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SHEAR WAVE VELOCITY PROFILE DETERMINATION BASED ON THE MULTI-CHANNEL ANALYSIS OF SURFACE WAVES METHOD FOR NEHRP SITE CLASSIFICATION IN THE CITY OF OTTAWA

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ABSTRACT

Active method of Multi-Channel Analysis of Surface Waves (MASW) was applied to obtain the shear wave velocity profiles for a few sites in the city of Ottawa. Estimated shear wave velocity profiles using this approach illustrate its capability in the determination of NEHRP classes. As expected, site classes of NEHRP E and D cover the most parts of the Orleans area while classes A to C are common in the western part of Rideau Canal. Considering its advantages, the MASW method is considered as one of the reliable, convenient and economical tools to determine NEHRP site classes in the Ottawa region.

Introduction

Surface waves are dispersive because their different wavelengths have different penetration depths and consequently they propagate with different velocities, when the velocity of seismic wave is changing with depth. It is common to use dispersion property of surface waves and obtain the dispersion curve, which is the phase velocity versus frequency, then; the obtained dispersion curve is analyzed and inverted to estimate the shear wave depth-velocity function **(**Nazarian *et al*., 1983; Stokoe *et al*., 1994; Park *et al*., 1998)**.** In near-surface seismic surveying with vertical sources, the energy of Rayleigh waves is about two thirds of the total seismic energy (Richart *et al*., 1970) and is very prominent on the multi-channel records. Hence, high signal to noise ratio can be attained and guaranteed by using surface waves. Furthermore, Rayleigh wave can be generated easily in comparison with the other types of seismic waves. If multi-channel system is used, body waves and higher-modes of Rayleigh wave can be recognized by their different resolutions on the multi-channel record and their different patterns on the associated dispersion curve. Multi-channel analysis of surface waves (MASW) is a quick method to evaluate the shear wave velocity profile compared to the other surface wave methods like SASW (Nazarian *et al*., 1983) since there is no need to change the configuration for reaching different depths.

Three steps are taken in an MASW application: a) data acquisition or collecting the required shot gathers, b), construction of the dispersion curve for the fundamental mode of the Rayleigh wave using the wavefield transformation technique, c), and non-linear inversion of the dispersion curve to obtain the shear wave velocity depth function. In this research, in the inversion procedures, Levenberg and Marquardt approach (Marquardt, 1963) is used for the selection of the damping factor, and singular value decomposition technique (Golub and Reinsch, 1970) is applied for the calculation efficiency

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Essential Parameters of the Methods

Essential parameters of the MASW method consist of type of receivers which are relatively low frequency geophones (4.5 Hz), spacing between two successive geophones, total length of spread, offset between the source and the first geophone, total time of recording and the sampling rate. In all cases the source of energy was a 12 lb sledge hammer striking vertically on a rigid and heavy plate to produce P waves. The combination of the reflected P and SV waves produce Rayleigh wave, which has a dispersive behavior.

Some important factors should be noted. First, an appropriate coupling between the plate and the ground is essential because the seismic wave should be transmitted properly. Both of the spike-coupled and plate-coupled geophones have their own limitations and advantages, hence, extra considerations are needed depending on the corresponding site conditions. Second, the natural frequency of geophones should be low, since the high frequency ones will limit the depth of investigation. Third, the length of the spread is supposed to be equal or comparable to the maximum resolvable depth of investigation. Forth, the spacing between geophones which controls the depth-velocity resolution is generally between 0.5 and 1.5 m. Fifth, the distance between source and the end of spread (offset) was between 10 m and 100 m. The minimum value of the offset was considered to avoid the non-linear propagation of Rayleigh waves at shorter distances. At larger distance than the maximum value of offset, the dominance of body waves or the ambient noise is probable.

Case Studies

Active MASW method was carried out for six sites in the Orleans area and around the west bank of Rideau Canal. Three of those sites, Heritage Park, Louis Perrault Park and Barrington Park are located in the Orleans area. The rest at the west bank of Rideau Canal are Brantwood Park, Browns inlet Park and Robinson Park. Fig.1 and Fig.2 show the locations of these sites in the west of Rideau Canal and Orleans area respectively. Geology of the sites indicates that the loose deposits fill the most part of the Orleans area. The geological evidences also show the existence of stiff soil and rocks in near-surface layers for the sites in the west bank of Rideau Canal.

Multiple stack hammering (e.g. 5 stacks) was necessary to get a continuous dispersion curve of the Rayleigh wave. In addition, Spike-coupled geophones were used to ensure the proper coupling. Recording was done when the background noise was low and negligible compared to signals, in order to produce clear and strong dispersion curves. Other survey parameters are; 1.0-1.5 m spacing, 20-30 m offset, 23-34.5 m length of spread. All of these parameters are illustrated in Table 1.

Table 1. Survey parameters for 6 mentioned sites in Ottawa region.

Offset	Spread length	Spacing	Record length	Stack #	Coupling
20-30 m	23-34.5 m	1-1.5 m	2 sec	5	Spike

The interpretation of the surveying results was done using Surfseis software (KGS, Park, 2004). Fundamental Mode of the Rayleigh wave was clearly recognizable because of its high energy (note to the amplitude bar in the top-right of the dispersion curve in Fig. 4 as an example). Then, the non-linear inversion technique was applied to this curve to obtain the shear wave velocity variation in depth. For three sites in the Orleans area, the extracted dispersion curves and shear wave velocity (V_s) profiles are shown in Figs. 3 to 8 (verifying the low shear wave velocity and loose soil of that part of the city which is confirmed by the geological information). For other three sites in the west of Rideau Canal, the results of interpretation are demonstrated in the Figs. 9 to 14. Dispersion curves and velocity profiles of these sites verify the nature of high shear wave velocity for the west bank of Rideau Canal. To evaluate the uncertainty, the confidence limit curves of V_s are shown in Figs. 15 to 16 for 2 selected sites. For sites in the Orleans area, confidence limit was tight. This low range confidence limit is mainly related to the clear pattern of dispersion curves for this area. As an illustration, Fig. 15 shows the confidence limit for the Heritage park in Orleans. For the sites near the Rideau Canal, confidence limit becomes wider in comparison with the confidence limits of the sites in Orleans area. For instance, Fig. 16 represents the confidence limit curves for the Robinson park. The mentioned larger limit in Robinson park can be attributed to the relatively complicated pattern of its dispersion curve (Fig.13). For this park, the produced dispersion curve gives a wide range to extract the fundamental mode of Rayleigh wave and this range imposes higher uncertainty.

Since the analysis was performed based on the fundamental mode of the Rayleigh wave, the extraction and recognition of the pattern of the dispersion curve was the most significant part of the method. The lowest frequency of the curve determines the limit of the maximum resolvable depth (Rix and Leipski, 1991), while the highest frequency controls the thickness of the upper most layer (Stoke *et al.*, 1994). For example, as shown in Fig. 11, dispersion curve (fundamental mode) appears in high frequencies between 25 and 32 Hz which implies the lower depths with higher velocities in comparison with low-frequency dispersion curves (e.g. Fig. 4).

Numerous advantages can be mentioned for MASW analysis. As an advantage, dispersion curves related to the body waves and ambient noise can be recognized and separated from the analysis. For instance, in Fig. 4, higher mode is obvious with higher frequencies and greater phase velocities which can be put away from the interpretation. On the contrary, active method suffers from some limitations. As shown in the most of the figures of the dispersion curves, it was not expected to observe the dispersion curve (fundamental mode) for the frequencies lower than 2 or 3 Hz. Besides it was impossible to investigate the depths much more than the spread length (~40 m).

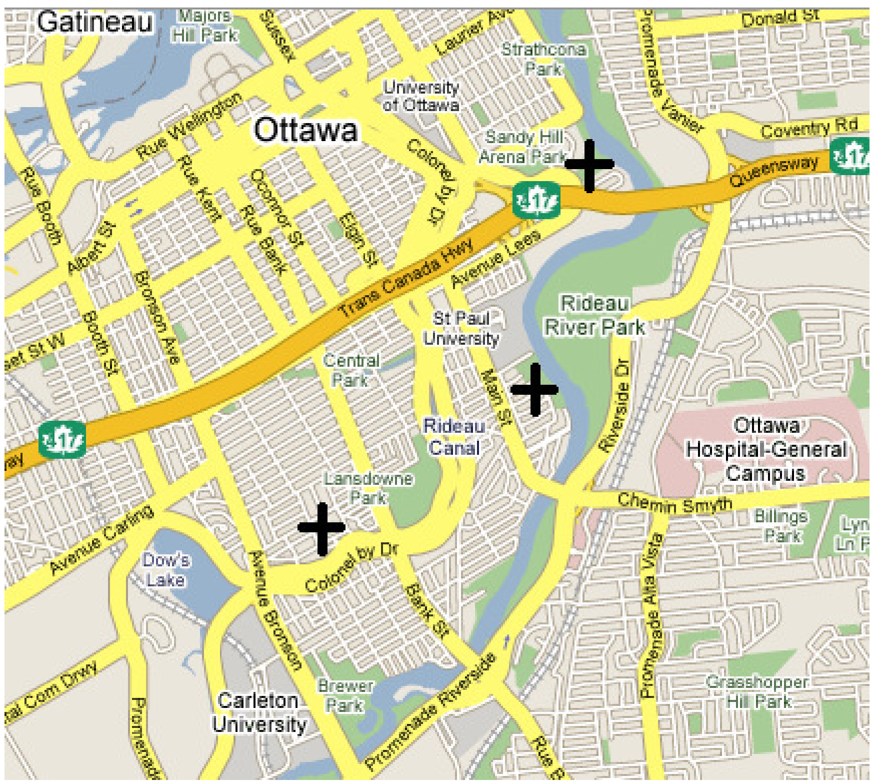

Figure 1. Locations of three MASW sites (specified with cross) in the west bank of Rideau Canal (Google website).

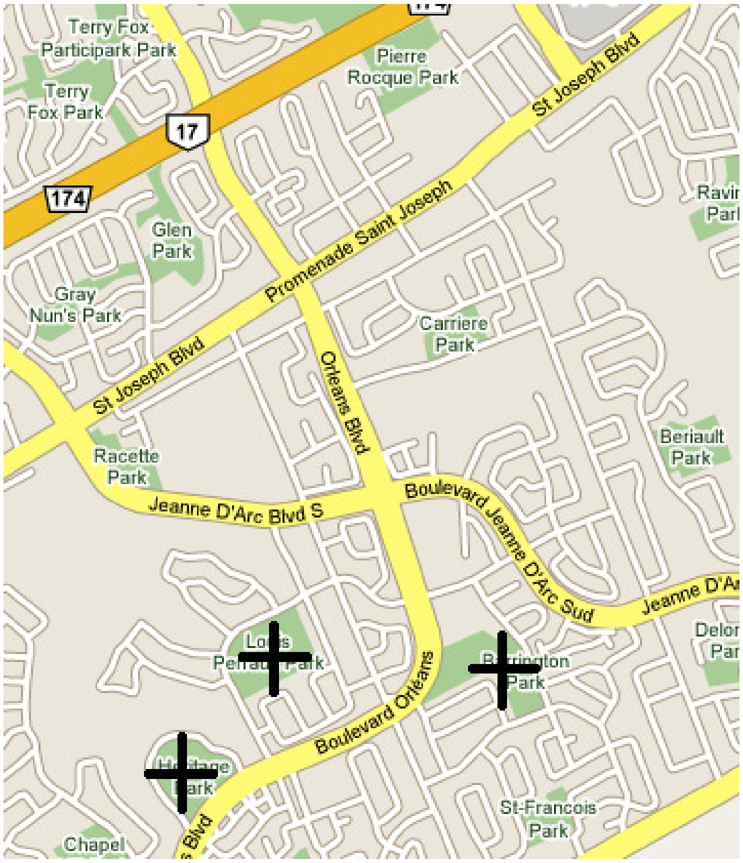

Figure 2. Locations of three MASW sites (specified with cross) in the Orleans area (Google website).

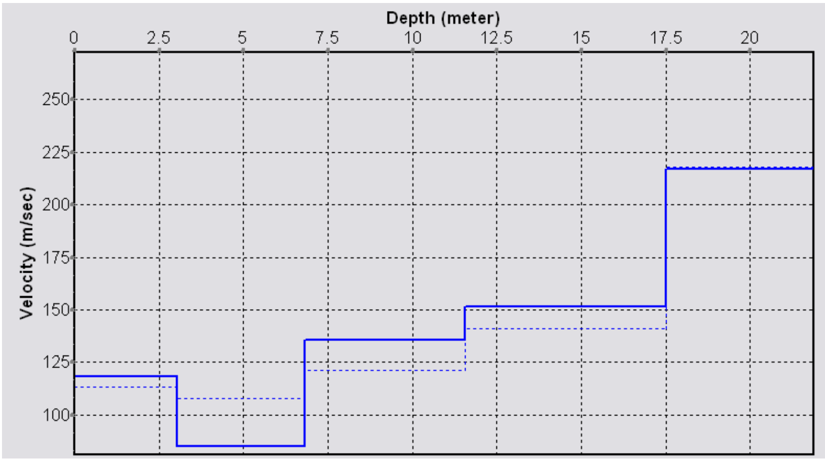

Figure 3. V_s profile for Heritage Park site. Solid and dot lines illustrate the final and initial models, respectively.

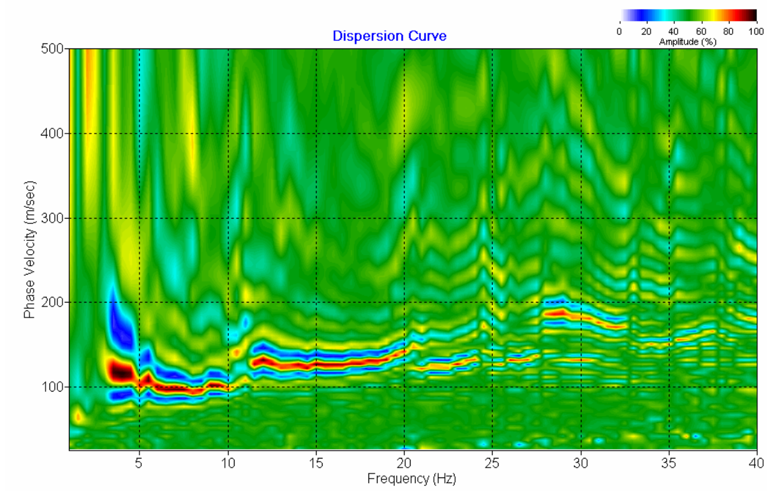

Figure 4. Dispersion curve for Heritage Park site.

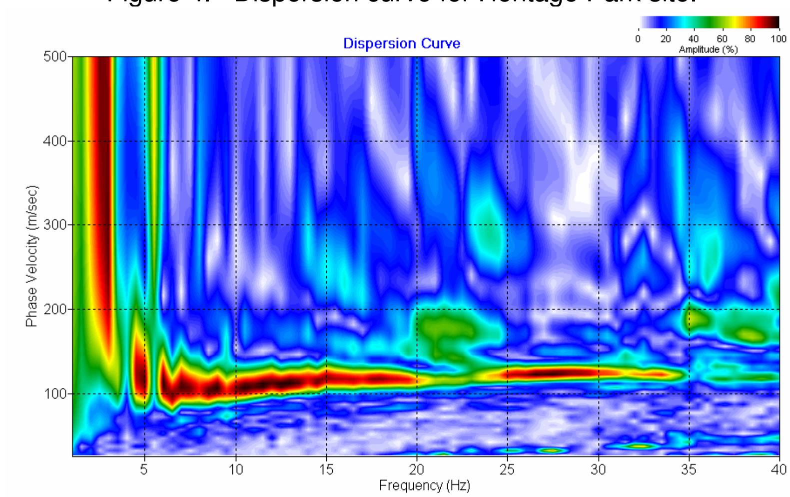

Figure 5. Dispersion curve for Louis Perrault Park site.

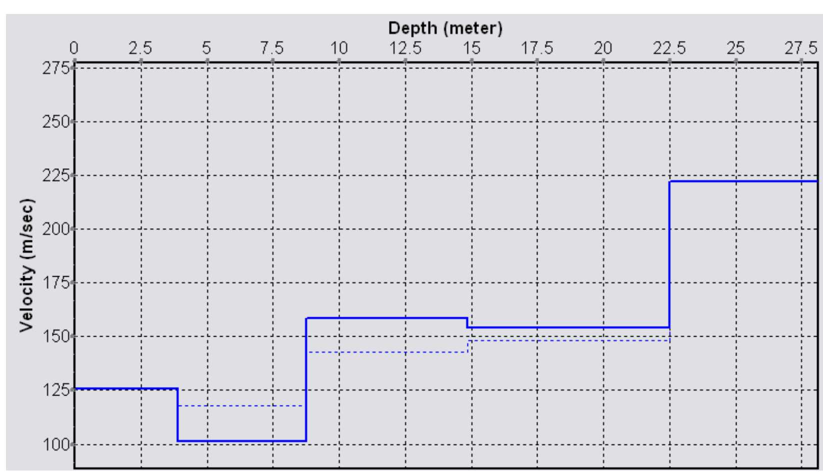

Figure 6. V_s profile for Louis Perrault Park site. Solid and dot lines illustrate the final and initial models, respectively.

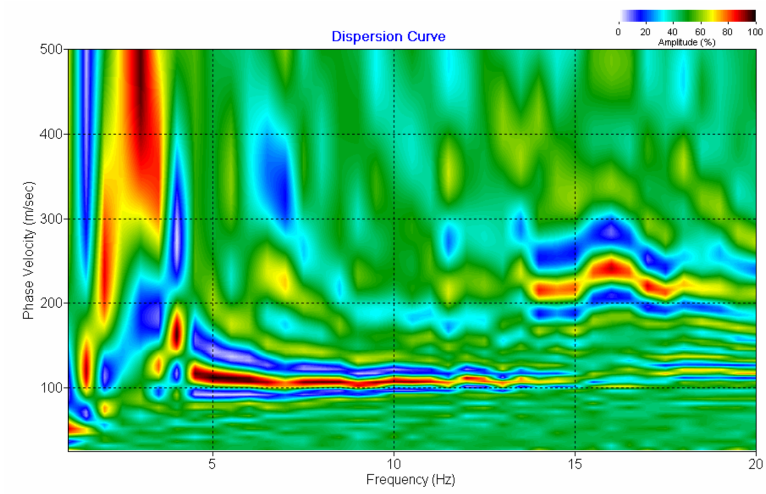

Figure 7. Dispersion curve for Barrington Park site.

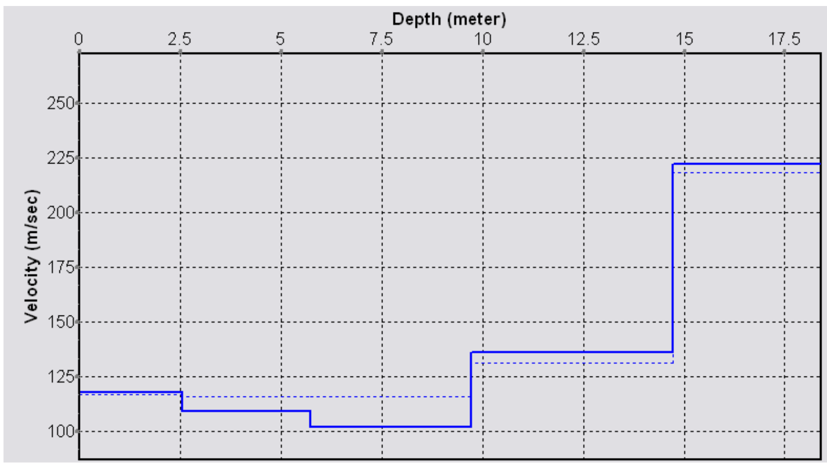

Figure 8. V_s profile for Barrington Park site. Solid and dot lines illustrate the final and initial models, respectively

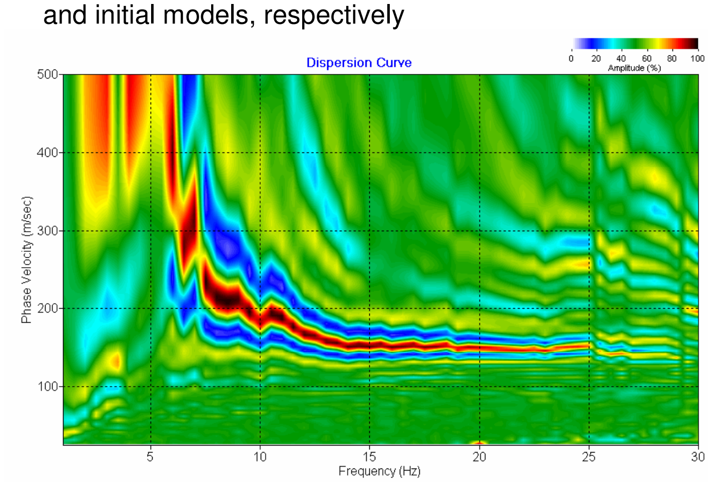

Figure 9. Dispersion curve for Brantwood Park site.

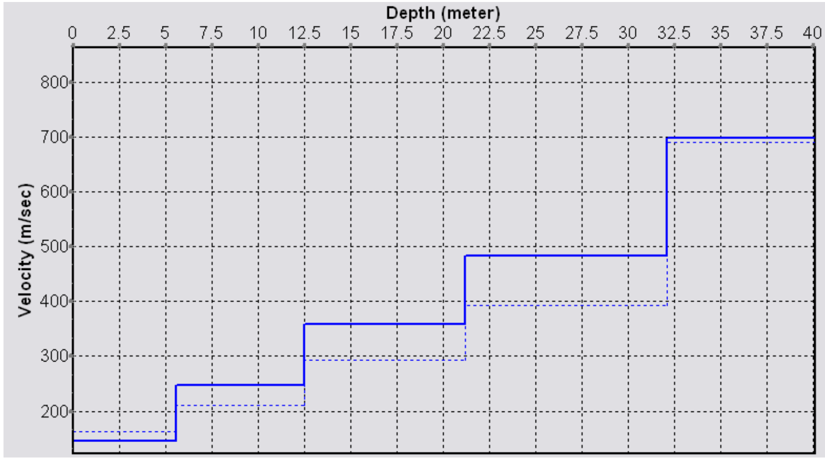

Figure 10. V_s profile for Brantwood Park site. Solid and dot lines illustrate the final and initial models, respectively.

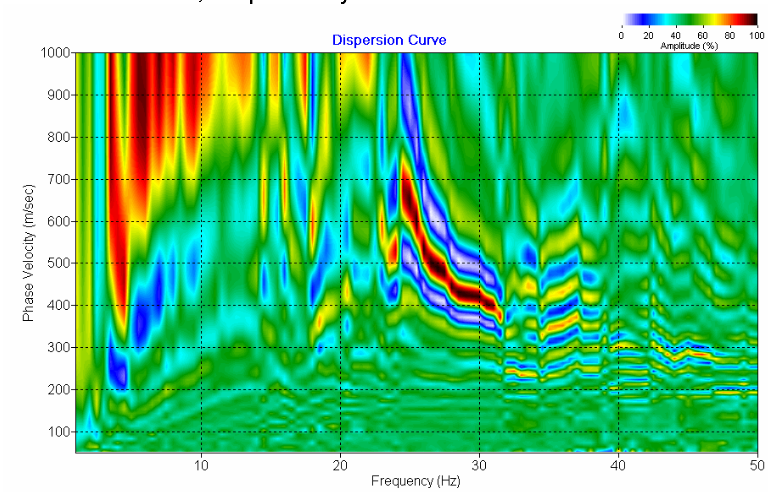

Figure 11. Dispersion curve for Browns inlet Park site.

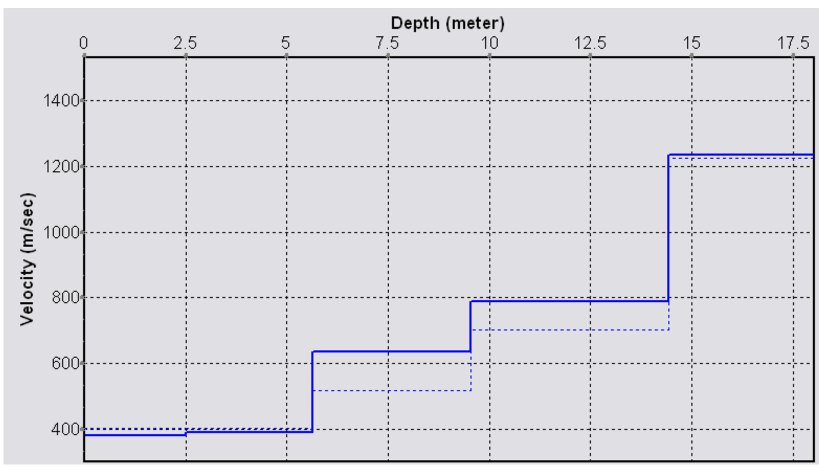

Figure 12. V_s profile for Browns inlet Park site. Solid and dot lines illustrate the final and initial models, respectively.

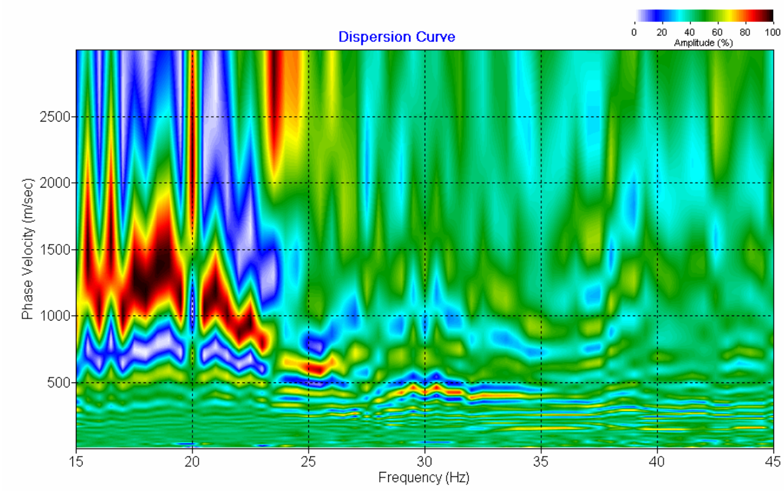

Figure 13. Dispersion curve for Robinson Park site

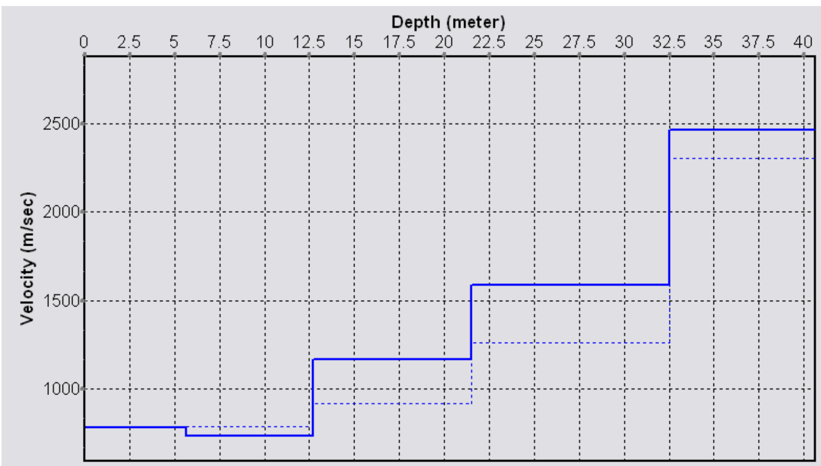

Figure 14. V_s profile for Robinson Park site. Solid and dot lines illustrate the final and initial models, respectively

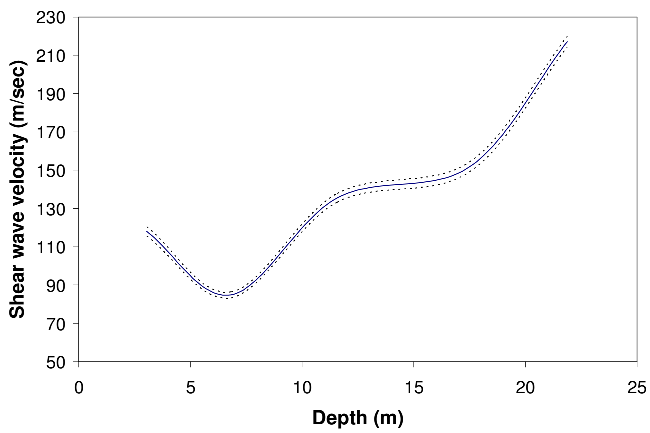

Figure 15. Shear wave velocity variation with confidence limits (dot lines) for Heritage Park site.

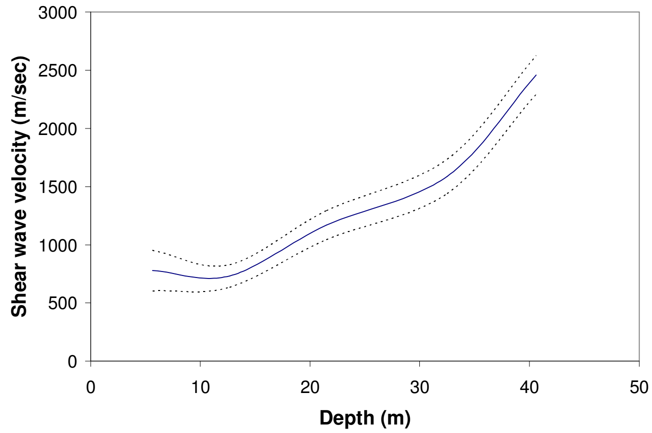

Figure 16. Shear wave velocity variation with confidence limits (dot lines) for Robinson Park site.

Discussions and Conclusions

Active multi-channel analysis of surface waves (MASW) method was applied to determine the shear wave velocity profiles for some parks of Orleans area and the west of Rideau Canal in the city of Ottawa. These profiles are useful for the determination of the NEHRP site classes according to the national building code of Canada (NBCC, 2005). NEHRP site classifications facilitate the determination of the seismic site response and seismic amplification factors.

To investigate the reliability of the method, six different sites were surveyed. The majority of these sites were at locations with known soil classes. Previous studies (Motazedian and Hunter, 2006), geological information, local maps and boreholes (GSC maps for surficial boreholes) give the range of site classes for these locations. Most of the Orleans area is covered by soft and loose clay; on the contrary, parks near the Rideau Canal are recognized with rocky and stiff near-surface layers in the local maps. Analyses results of those sites are presented in the Figs. 3 to 12. As the first interpretation step, dispersion curves of the fundamental mode of the Rayleigh wave were extracted for the specific frequency range (not less than 3 HZ). The next step was the non-linear inversion which its precision depends on the accuracy and the resolution of the dispersion curves. If the extracted curve lies in the desirable range of the frequency with clear and recognizable tails in low and high frequency phase velocities, reliable shear wave velocity profile is obtained.

Figs. 3 to 8 show low phase velocities for dispersion curves and small values of shear wave velocity which confirm the previous studies and geological maps. Heritage Park, and Barrington Park (Figs. 3 and 8) lie in NEHRP zone D and Louis Perrault Park (Fig. 6) is classified in class E since the average shear wave velocity value of this park is below 180 m/sec. Furthermore, the interpretations verify the MASW capability in yielding reasonable results for stiff and rocky sites. High values of shear wave velocity for Robinson Park (Fig. 14) categorize this park in NEHRP class A (V_s > 1500 m/sec). Browns inlet and Brantwood parks (Figs. 12 and 10) are located in classes B (760 < V_s < 1500 m/sec) and C (360 < V_s < 760 m/sec), respectively. These results validate the capability of MASW method as a reliable and convenient tool to obtain the shear wave velocity profiles for different NEHRP site classes. These classifications are valuable for the evaluation of the site amplification factors and the seismic site responses. The corresponding amplification factors have been defined in the technical literature by Finn and Wightman (2003).

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