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SEISMIC SITE CLASS DETERMINATION USING MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW)

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Abstract

NBCC(2005) and IBC (2006) seismic provisions emphasize that a quantitative approach is required for the determination of seismic site class for construction projects. According to these Codes the preferred method for proper site class assessment is the measurement of shear wave velocities within the upper 30 m of the underlying soil/rock profile (V_{S30}). In some cases, other methods such as SPT test are allowed to be utilized for this purpose; however, these methods are generally time consuming, costly and provide localized information at the site.

Multi channel analysis of surface waves (MASW) method is used to measure shear wave velocities within the underlying soil/rock profile at three sites for seismic site class determination. The MASW test results are compared to the information obtained from deep boreholes. The results show that in some cases seismic site class determination using different methods may end up with different results. Two cases are presented in which the measured V_{S30} at different locations at the Site resulted in different site classes. Suggestions are made to clarify the site class determination procedure provided in the Codes.

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 (F_a and

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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 velocities, SPT 'N' values or undrained shear strength within the upper 30 m of the subsurface soil below the founding level of the foundations or the top of the piles. According to NBCC User's Guide (2006), in this approach the time average shear wave velocity of the subsurface soil measured within the upper 30 m of soil below the founding level of the structure or top of the piles (V_{S30}) are calculated. Based on the following averaging scheme:

$$\overline{V_s} = \frac{H}{\sum \frac{h_i}{V_{si}}} \qquad \text{(EQ-1)}$$

where H is the total depth of the subsurface layers (i.e. 30 m), h_i is the depth of layer i, and V_{si} is shear wave velocity of layer i. Similar schemes are also introduced to calculate the average SPT 'N' values and undrained shear strengths of the soil deposit.

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 velocity measurements. For other site classes either of the three methods (V_{s30}, 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 should be installed (to obtain average SPT or s_u 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 more attractive for the following reasons:

- they are carried out from surface without any need for installing additional boreholes,
- the 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 the multichannel analysis of surface waves (MASW) was combined with conventional geotechnical investigations for seismic site class assessment. These studies show the potentials of MASW for proper site class determination. Further, 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. SPT 'N' values and shear wave velocities) may result in different site classes. Further, sharp changes in the spectral factors 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.

MASW Background

The MASW method is a seismic geophysical technique to estimate the soil shear wave velocity profile. MASW was developed in late 1990's as an advancement of other surface wave techniques, which were in use since early 1960's (Park et. al. 1999, Nazarian 1984, Ballard Jr. 1964). This method has been used is various applications such as seismic site characterization according to building codes, dynamic soil parameter estimation, non-destructive evaluation of subsurface soil condition including hard-to-sample soil deposits, pre and post construction soil conditions, detection of underground cavities (Xia 2006, Nasseri- Moghaddam 2006).

To carry out an MASW test, several transducers (i.e. geophones) are deployed along a line at certain distances from an impact source (Figure 1). The length of the geophone array (D) determines 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. A common source is a sledgehammer; though more complicated sources with better control over the generated frequency range are also available. The existing traffic noise can also be utilised as a 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. Successful application of MASW method to investigate depths of more than 100 m has also been reported, though these types of applications are not common and are labour and resource intensive (Stokoe 2008).

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. The recorded signals in the field, which are in time domain, 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 modulus profile of the medium. Figure 2A shows typical time domain data recorded in the field, and Figure 2B shows typical dispersion curves (variation of shear wave velocity with frequency) obtained from MASW data analysis.

Seismic Site Class Determination using MASW

The three case studies presented herein show the capabilities of MASW to evaluate subsurface soil conditions when combined with conventional geotechnical investigations. Cases 1 and 3 compare the results of MASW with the ones obtained from a deep borehole investigated with conventional Standard Penetration Test (SPT – ASTM 1586). Case 3 presents another example in which shallow boreholes were used in combination with MASW in a liquefiable soil. The case studies show that in some cases poor correlations between SPT 'N' values and shear wave velocities may exist. Therefore site class determination using different methodologies may result in different results. Further, these cases 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.

Case 1: MASW – SPT comparison

The subjected site (Site A) was located in south-eastern Ontario, Canada. The site was investigated by a borehole drilled to a depth of about 31.0 below existing ground surface (bgs) 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 was carried with the geophone array centered at the location of the borehole. The geophone array consisted of a total of 24 geophones which were laid down with 2.0 m and 4.0m spacings. A 20 lb sledge hammer was used as active source 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 3A.

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 3B 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 ms to 419 m/s. However below this depth the SPT 'N' values are generally in the 10 to 15 blows per 0.3 m of penetration range, 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' values within the upper 30 m of the soil profile is calculated (NBC User's Guide 2006). The average shear wave velocity is 373 m/s and average SPT 'N' value is 14. Therefore, the site is classified as site Class D 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.

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 borehole was deepened using dynamic cone 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 in turn 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 (V_{S30}) 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 4 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 Vs 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 (sieve analysis and Atterberg limits) to confirm that the soil is not liquefiable (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 likely if the SPT investigation was 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 V_{S30} 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.

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 V_{S30}. 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 within the upper 30 m of the soil deposit (V_{S30}) 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 5 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 5.

Comparing the variation of SPT 'N' values and shear wave velocities with depth indicate a good match within the upper 24 m (Figure 5). 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 (details not presented) that confirmed the potential for liquefaction at this site.

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. It is concluded that MASW provides a reliable, fast and relatively inexpensive complementary method for subsurface soil investigations. 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 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 reliable 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 lots of 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 function 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.

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Tables

Table 1. Site classification for seismic site response (NBCC 2005)

Site class	**Soil Profile Name**	**Average Properties in Top 30 m**		
		Average Shear Wave Velocity V_s (m/s)	**Standard Penetration Resistance, N_{60}**	**Soil Undrained Shear Strength, s_u**
A	Hard Rock	$V_s > 1500$	Not Applicable	
B	Rock	$760 < V_s < 1500$	Not Applicable	
C	Very Dense Soil and Soft Rock	$360 < V_s < 760$	$N_{60} > 50$	$s_u > 100$ kPa
D	Stiff Soil	$180 < V_s < 360$	$15 \leq N_{60} \leq 50$	$50 < s_u \leq 100$ kPa
E	Soft Soil	$V_s < 360$	$N_{60} < 15$	$s_u < 50$ kPa
E	Soft Soil	Any profile with more than 3 m of soil with the following characteristics:		
		• Plastic Index PI >20		
		• Moisture content $w \geq 40\%$, and		
		• Undrained shear strength $s_u < 25$ kPa		
F	Others	Site specific evaluation required		

Figures

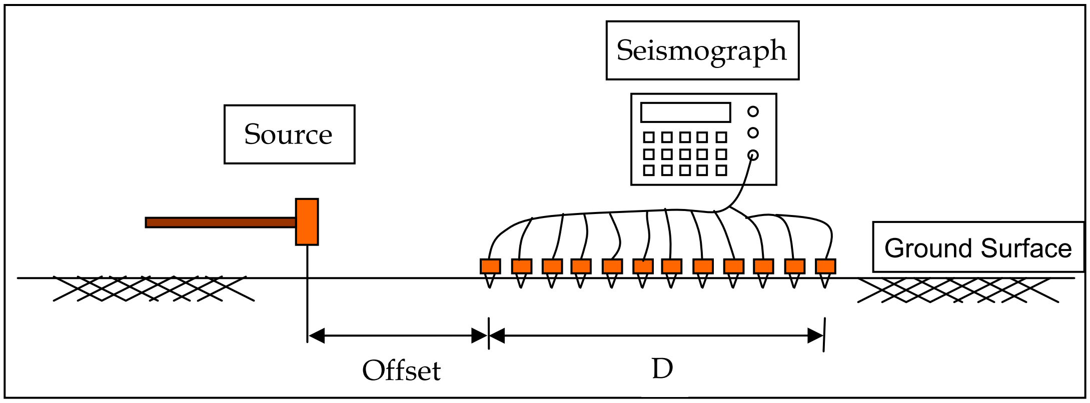

Figure 1. General field set up for MASW test

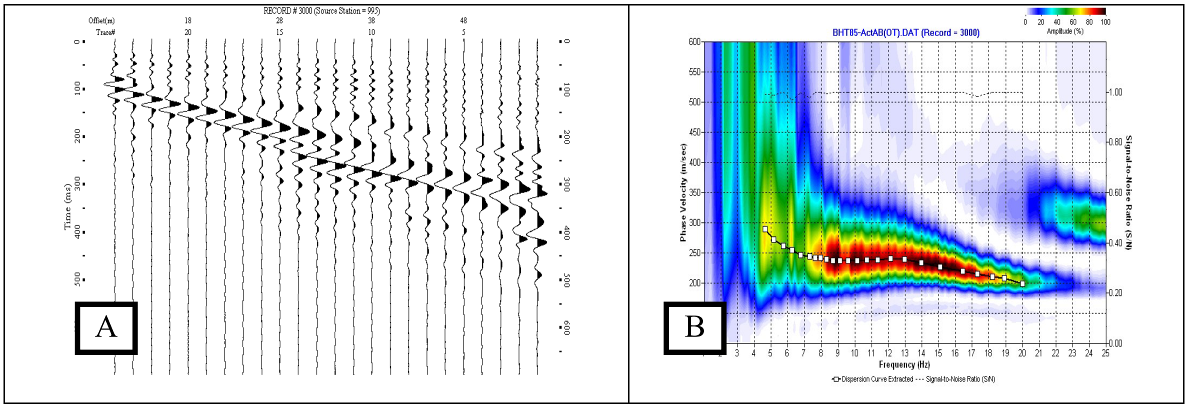

Figure 2. A- Typical surface wave data in time domain and B – Typical dispersion curves obtained from the field data

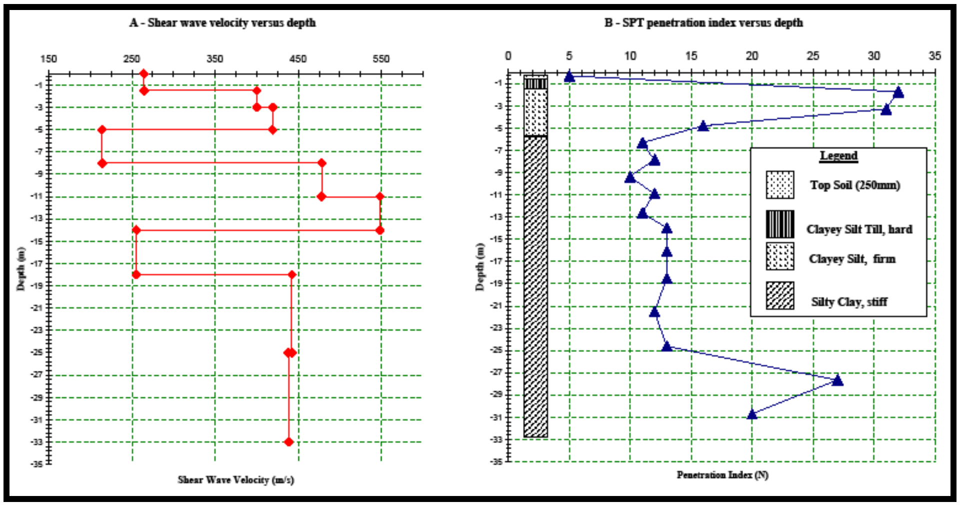

Figure 3. Case 1 variation of shear wave velocity and SPT ‘N’ values with depth

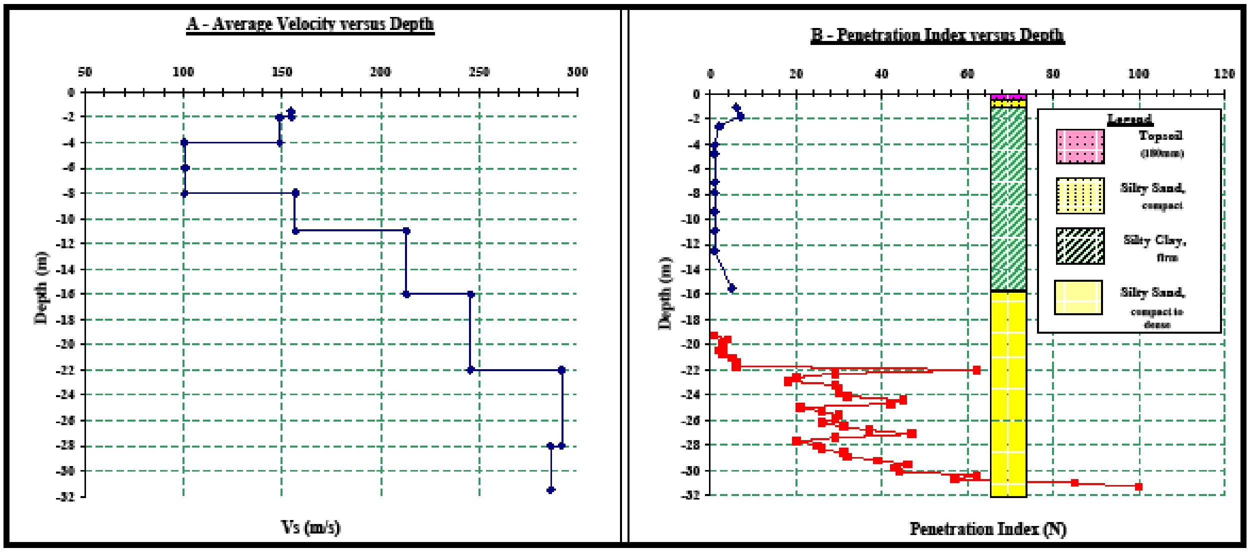

Figure 4. Case 2 variation of shear wave velocity and SPT ‘N’ values with depth

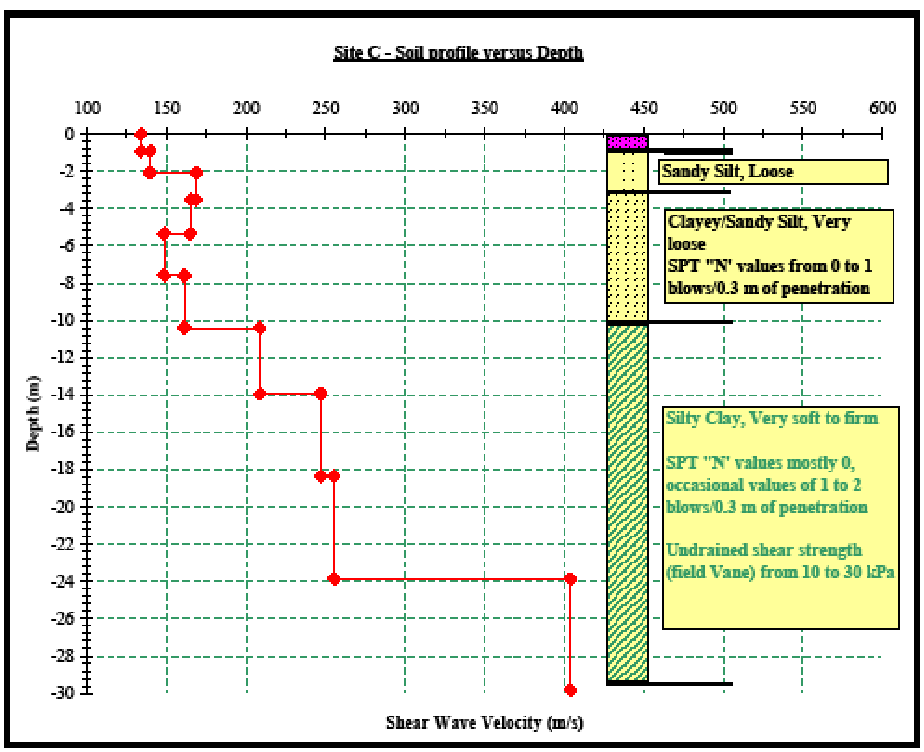

Figure 5. Case 3 variation of shear wave velocity and soil profile with depth

References

NBCC, 2005. National Building Code of Canada, National Research Council of Canada, Ottawa, Ontario

Heidebrecht, A. C., 2003. Overview of seismic provisions of the proposed edition of the National Building Code of Canada, *Canadian Journal of Civil Engineering* 30:241-254

NBCC User's Guide, 2006. User's Guide – NBC 2005 Structural Commentaries (Part 4 of Division B), National Research Council of Canada, Ottawa, Ontario

Stokoe II, K. H., 2008. The increasing role of seismic measurements in geotechnical engineering, The sixteenth Buchanan lecture, https://ceprofs.civil.tamu.edu/briaud/buchanan%20web/2008BuchananLecture.pdf

Park, C. B., Miller, R. D., Xia, J., 1999. Multi channel analysis of surface waves, *Geophysics* 64, 3, 800-808

Nazarian, S., 1984. In situ determination of elastic moduli of soil deposits and pavement systems by spectral-analysis-of-surface-waves method, PhD dissertation, The university of Texas at Austin, Austin, Texas

Xia, J., 2006, Delineating Subsurface Features with the MASW Method at Maxwell AFB in Montgomery, Alabama, KGS Open-File Report 2006-1, http://www.kgs.ku.edu/Geophysics/OFR/2006/OFR06_01/index.html

Nasseri-Moghaddam, A., Cascante, G., Philips, C., Hutchinson, D.J., 2007. Effects pf underground cavities on Rayleigh waves: field and numerical experiments. *Soil Dynamics and Earthquake Engineering* 27, 300-313

Louie, J. N., 2001. Refraction Micrometer (ReMi) Field Tutorial - 30-m Shear Wave velocity with Two Hours Effort, http://www.seismo.unr.edu/remi/field-tutorial.html, Retreived October 2007

Park, C.B., Miller, R.D., 2006. Roadside passive MASW, Proceedings of SAGEEP, April 2-6, Seattle, Washington.

KGS, 2008. MASW/Surfseis 2 workshop, Kansas Geological Survey, April 24-25, Lawrence, Kansas

Rix, G. J., 2005. Near-Surface Site Characterization Using Surface Waves, in Surface Waves in geomechanics: direct and inverse modelling for soils and rocks, edited by Lai, Carlo G., and Wilmanski, Krzysztof, 2005, International Center for mechanical science, courses and lectures no. 481, SpringerWien, NewYork

Borcherdt, R.D., 1994. New developments in estimating site effects on ground motion, Proceedings of the ATC-35 seminar on new developments in earthquake ground motion estimation and implications for engineering design practice, Applied Technology Council, California, pp. 10-1 to 10-44