Earthquake Site Characterization of Southwestern Ontario for Microzonation Mapping

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ABSTRACT

An earthquake of Nuttli magnitude (M_N) 4.1 was felt in Essex county area in Southwestern Ontario, Canada on April 19th, 2018 with epicentre at 42.12 °N and -83.03 °E, and a depth of 5 km. The earthquake was located 6 km ENE of Amherstburg and 20 km S of Windsor, Ontario. Earthquakes Canada collected 812 online felt reports from the southwestern Ontario region although most residents felt very weak shaking (intensity II-III). Five sites are chosen in populated areas of Windsor and Amherstburg to study the subsurface conditions, in terms of soil stiffness, and how they vary between the two regions. Active- and passive-source surface wave array recordings were performed to obtain Rayleigh wave dispersion curves at each site. The use of three-component seismographs also permits calculation of horizontal-to-vertical spectral ratios (HVSRs) from the passive seismic (microtremor) array recordings. Joint inversion of microtremor HVSR (MHVSR) and dispersion curves are performed to estimate V_S depth profiles. Earthquake site classification in Canadian seismic design provisions for buildings and bridges is based primarily on the site's time-averaged shear-wave velocity of the upper 30 m (V_{S30}). Sites in Windsor are categorized as site class D with V_{S30} estimates of 240 to 298 m/s, indicating stiff soil conditions. Sites in Amherstburg are typically stiffer, with V_{S30} of 444 m/s (site class C) and 909 m/s (site class B), indicating the presence of rock beneath the uppermost thin soil layer. This study documents measured lateral variation of subsurface ground conditions in southernmost Ontario.

Keywords: Earthquake site characterization, V_{S30}, ambient vibration array, MASW, MHVSR.

INTRODUCTION

The objective of earthquake site characterization is to measure subsurface material properties, required to accurately predict earthquake ground shaking at a site. Generally softer sites experience stronger and longer ground shaking in the occurrence of a low-to-moderate magnitude earthquake, when compared to stiffer or rocky sites [1]. According to the definition given in the Seismic Provisions of the 2005 National Building Code of Canada (NBCC), sites are categorized into different site classes from Class A to E depending on the time-averaged shear-wave velocity (V_S) over the upper 30 meters (V_{S30}), where Class A corresponds to hard rock sites (higher V_{S30}), and Class E corresponds to soft soil sites (lower V_{S30}) [2]. Non-invasive V_S depth profiling methods include inversion of dispersion curves or amplification functions from surface wave array and MHVSR methods, respectively. While estimating V_S from either dispersion curve or MHVSR, or both methods together, the subsurface structure is assumed as a one-dimensional (1D) vertically heterogeneous medium [3]. A surface wave dispersion curve, i.e., surface wave velocity as a function of wavelength or frequency [1], is obtained from tracking the phase or group velocity of particular wavelength surface waves, across a seismic array. MHVSR is the ratio of average horizontal components (H) frequency spectra with the vertical component (V) spectrum of a tri-axial seismometer's microtremor recordings [4]. MHVSR amplification functions are often used for seismic microzonation studies, as their peak frequency (f_{peak}) typically corresponds to the site's fundamental frequency (f_0) [4].

Performing joint inversion of the dispersion curve with MHVSRs is known to help in generating more robust subsurface V_S models and reduce uncertainties involved with their estimation [5][6]. Dispersion curve methods are based on the phenomenon of dispersion, in which waves with longer wavelengths will travel at depth in higher velocity material and thereby arrive earlier than shorter wavelengths, which travel at shallower depths in lower velocity sediments [7]. To investigate deeper, MHVSRs are used as they provide amplified peak frequencies related to impedance contrasts at depth, typically at lower frequencies where dispersion curve estimates are absent [8]. The current study utilizes the joint inversion technique for V_{S30} estimation in the region of Windsor and Amherstburg, after an earthquake of M_N 4.1 occurred in the Essex county. Figure 1a shows the felt intensity map for this earthquake, along with the five test sites at Windsor (W) and Amherstburg (A) (S. Halchuk, personal communication, 2018). The reported felt intensities are primarily II-III and consistent in Windsor at 20 km epicentral distance and Amherstburg at 6 km epicentral distance. To verify similarity in regional earthquake shaking intensities, five test sites are selected to perform active- and passive-source seismic array surveys. The recorded array data were used to obtain V_S depth profiles through joint inversion for each site. Geotechnical reports around the five test sites indicate soils with higher shear strengths in Amherstburg compared to Windsor [9][10]. These reports and the drift thickness map (Figure 1b) of the Ontario Geological Survey (OGS: https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth) demonstrate increasing soil layer thickness from 0-20 m depth in Amherstburg to 20-120 m depth in Windsor [9][10][11].

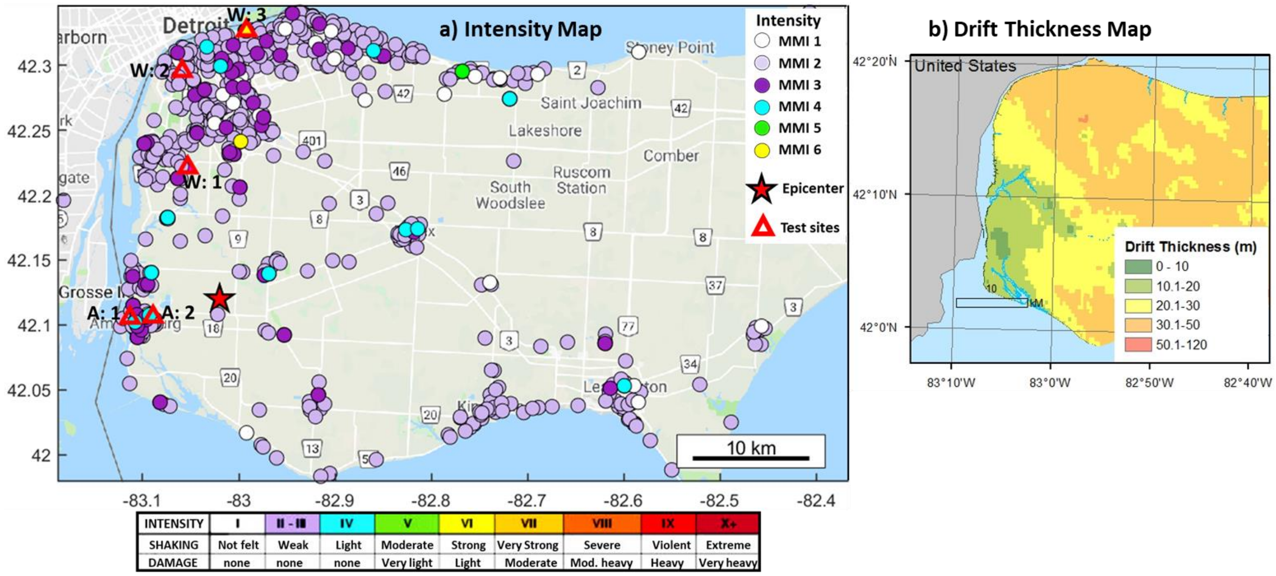

Figure 1. (a) Earthquake felt intensity map from Earthquakes Canada felt reports. The five test site locations are shown as triangles, star represents the 2018 M_N 4.1 earthquake epicentre location. (b) OGS drift thickness map [11].

Previous efforts in understanding earthquake site amplification and subsurface site characterization (V_S depth profiling) in southwestern Ontario includes development of a site amplification model from earthquake and microtremor HVSRs at seismograph stations in Ontario [11]. The amplification response of particular geologic units was then applied to mapped surficial geology units across Ontario. In addition, Bilson Darko et al. (2019) performed *in situ* ambient vibration array recordings at six bridge sites in Windsor (see Figure 2). They determined V_{S30} estimates of 247 to 286 m/s at these six bridge locations from Vs profiles determined from joint inversion of dispersion curves and MHVSRs [12].

GEOLOGICAL SETTING

Windsor and Amherstburg lie in the St. Clair Clay Plain of Essex county [13]. Figure 2 shows the main physiographic regions and features of Essex county.

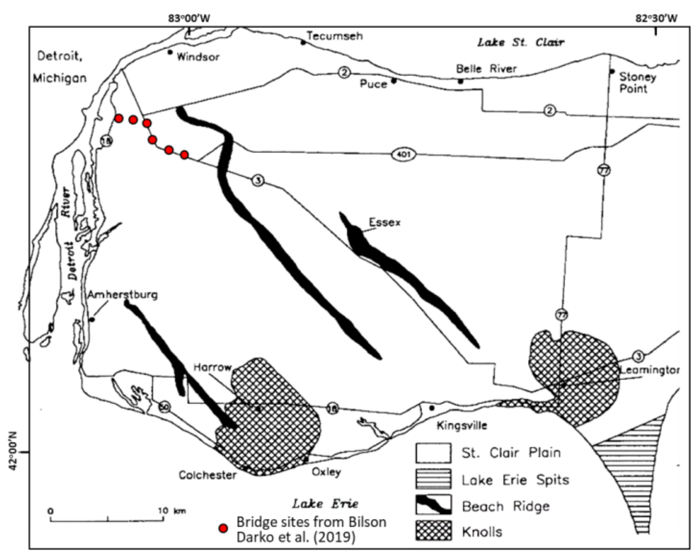

Figure 2. Map showing the main physiographic regions and features of Essex county [13]. Also shown as filled circles on top left are the six bridge sites from Bilson Darko et al. (2019) [12].

The basement is composed of Precambrian metamorphic rocks and is overlain unconformably by Middle Devonian limestones and dolostones that were deposited during periods of high sea level [13][14][15]. Bedrock is generally uplifted in a NE-SW trend through Essex county as part of the Findlay Arch uplift [16]. Quaternary unconsolidated glacial till sediments overlie the limestone bedrock [14][15]. The glacial till deposits are composed of the gravelly Catfish Creek till, which is overlain by clayey-to-silty Tavistock till. A glacio-lacustrine silty-clay overlies the Tavistock till [14]. Windsor lies in the St. Clair Clay Plain and is generally flat [13]. Minimal topographical features are present and occur as till ridges, overlain by beach sand or knolls in central and southern Essex county, respectively. Orientation of rivers and streams is controlled by the bedrock [13] and subsurface drainage is divided by the Essex beach ridge to flow north into Lake St. Clair and south into the Detroit River and Lake Erie [13].

DATA AND METHODOLOGY

Non-invasive V_S profiling methods are performed at three locations in Windsor and two locations in Amherstburg (Figure 1). Passive-source ambient vibration array (AVA) recordings were collected with 4 three-component Tromino® sensors in sparse nested triangle geometries. Passive seismic array data were recorded for about 20-30 minutes for 3-5 arrays at each site by varying the sensor spacing (array sizes of 5, 10, 15, 20 and 30 m varied, depending on the location). The days when the data were collected were windy, therefore, to avoid the wind effect on passive seismic data, holes were dug in the grass fields and the sensors were placed inside these holes. Active-source seismic array testing, known as the Multi-channel Analysis of Surface Waves (MASW) method, is also performed at each site using a linear array of 12 vertical-component 4.5 Hz geophones spaced at 0.5, 1 and 3 m intervals (array lengths of 5.5, 11 and 33 m, respectively). Surface waves are generated by vertical sledgehammer blows on an aluminum plate placed at 5 m offset for 0.5 and 1 m receiver spacings and 10 m offset for 3 m receiver spacing, at each end of the linear array. Figure 3 shows the array data collection accomplished at Windsor site 1 and Amherstburg site 1.

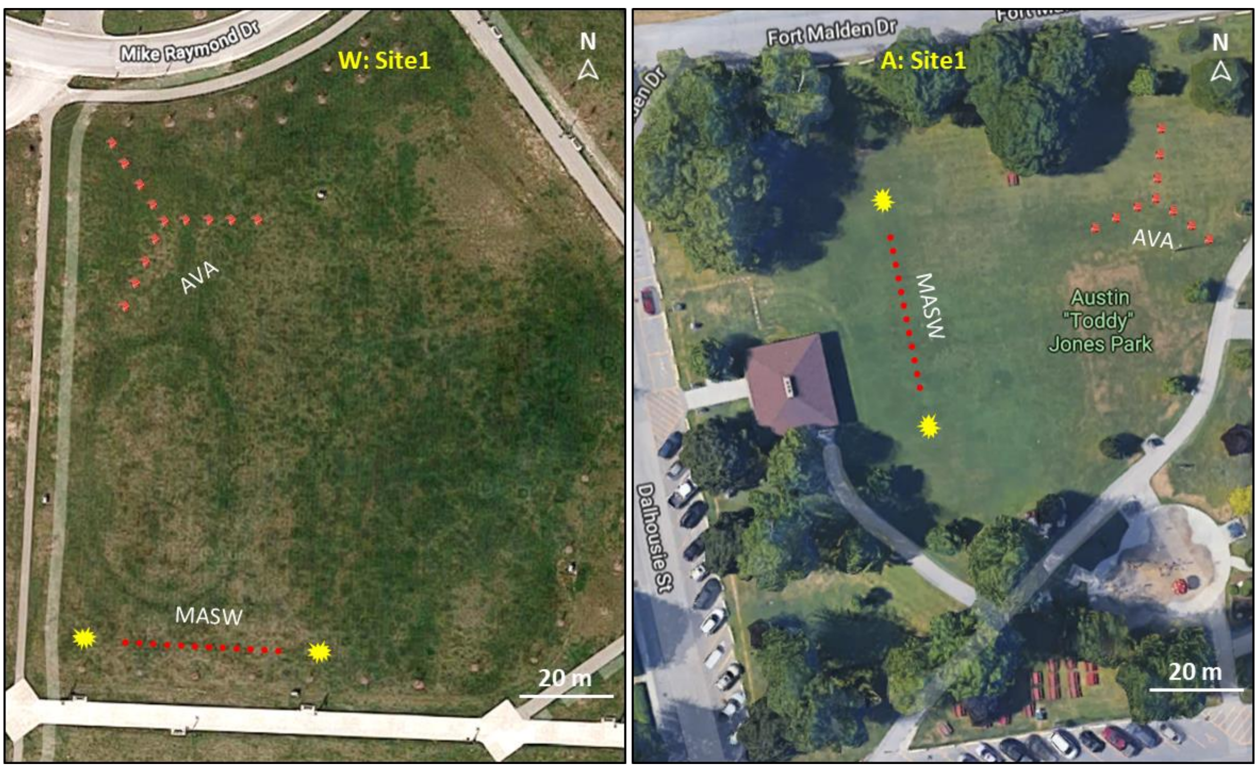

Figure 3. Left panel shows a schematic of the AVA and MASW array data collection for Windsor site 1, and right panel shows the same for Amherstburg site 1.

The active- and passive-source array recordings are loaded into Geopsy (http://www.geopsy.org/) databases for dispersion analysis. Rayleigh-wave phase velocity estimates are retrieved at selected frequencies using frequency-wavenumber (f-k) and modified spatial autocorrelation (MSPAC) processing [18][19][20]. Fundamental-mode Rayleigh wave phase velocity dispersion curves are manually picked from the f-k and MSPAC histograms (Figure 4 and 5). The smaller array size and receiver spacings used in active-source MASW testing leads to phase velocity estimates at higher frequencies compared to passive-source AVA testing. Combining reliable dispersion estimates from both array methods enables constructing the final or full dispersion curve over a wide frequency band for each site.

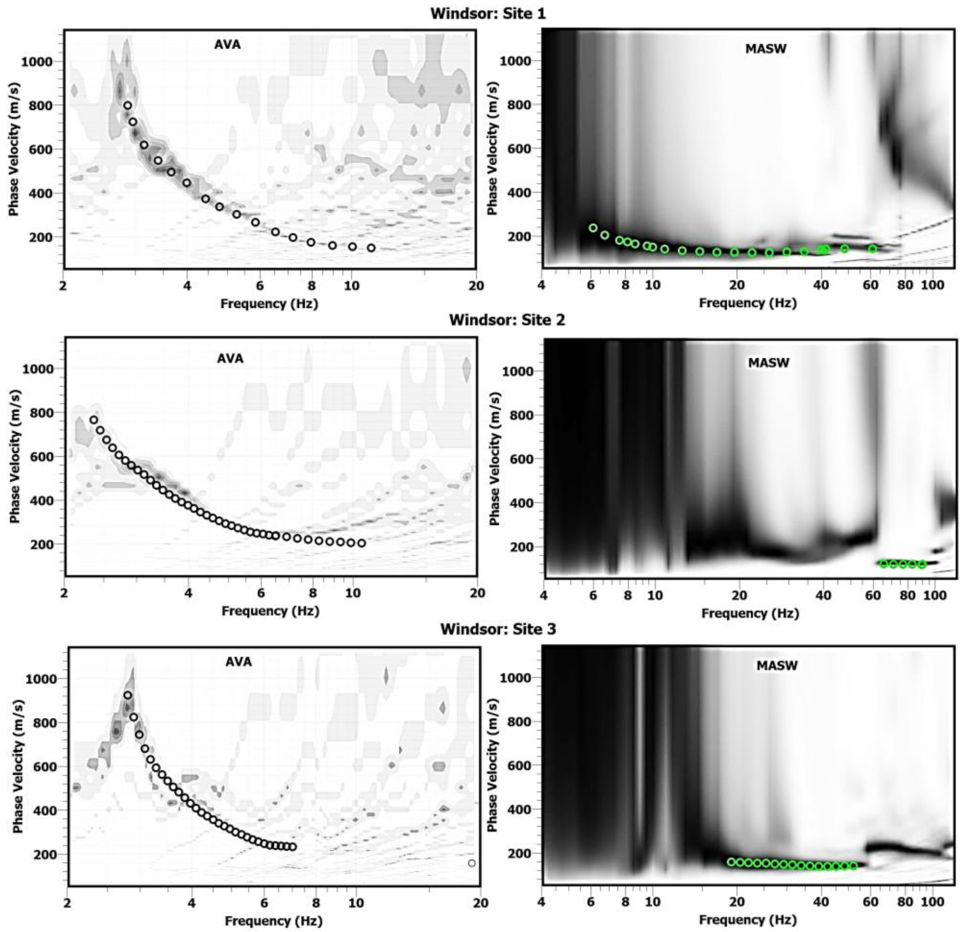

Figure 4. MSPAC-processed dispersion histograms from AVA recordings (left panels) and f-k-processed dispersion histograms from MASW recordings (right panels) generated for the three sites in Windsor. Open circles show manually picked dispersion estimates.

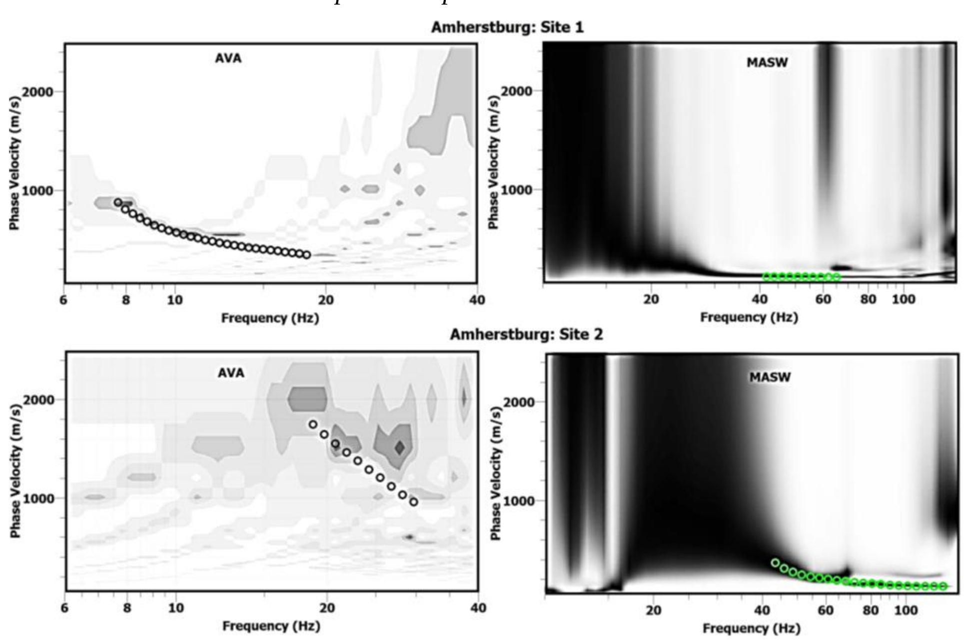

Figure 5. MSPAC-processed dispersion histograms from AVA recordings (left panels) and f-k-processed dispersion histograms from MASW recordings (right panels) generated for the two sites in Amherstburg. Open circles show manually picked dispersion estimates.

The three-component passive seismic array recordings were also used to calculate MHVSRs for the five sites. In the presence of a strong impedance contrast between soil and bedrock layer, the MHVSR peak frequency corresponds to the observed earthquake resonance frequency [4][17]. The fundamental mode peak frequency (f_0) is related to average V_S of the sediment layer ($V_{S_{ave}}$) and its thickness (h) by the relation, $f_0 = V_{S_{ave}}/4h$ [3]. MHVSRs can be modeled as amplification functions for a given 1D soil column (layered earth model). Figure 6 presents the MHVSR results for the five sites tested in Essex county. The MHVSR response is a narrow high-amplification f_{peak} for Windsor site 1, 2 and 3 at ~2.5, ~1.9 and ~2.1 Hz respectively. There is a single significant impedance contrast at depth. These MHVSR results are similar to the six bridge sites along Huron Church Road [12] and demonstrate a rather consistent narrow ~2 Hz f_{peak} in southwest Windsor. In contrast, the MHVSR f_{peak} is much higher in Amherstburg with 5.7 Hz at Site 1 and 16.2 Hz at Site 2, suggesting shallower impedance contrasts or thinner soils. Windy conditions lead to higher standard deviations in the MHVSRs for Site 2 at lower frequencies (< 10 Hz).

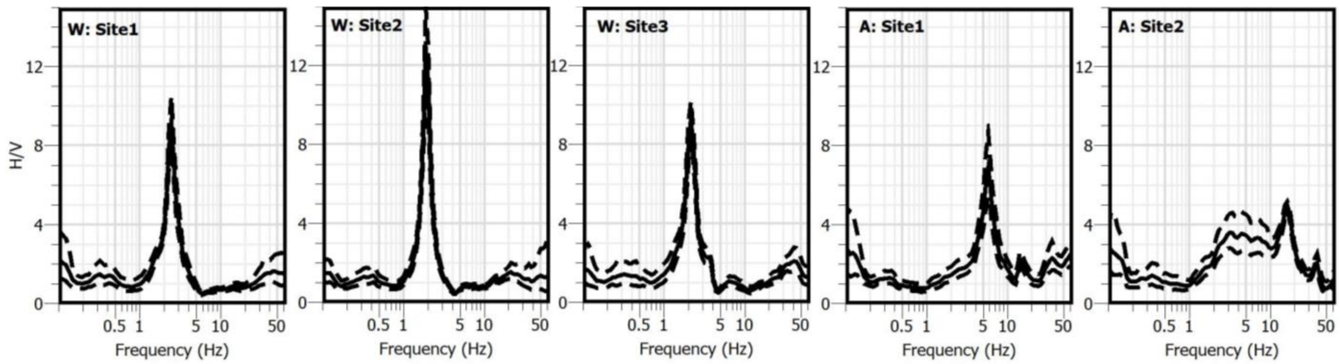

Figure 6. MHVSR curves from the ambient vibration array recordings for each of the five sites.

INVERSION RESULTS

V_S depth profiles estimated by either inverting the dispersion curves or the MHVSRs can be highly non-unique. However, when inverted jointly, the uncertainty and non-uniqueness can be reduced. Both dispersion curve and MHVSR inversion techniques give information at different frequency range and are often used to constrain the V_S profile(s) at different depth (frequency) ranges [5]. Peak frequency in MHVSRs is an indicator of depth of the soil/resonator interface, which is often not possible to obtain from inversion of the dispersion curve due to the lack of low frequency dispersion estimates because vertical-component energy disappears at the MHVSR peak frequency. In a joint inversion, higher-frequency Rayleigh-wave dispersion curves constrain or determine the shallower V_S profile whereas the peak MHVSR frequency typically is lower frequency and constrains the depth of soil/resonator interface at depth in the Vs profile [7][17]. Therefore, joint inversion of dispersion curves and MHVSRs provide robust V_S estimates over the full depth profile.

Joint inversions are performed using the fundamental-mode Rayleigh-wave dispersion and MHVSR curves as input. A stochastic direct-search method based on the neighborhood algorithm is utilized for the joint inversion of dispersion curves and MHVSRs [21]. The algorithm needs *a priori* ranges of the subsurface parameters (i.e. thickness, V_S, V_P, density and Poisson's ratio) for each layer, including the half-space. Rayleigh-wave ellipticity curves are being used as the theoretical amplification functions [22][23]. It is assumed that the sources are far away from the sensors and since body waves attenuate much faster than the surface waves [7][17], they have negligible contribution in the recorded seismic wavefield. Rayleigh waves are characterized by elliptical particle motion and phase velocity, and both these factors depend on the frequency/depth. At the MHVSR peak, the vertical component of Rayleigh waves is minimum, and the horizontal component is maximum.

Figure 7 shows the joint inversion results for the three array sites in Windsor. The gray colored MHVSRs were not used in the inversion due to their high standard deviations. The theoretical dispersion curves and Rayleigh-wave ellipticity curves agree well with the observed data (picked dispersion curves and computed HVSRs) for all the three sites. For Site 1, the velocity of layer 1 and 2 is in the range of about 120-190 m/s and increases for the layer 3 to ~500 m/s. The velocity of half-space is ~1440 m/s and its top is at ~36 m. For Site 2, the velocity of layer 1 and 2 is in the range of about 130-230 m/s and increases for layer 3 to about 480 m/s. The velocity of half-space is ~1100 m/s and its top is at ~43 m. For Site 3, the velocity of layer 1 and 2 is in the range of 150-280 m/s and increases for layer 3 to about 750 m/s. The half-space velocity is about 1850 m/s and its top is at ~99 m. From the prior knowledge of the geology of Windsor, layer 1 and 2 are the upper soil layers, layer 3 is intermediate till, and the half-space is the bedrock composed of limestone and dolostones. The V_S profiles for sites 1 and 2 are similar to each other, whereas the V_S profile for Site 3 is quite different, probably due to its proximity to the Detroit River bed leading to higher thickness of the layer above the bedrock. Site 3 is located right next to the river and may have a thicker sedimentary cover overlying the bedrock. The V_{S30} values for Site 1 (250 m/s), 2 (240 m/s) and 3 (298 m/s) categorize the Windsor sites as corresponding to site class D.

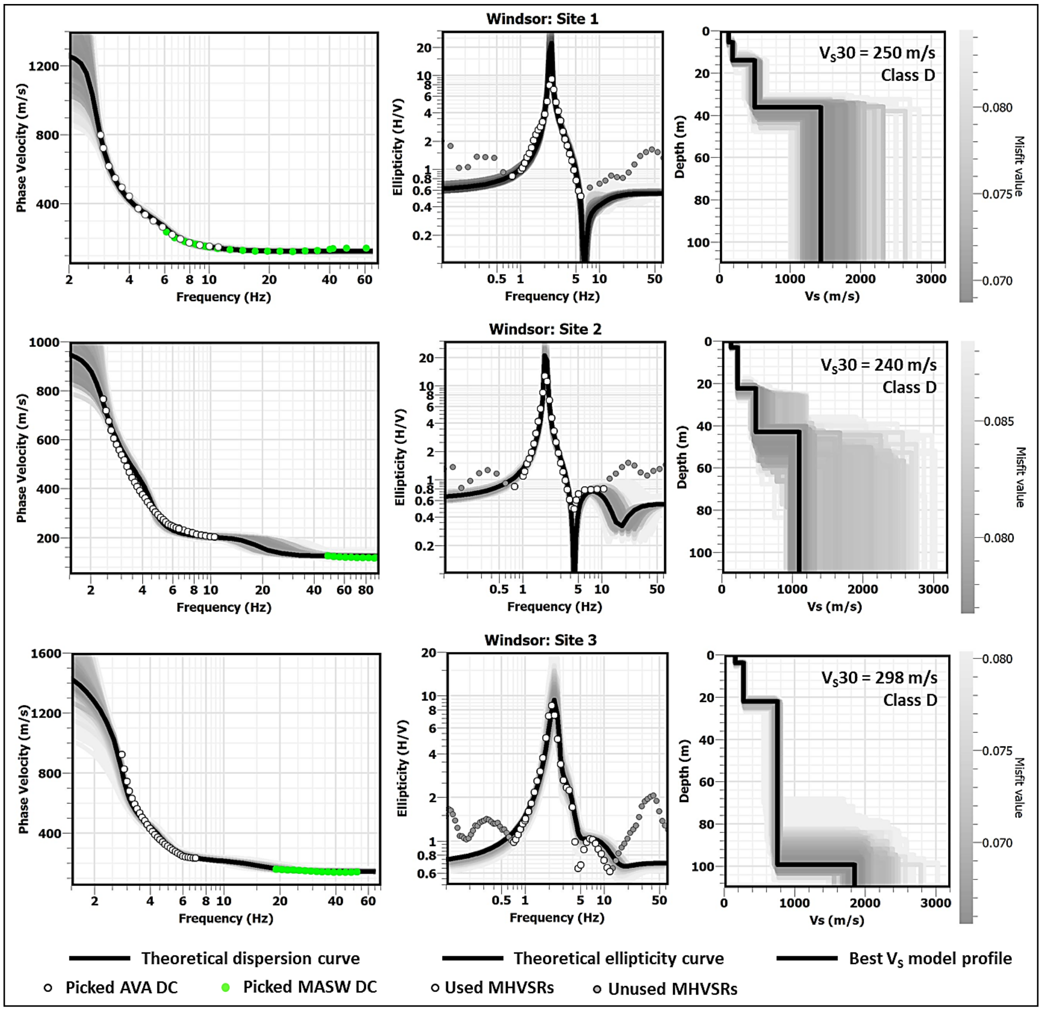

Figure 7. Joint inversion results for the three sites in Windsor. Input dispersion and MHVSR data are plotted as circles compared to theoretical dispersion and MHVSR curves (shaded lines) calculated from low misfit V_S profiles (grey lines) and the minimum misfit Vs profile (black line).

Figure 8 shows the results from joint inversion of dispersion curves and MHVSRs for the two sites at Amherstburg. For Amherstburg sites there is a significant velocity contrast between the upper two layers, which correspond to the higher-frequency MHVSR peaks for the two sites. The very thin uppermost soil layer with thickness in the range of 1.1-1.9 m and V_S in the range of 130-150 m/s, lies above a much stiffer layer with V_S in the range of 390-750 m/s. The depth to bedrock at the two site locations is similar, about 30 m. V_{S30} value for Site 1 (444 m/s) falls in the category of Class C and that of Site 2 is 909 m/s making it a Site Class B.

Table 1 provides a summary of the findings from analyzing the selected sites. The joint inversion results for Windsor and Amherstburg indicate the latter to have higher velocities in the upper layers. Another main observation is that the top of the bedrock is shallower in Amherstburg than in Windsor, which corroborates the previous geological and geotechnical studies done in this region of southwestern Ontario.

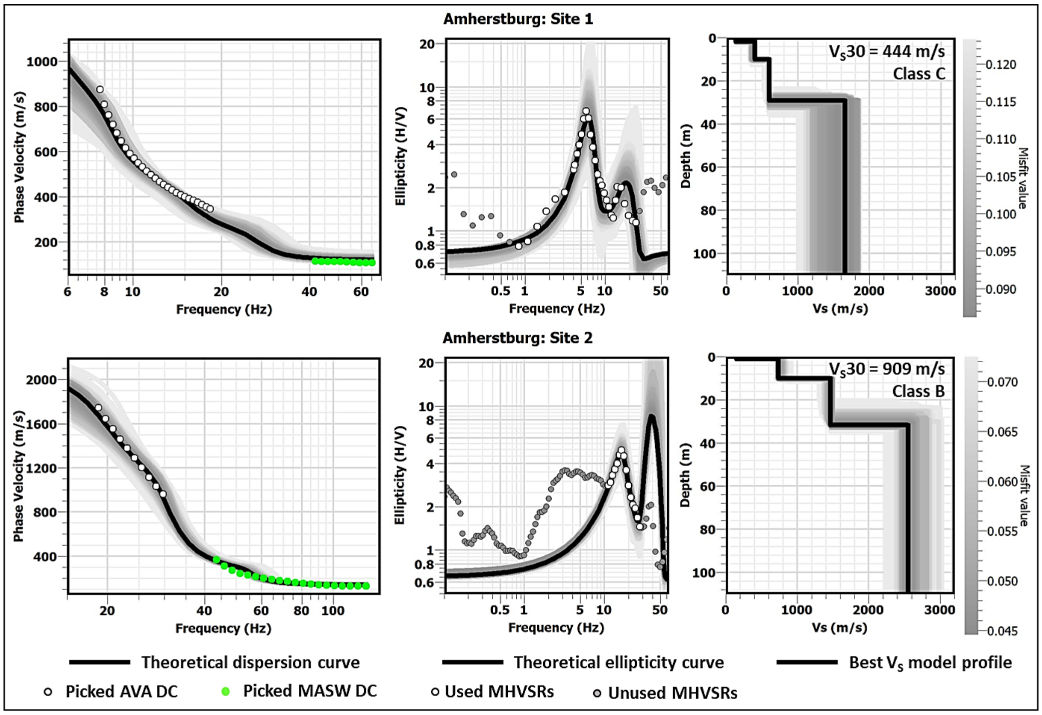

Figure 8. Joint inversion results for the two sites in Amherstburg. Input dispersion and MHVSR data are plotted as circles compared to theoretical dispersion and MHVSR curves (shaded lines) calculated from low misfit V_S profiles (grey lines) and the minimum misfit Vs profile (black line).

Table 1. Summary of the inversion results for Windsor and Amherstburg sites.

Site	Lat (°N), Long (°E)	V_{S30} (m/s)	Depth-to-bedrock (m)	MHVSR Peak frequency, f_0 (Hz)	Bedrock V_S (m/s)	Site class (as per NBCC)
W: Site 1	42.221286, -83.053121	250	36	2.5	1440	D
W: Site 2	42.295575, -83.05883	240	43	1.9	1100	D
W: Site 3	42.326921, -82.991931	298	99	2.1	1850	D
A: Site 1	42.10551, -83.113076	444	29	5.7	1660	C
A: Site 2	42.106273, -83.089157	909	32	16.2	2550	B

CONCLUSIONS

The joint inversion of dispersion curves and MHVSRs helped in generating constrained velocity models from which to determine V_{S30}. Dispersion curves generally provide more detailed information about shallower velocity profile and MHVSRs provide the average velocity and thickness of the profile above the bedrock. The three array sites at Windsor fall in Site Class D implying that the soil stiffness does not vary a lot in the Windsor area. Velocity depth profiles for Site 1 and 2 corroborate with the previous geological observations that the bedrock is flatter in Windsor. However, for Site 3 that lies at the Detroit River bank, the bedrock is deeper. The two sites at Amherstburg have quite different velocity profiles in terms of their velocities, but the depth to bedrock is quite similar and shallower than at Windsor, which is corroborated by the previous geotechnical and geology reports. Site 1 at Amherstburg falls in Class C category, whereas Site 2 falls in Class B. This indicates that the soil stiffness is higher in Amherstburg area than in the Windsor and is highly variable. The subsurface velocity profiles at these five sites across Windsor and Amherstburg, combined with the six sites of Bilson Darko et al. (2019), provide *in situ* measurements of subsurface stiffness. It is intriguing that the 2018 M_N 4.1 earthquake was consistently reported as intensity II-III in both Amherstburg and Windsor. Our current hypothesis is the intensity of shaking in Amherstburg would primarily result from proximity of the earthquake source with site effects amplifying higher frequencies (i.e., the shaking would have been felt as high-frequency vibrations and likely audible noise or sound) compared to Windsor, where the further epicentral distance and thicker and softer ground conditions would attenuate higher frequencies and amplify shaking at ~2 Hz (i.e., the shaking level would have similar intensity but with lower-frequency vibrations and less audible noise or sound). Subsurface ground conditions in southwestern Ontario from our *in situ* non-invasive seismic testing, combined with previous geological and geotechnical information, and regional mapping of Braganza et al. (2016) will enable an improved regional mapping of site amplification hazard in future, and for further comparison with intensities of the 2018 M_N 4.1 earthquake.

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