the different tests.

2 SITE CONDITIONS

Both study areas were located in Toronto, Ontario. Test location 1 was carried out between the proposed Finch West Station and York University Station while test location 2 was carried out at the Vaughan Corporate Centre Station.

Both study sites consist of variable thickness of soil overburden. They are underlain by various types of sediments including silty sand, sand, sandy silt, sand and gravel, silty clay and clayey silt. A representative lithological log for each test is shown in Figure 1.

3 FIELD METHODS

Results from four (4) in-situ testing methods have been used to assess the NBCC 2005 site classification for seismic Site Response at both sites. These methods were MASW, VSP, crosshole, and SPT. A brief description of each technique is provided below.

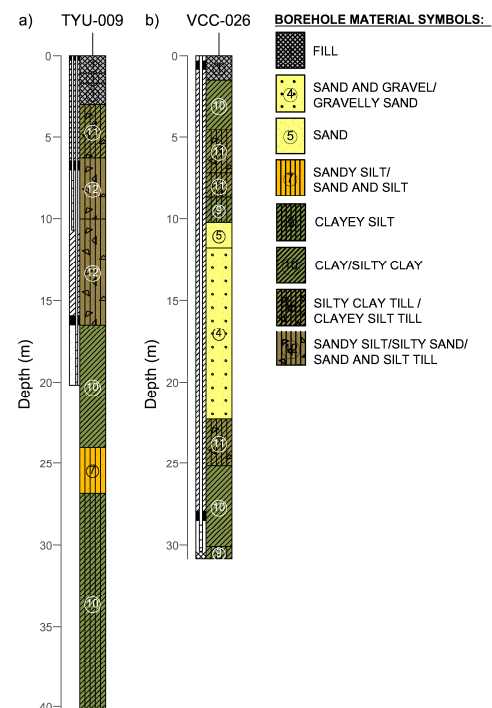


Figure 1: Typical stratigraphic sequence at the two selected sites; (a) borehole TYU-009 (Site 1) and at (b) borehole VCC-026 (Site 2).

3.1 MASW

MASW is a geophysical method that uses the propagation of Rayleigh seismic surface wave to generate a shear-wave velocity depth profile. Surface wave data were acquired using a series of 24 low frequency (4.5 Hz) geophones spaced at 2 metre intervals. A seismic weight drop of 45 kg was used as the seismic source for this investigation. Seismic records were collected with seismic sources located 30, 20, 15, 10 and 5 metres from the end and collinear with the geophone array. The acquired MASW data were processed and transformed into a 1-D shear-wave velocity profile (Park et al., 1999). The processing involved the determination of the phase velocity for each frequency of the field-recorded Rayleigh waves. At each site the calculated phase velocities for each seismic shot point were combined and the dispersion curve generated by choosing the minimum phase velocity calculated for each frequency component as shown in Figure 2. The resultant dispersion curve is then inverted using least square inversion procedures and a vertical shear-wave velocity profile is generated (e.g. Park et al., 1999). MASW is one of the easiest and least expensive methods for measuring shear-wave velocity. It is a non-intrusive geophysical method. The main disadvantage of active MASW is that the maximum depth of penetration is often limited to 20-30 metres.

The minimum measured surface-wave frequency with sufficient signal-to-noise ratio to accurately measure phase velocity was approximately 12 and 16 Hz at sites 1 and 2, respectively (Figure 2).

3.2 Crosshole Seismic

The crosshole seismic technique measures the velocity of elastic wave propagation through the subsurface to infer rock/soil types, stratigraphy, small strain properties and soil conditions. At the two sites, crosshole seismic tests were used to determined velocity profiles of V_p and V_s with depth as defined in ASTM Standard D 4428/D 4428M-07(American Society for Testing and Materials, 2000). At each test location, three installed boreholes separated by a known distance (approximately 3 m) were cased using a 3-inch inner diameter PVC casing and grouted in place to ensure good coupling to the medium. The grout was then allowed to set for a minimum 48 hours prior to testing (Golder, 2011).

The borehole deviation surveys were completed using a borehole deviation probe manufactured by Mount Sopris Instrument Co., Inc. The deviation system consists of an electric winch system and a probe which measures the magnetic field and roll and pitch of the probe.

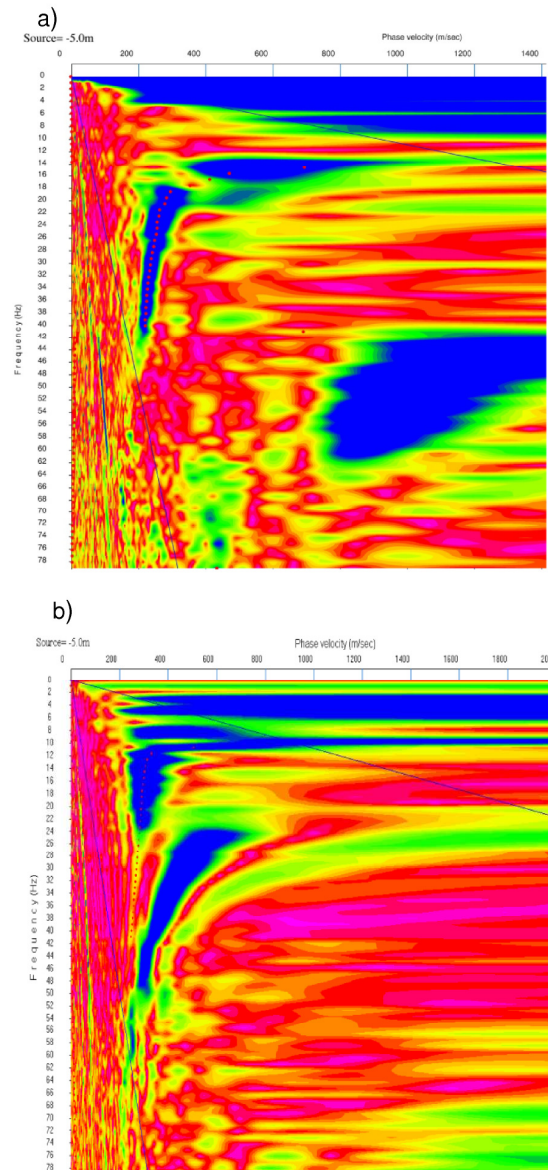


Figure 2: Typical MASW dispersion curves at (a) site 1 and (b) site 2 (red dots are fundamental mode picks).

The probe was centralized in the borehole and measurements are recorded at 10 centimetre intervals both up and down and up the borehole. Distance and orientation of the boreholes was also measured at the time of the borehole deviation survey. The offset between the three boreholes at each test location was calculated using the deviation data collected for each borehole and was used to determine the offset between the two borehole geophones for accurate calculation of shear-wave velocities.

The crosshole survey involves the use of compressional and shear-wave downhole hammer sources and two downhole 3-components geophones in a horizontal array

of three boreholes. Measurements were performed between three boreholes with the source and receivers at the same depth at increments of 1 metre following the ASTM standard to the maximum depth of the borehole. Each geophone was coupled to the sides of the PVC casing using spring-loaded clamps. Data is collected using both compression-wave and shear-wave sources. The shear-wave downhole source, which has reversible impact direction, was used to generate vertically-polarized horizontally-propagating shear waves.

The recorded data are subsequently analyzed by splitting the three recorded components (vertical, longitudinal, and transverse) into depth-wave trains. P- and S-wave arrivals are then picked and velocities are calculated based on the borehole separations calculated from a deviation survey performed on the boreholes. To accurately pick the first shear-wave arrivals, the two components showing shear-waves reverse polarity were superposed as shown Figures 3 and 4. The crosshole seismic method is considered the most accurate in estimating V_s because it uses a direct measurement of the wave speed and therefore sampled a limited volume of material at each investigated depth. Because vertical transverse isotropy (VTI) is the most common type of anisotropy in sedimentary rocks with generally the faster S wave oscillating in the plane of layering, the crosshole seismic method has the potential to underestimate the V_{s30} average compared with the VSP method.

The disadvantages of the techniques are its relatively high costs associated with the drilling and grouting of three boreholes.

Examples of picked shear-wave (S-wave) arrival times at the two borehole geophones and at the two investigated sites are shown in Figures 3 and 4.

3.3 VSP

Vertical seismic profiling (VSP) implements a single borehole. A PVC casing is installed and grouted into the borehole. A 3-component borehole geophone is lowered to a given depth below ground surface and seismic energy is generated at the ground surface by an active seismic source and recorded by a geophone located in a nearby borehole at a known depth. The seismic source for the shear-wave test consisted of a 2.4 metres long, 150 millimetres by 150 millimetres wooden beam, weighted by a vehicle and horizontally struck with a 5.5 kilogram sledge hammer on alternate ends of the beam to induce horizontally polarized shear waves (SH). Data were recorded in the borehole with a 3-component receiver spaced sequentially at 1-metre intervals below the ground surface, to a maximum depth of the borehole. The time required for the energy to travel from the source to the geophone provides a measurement of the average shear-wave seismic velocity of the medium between the source and the receiver. Data obtained from different geophone depths are used to calculate a vertical seismic velocity profile of the subsurface in the immediate vicinity

of the test borehole. VSP is the simplest and cheapest borehole seismic technique as it only requires a single borehole and unlike crosshole testing it does not require deviation survey. The technique is not as accurate as the crosshole seismic technique; it measures average traveltimes between the source and receiver at a given depth. Knowing the distance source-borehole and the depth of the receiver that the average traveltimes are used to calculate average velocities granted that the zero time is accurate.

Similar to the crosshole technique, the two shear waves reverse polarity are superposed to accurately pick shear-wave arrivals (Figures 5 and 6). A small variation in the picked first arrivals can generate large changes in the measured velocity.

Examples of picked shear-wave arrival times at both sites are displayed in Figures 5 and 6.

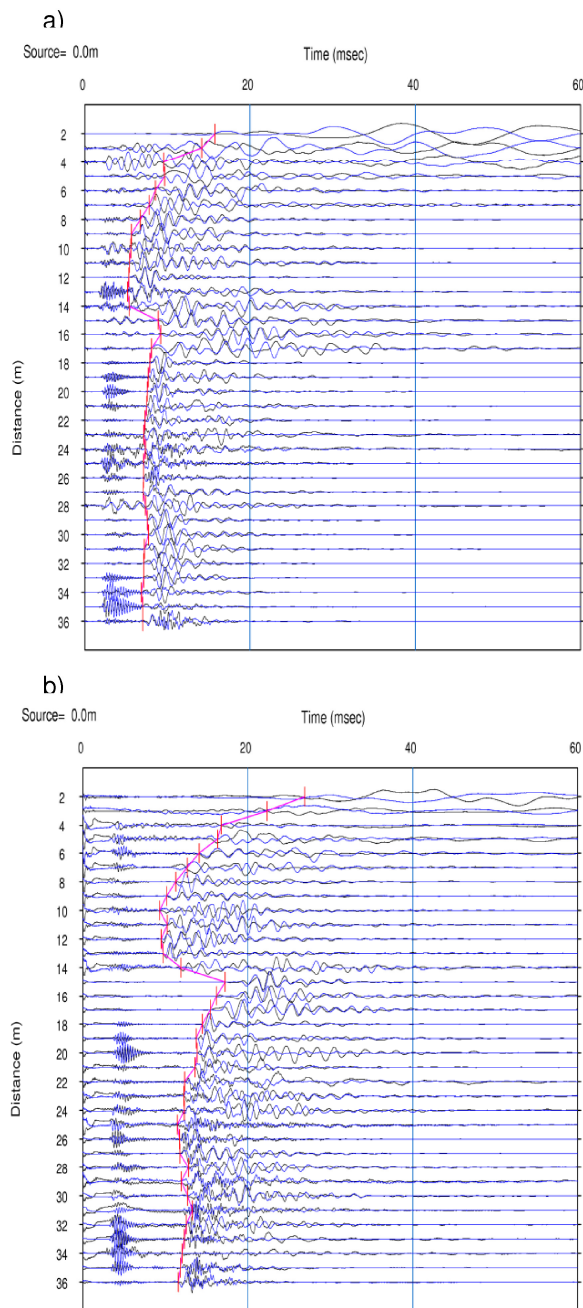


Figure 3: Site 1: First break picking (red) of shear wave arrivals at geophone 1 (a) and at geophone 2 (b) along the seismic traces recorded at each receiver depth.

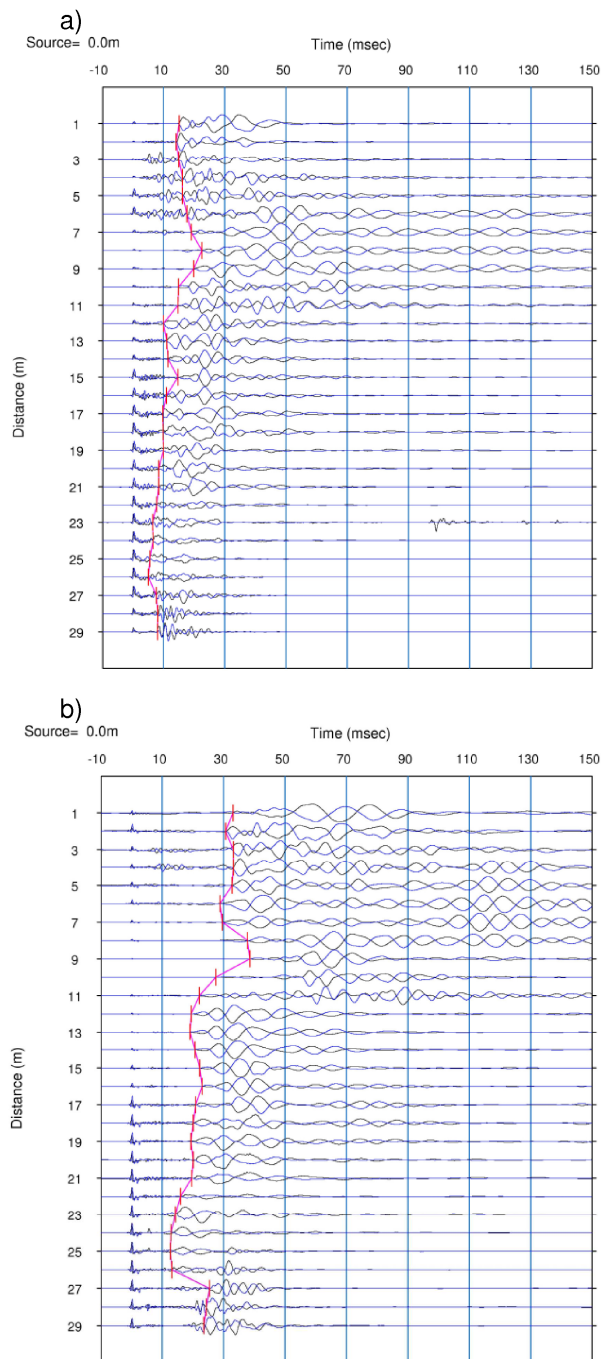


Figure 4: Site 2: First break picking (red) of shear wave arrivals at geophone 1 (a) and at geophone 2 (b) along the seismic traces recorded at each receiver depth.

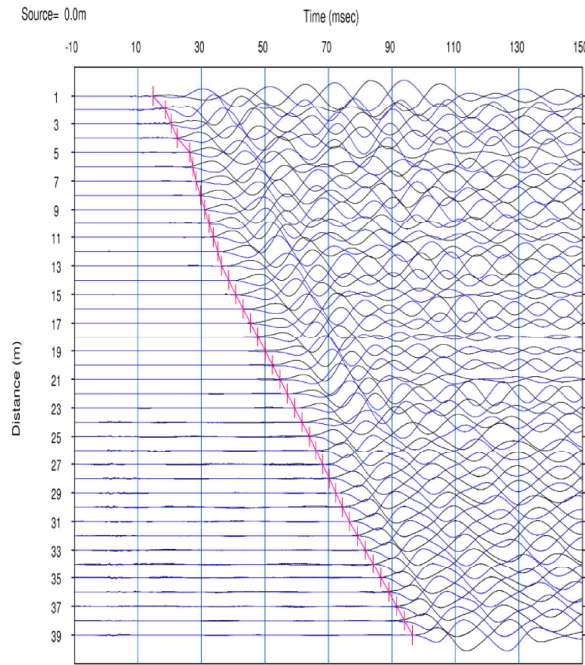


Figure 5: Site 1: First break picking (red) of shear-wave arrivals along the seismic traces recorded at each receiver depth

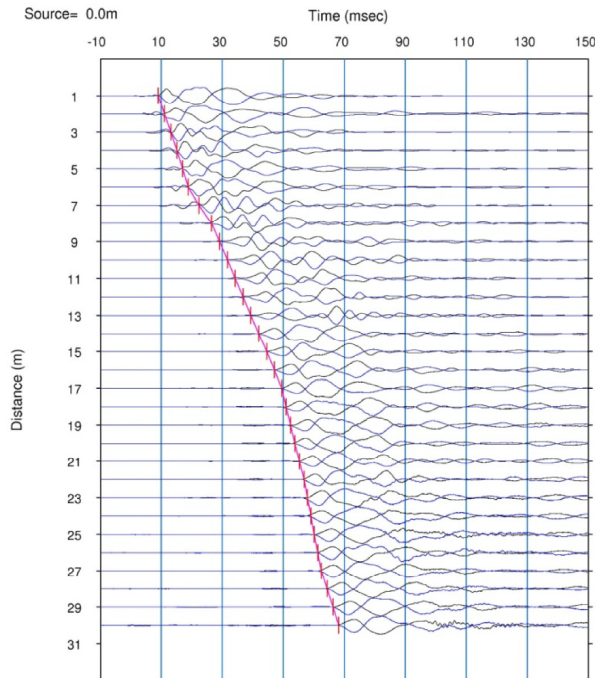


Figure 6: Site 2: First break picking (red) of shear-wave arrivals along the seismic traces recorded at each receiver depth

3.4 SPT

Standard Penetration Tests consists of driving into the ground a barrel to obtain a measure of the resistance of the soil to penetration for a standard sampler. The resistance of standard penetration testing is determined by counting the number of blows required to drive the spilt-spoon sampler into the soil to a specified distance using a specific hammer. The SPT blowcount, N , is a measure of the firmness of the foundation material. The SPT blowcount are corrected for field procedures to N_{60} values where 60 is the percentage of the theoretical free-fall hammer energy. The SPT N value corrected for field procedure is expressed by the following equation:

$$N_{60} = N_f C_E C_B C_R C_S$$

[1]

where

N_f = measured standard penetration resistance;

C_E = correction for hammer energy ratio, 0.9 considered for this assessment;

C_B = correction factor for borehole diameter, 1.15 considered for this assessment;

C_R = correction factor for rod length; and

C_S = correction for sampling method, 1.0 considered for this assessment.

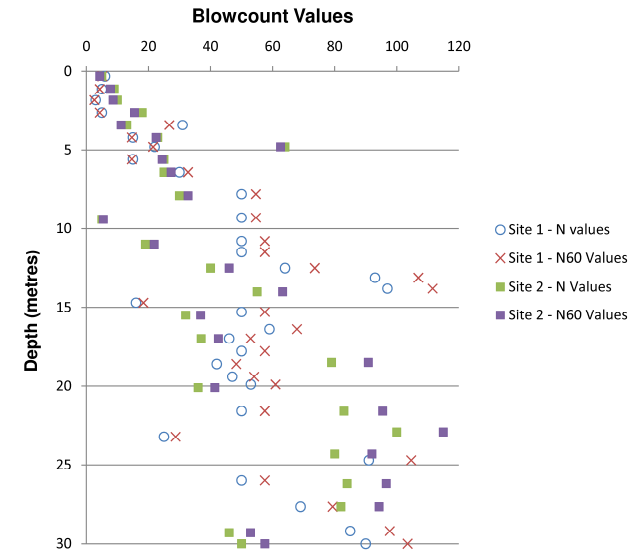


Figure 7: Plot showing the variations between the SPT N values and the corrected N_{60} values at the two investigated sites.

At both sites, the SPT N field measurements were corrected for field procedures and converted to SPT N_{60} values. A comparison plot between the N and N_{60} values at each site is shown in Figure 7. The SPT N values are consistently smaller than the N_{60} values.

4 DISCUSSION

To determine the 2005 NBCC Seismic Site Classification of a site it is preferred to determine the shear-wave velocities (V_s) using seismic testing. If the shear-wave velocities are not available at a particular site the use of SPT values may be an option. The other advantage of measuring small-strain shear-wave velocity (V_s) in the field is its applicability to calculate indirectly other dynamic properties needed to perform a soil response analysis. One of the key properties is the small-strain shear modulus (G_{max}). Other values such as Poisson's ratio (ν), Young's modulus (E) and Bulk modulus (K) can also be calculated from compression-wave and shear-wave velocities.

The shear-wave velocity profiles with respect to depth from the three geophysical methods are displayed for comparison in Figures 8 and 9 for sites 1 and 2, respectively. N_{60} profiles calculated at each site are also plotted for visual comparison.

Shear-wave results from the MASW tests were not able to resolve below 12 metres. The use of active source MASW usually provides a maximum depth of investigation in the range 10-30 m depending on the source used, the array length and the site conditions. In theory increasing the receiver spread length or using a higher energy or vibrating source should increase the depth of investigation but this was unable to be done at these sites due to site conditions. Unfortunately investigation depths at both sites were insufficient to obtain shear-wave velocities down to 30 metres. Therefore, and for illustration purposes only, at both MASW tests, the average velocity was calculated assuming that the velocity of the deepest layer of each model was constant to a depth of 30 metres. If this assumption is reasonable in the presence of bedrock, such an extrapolation should not be done within sedimentary layers where high and low velocity layers are often alternating.

The VSP and crosshole compression and shear-wave velocity profiles correlate relatively well as shown in Figures 8 and 9. Although the MASW shear-wave profiles do not extend to 30 metres, it is comparable to the other two profiles at shallow depths. At a specific site the general trend between the compression and shear-wave velocity profiles is similar. Similarities are also observed between the velocity profiles and the N_{60} profile at both sites.

There is no consistent shift in velocity between the crosshole and VSP profiles at each investigated depth. At site 1, there is on average a 10% increase in shear-wave velocity (45 m/s) using crosshole seismic while at site 2 there is on average a 20% decrease in shear-wave velocity (61 m/s) using crosshole seismic.

To evaluate the site specific classification, V_{s30} to a depth of 30 metres below ground surface have been calculated using the methodology given in National Building Code (NBCC, 2005).

The seismic site characterization used in the seismic hazard analysis is usually based on the average shear-wave velocity within the upper 30 metres. At each seismic test V_{s30} is defined as the travel-time weighted average shear wave velocity from surface to 30 m depth as defined in the following formula (Commentary J paragraph 101):

$$V_s = \sum_{i=1}^n d_i \div \sum_{i=1}^n (d_i \div V_{si})$$

[6]

Where:

V_s = the assigned shear wave velocity; V_{si} = the layer shear-wave velocity in m/s; d_i = the thickness of any layer (between 0 and 30 m); and

$\sum_{i=1}^n d_i$ is equal to 30 m

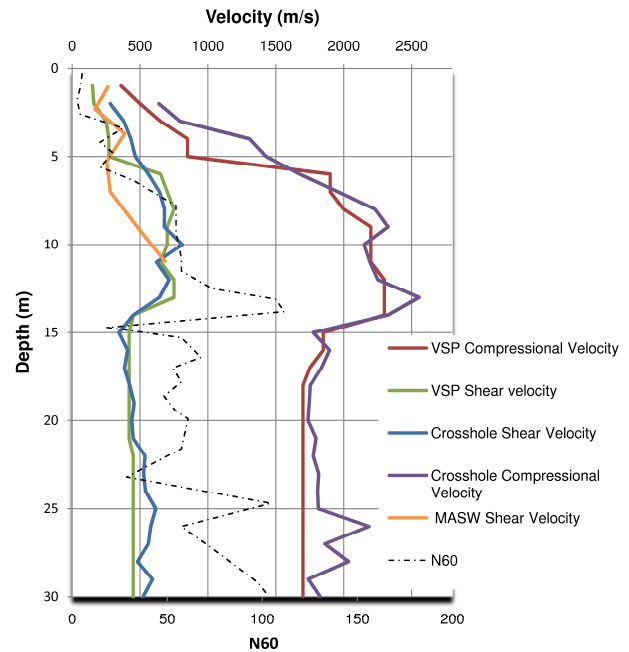


Figure 8: Comparison of VSP and crosshole compression and shear-wave velocity profiles at site 1. N_{60} graph is plotted with depth for visual correlation.

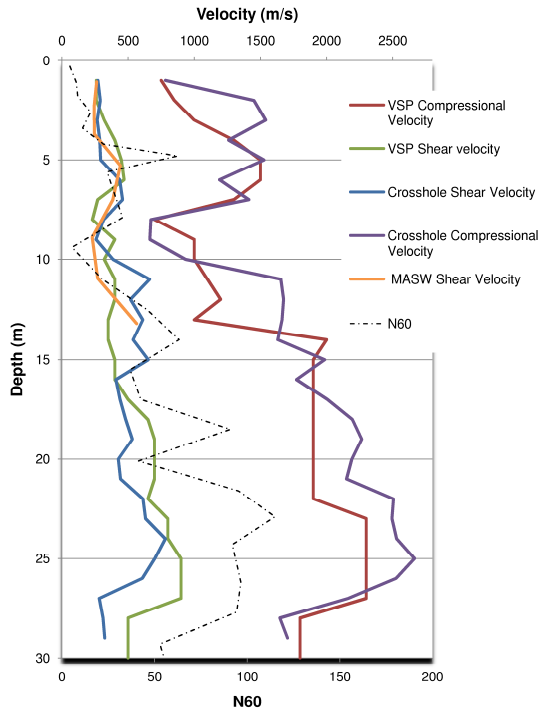


Figure 9: Comparison of VSP and crosshole compression and shear-wave velocity profiles at site 2. N_{60} graph is plotted with depth for visual correlation.

	Site 1		Site 2	
	V_{s30} m/s	NBCC 2005 Site Class Seismic Site Class	V_{s30} m/s	NBCC 2005 Site Class Seismic Site Class
MASW	482	C	413	C
Crosshole	484	C	404	C
VSP	402	C	427	C

Table 2: Table showing V_{s30} and Site Class for the three different tests at sites 1 and 2.

Table 2 provides a comparison between V_{s30} and N_{60} within the top 30 m below ground surface. We demonstrate variations in V_{s30} between the two seismic techniques. At site 1, V_{s30} from the crosshole and MASW tests are nearly identical but are approximately 20% higher than V_{s30} from the VSP test. At site 2, the crosshole test is approximately 5% lower than V_{s30} from the VSP and 2% lower than V_{s30} from the MASW.

V_{s30} calculated at the three seismic testing and at the two sites range from 402 to 484 m/s, which suggests that the two sites along the TYSSSE are classified as Seismic Site Class C (very dense soil and soft rock), as per guidelines given in Table 1. N_{60} values are well below 50 indicating that the use of N_{60} is conservative compared to the geophysics for these two sites.

The evaluation of site classification indicated a Site Class discrepancy between the geophysical and the geotechnical methods, showing that at least in this instance the use of SPT to determine seismic site

classification is more conservative than using seismic methods.

5 CONCLUSION

Site classification in the 2005 NBCC is defined primarily by looking where V_{s30} at a specific site stands relative to various defined ranges in the average shear-wave velocity (V_{s30}). If V_{s30} is not available at a site, the 2005 NBCC permits the use of N_{60} . At the two test locations results from the seismic methods have all designated both sites as Seismic Class C. This paper also demonstrates that, at least in this instance, the use of SPT tests is more conservative in estimating the seismic site class.

The three geophysical methods used at the two sites give comparable V_{s30} results and provide good agreement in terms of Seismic Site Classification. The observed shear-wave discrepancies between VSP and crosshole could be attributed to the picking of the VSP arrivals where small changes in picked arrival times can result in large changes in the estimated velocities. While

crosshole seismic is considered to be the most accurate, both the VSP and MASW show very comparable V_{s30} values. VSP is considerably faster because no deviation survey is required and less expensive because it does not necessitate the use of three boreholes. MASW is the cheapest and the fastest of the three seismic techniques, but the site conditions (e.g. not enough available distance) make it often difficult to provide a depth of investigation down to 30 metres. At the two sites the MASW V_{s30} are in good agreement with the other two seismic methods despite that the MASW depth of investigation was extrapolated below 13 metres. This is the case because as shown in Figures 8 and 9, shear-wave velocities below 15 metres are relatively consistent. Of course the MASW V_{s30} may have been in disagreement with the other seismic methods if a large change in velocity existed below 15 metres (e.g. bedrock).

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