THE USE OF LOW COST SEISMIC AND MICROTREMOR SURVEY TECHNIQUES TO DETERMINE SHEAR WAVE VELOCITY STRUCTURE

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ABSTRACT

We seek to identify reliable and inexpensive geotechnical survey methods to determine shear wave velocity (Vs) structure, for use in site effect studies and building codes of earthquake proned developing countries such as Jamaica. Two microtremor survey techniques spatial autocorrelation (SPAC) and centerless circular array (CCA) along with seismic survey technique multichannel analysis of surface waves (MASW) were identified as suitable candidates for testing.

For our test site we selected Yoshino Park, Ibaraki Prefecture, Japan, which suffered liquefaction damage during “The 2011 Off the Pacific Tohoku Earthquake”. As our study site had liquefaction damage, the liquefaction potential was estimated using the factor of safety (Fs) method and the Vs from our velocity structure results. Both the liquefaction potential (Fs: 0.077-0.32) and the probability of liquefaction occurrence were very high (0.9 to 1.0).

These exploration methods and Fs-method for estimating liquefaction potential would be affordable and applicable in Jamaica.

Keywords: microtremors, velocity structure, dispersion curve, liquefaction.

1. INTRODUCTION

Jamaica has experienced numerous earthquakes in its 300 year recorded history. This is attributable to its location within the boundary zone of the North American and Caribbean plates. The two most damaging tremors which destroyed the existing capitals (Port Royal 1692, Kingston 1907), also cause damage from liquefaction, mass movement and tsunami. Budgetary constraints over the years have resulted in insufficient geotechnical data for comprehensive earthquake risk assessment. The purpose of this study is to learn cost effective microtremor survey techniques suitable for densely populated urban areas in order to determine shear wave velocity structure for the coastal plains such as Kingston.

2. METHODOLOGY

Three potentially viable methods are common midpoint–cross correlation multichannel analysis of surface waves (CMPCC-MASW), spatial autocorrelation (SPAC) and centerless circular array (CCA).

2.1. CMPCC-MASW

MASW was proposed by Park et al. (1999) and Xia et al. (1999) using the integration transformation that directly converts time-distance domain waveform data into an image of phase velocity versus

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frequency. Long receiver arrays are essential to precisely determine phase velocities at low frequencies (Park et al. 1999), but decrease the lateral resolution of the survey. This trade-off relation between high lateral resolution and accuracy of phase velocity was overcome by CMPCC-MASW proposed by Hayashi and Suzuki (2004). With each shot, a shot gather cross-correlation is calculated for all trace pairs. Trace pairs with common midpoints (cmps) are grouped together. Other cross-correlations for minor cmps with equal spacing (CMPCC gathers) are stacked and ordered with respect to spacing as, only the phase difference between 2 traces is stored. Fast Fourier Transform is applied for conversion to frequency domain, with integration over spacing with respect to apparent phase velocity.

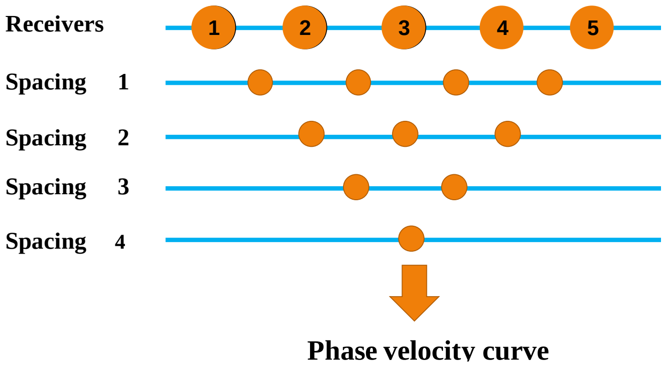

Figure 1. Receivers 1-5 and 2-4 are shot gathers with a common midpoint. 1-4 and 2-5 are CMPCC gathers at spacing 3.

$$F(c,\omega) = \int_{-\infty}^{+\infty} F(x,\omega) \cdot e^{i\omega x/c(\omega)} dx, \qquad (1)$$

where $c(\omega)$, ω and x are the phase velocity, the frequency and spacing, respectively. The maximum amplitude at each frequency gives the phase velocity.

2.2. SPAC

The SPAC method of extracting phase velocities from microtremors is based on theory proposed by Aki (1957, 1965). The SPAC coefficient is defined as the azimuthal average of the coherence between the vertical component records of a central sensor with those of each sensor on the array circumference (Figure 4), and may coincide to a known function shown in the fourth member Eq. (2).

$$\rho(r,\omega) = \frac{1}{2\pi}\int_0^{2\pi} \exp[ikr\cos(\theta-\varphi)]d\theta = \frac{R_e[E(C_{AB},(\omega))]}{\sqrt{E[C_{A,A}(\omega)]E[C_{B,B}(\omega)]}} = J_0(kr), \qquad (2)$$

where r and θ are inter-station distance and azimuth between two observation points x_A and x_B, respectively; ϕ the azimuth of incidence for incoming plane waves; k the wave number. The second member denotes the theoretical core of SPAC whereas the third one is the practical way to calculate SPAC coefficient $\rho(r,\omega)$ from microtremor records, where J_0 is the zero order Bessel function of the first kind. $E[\ ]$ denotes the ensemble average over the time; $C_{A,B}(\omega)$ the cross spectra of the records obtained at x_A and x_B. The wavenumber $k(\omega)$ is estimated by fitting $J_0(kr)$ with the observed SPAC coefficient at various inter-station distance r for each frequency. The phase velocity $c(\omega)=\omega/k(\omega)$ is calculated for each frequency.

2.3. CCA

Center-less circular array (CCA) method developed by Cho et al. (2004) uses a spectral representation which may be considered a general case to SPAC. Similarly the vertical component of microtremor records are used to determine the phase velocities of Rayleigh waves from sensors located on a circle, but with none at its centre. The CCA coefficient is defined as follows,

$$\frac{G_0(\omega,r)}{G_1(\omega,r)} = \frac{J_0^2[rk_1(\omega)]}{J_1^2[rk_1(\omega)]}, \quad (3)$$

where r and k represent the sensor spacing and the wavenumber, respectively, whereas J_0 and J_1 denote the zero and first order Bessel functions of the first kind, respectively. G_0 and G_1 are the power spectral densities. The wavenumber $k(\omega)$ is estimated by fitting $\{J_0(kr)/J_1(kr)\}^2$ with the observed CCA coefficient at various inter-station distance r for each frequency. The phase velocity $c(\omega)=\omega/k(\omega)$ is calculated for each frequency.

3. MEASUREMENT

3.1. Experimental Site

Yoshino Park (36.074982N, 140.000737E) is an oxbow lake along the Kokai River, in Joso City, Ibaraki Prefecture, which is used for recreational fishing (Figure 2). Strong ground shaking during "The 2011 Off the Pacific Coast of Tohoku Earthquake" (magnitude 9.0) caused localized liquefaction within the park.

Multiple arrays were deployed (Figure 3). Two mutually orthogonal, stationary linear MASW arrays (MASW1, MASW2) of 24 sensors with inter-sensor spacing of 1 meter; one triangular SPAC array of seven sensors, with sides of 30 meters; and one hexagonal CCA array with maximum inter-station distance of 3.0 meters. The undamaged side of the lake had one triangular SPAC array (7 sensors) with sides of 50 meters and a large triangular SPAC array (3 sensors') with sides 90 meters in length spanning the lake from undamaged side to the island. For MASW the shot points were moved along the array from -0.5m to 23.5m at 1.0m intervals. This symmetry allowed the records to be processed in both forward and reverse order.

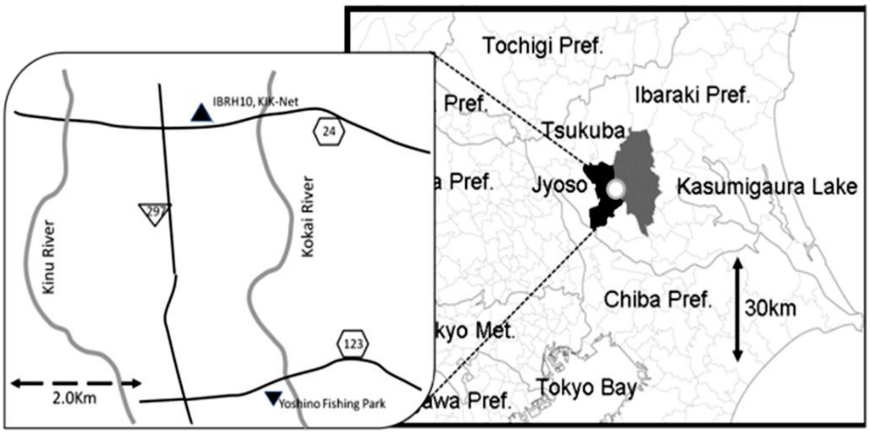

Figure 2. Location map of survey site.

3.2. Data Processing and Analysis

All array data were individually processed with a series FORTRAN programs, following a four-step procedure involving. (1) multiplexing and or resampling and along with digital anti-alias filtering; (2) Data processing mainly composed of cross-correlating the records; (3) Determination of Rayleigh wave phase velocity; (4) Inversion to determine shear wave velocity structure.

Averaged dispersion curves were

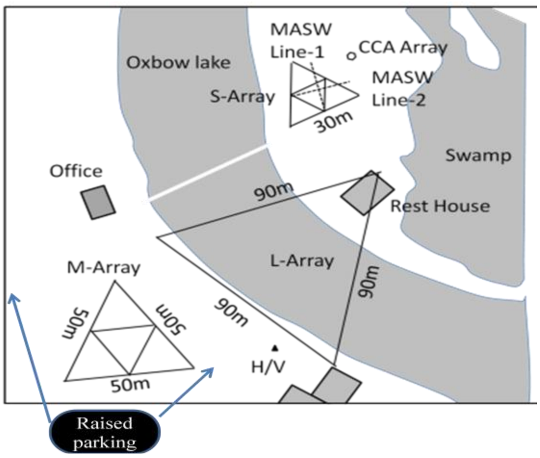

Figure 3. Map of arrays deployed at Yoshino Park.

calculated for MASW (forward and reverse) and SPAC.

4. RESULTS AND DISCUSSION

4.1. Dispersion Curves and Velocity Structure

The dispersion curve for CCA showing much variation in the 6-8Hz frequency range (Figure 4 (a)) and due unresolved problems with the data no further analysis was done. All three SPAC arrays showed good agreement, with a strong peak at 3Hz and a weaker peak at 8Hz, MARRAY also has a distinct peak

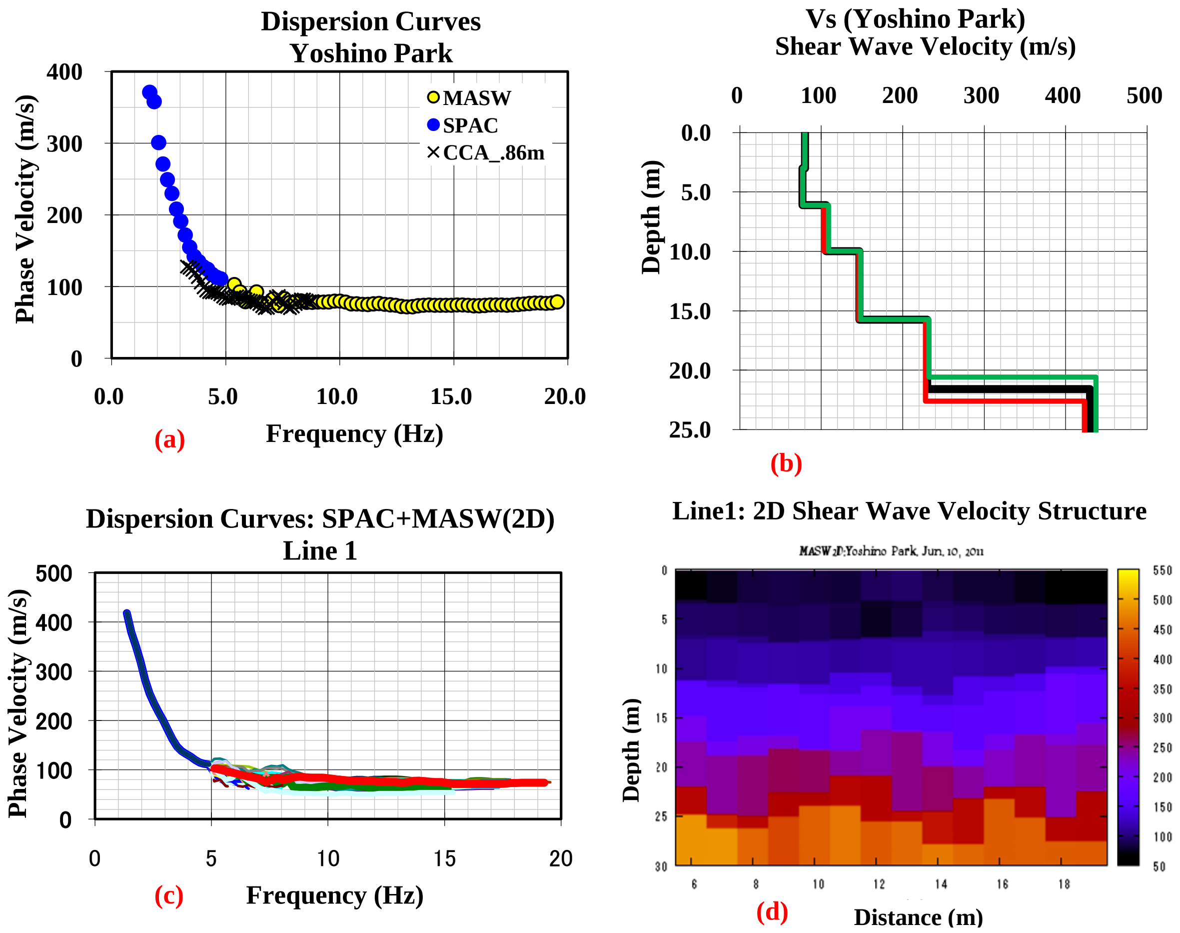

Figure 4. (a) Dispersion curves for MASW, SPAC and CCA. (b) Vs structure from combined dispersion curve (SPAC+MASW). (c) MASW 2D dispersion curve (0-5Hz, 1D SPAC). (d) 2D Vs structure using (c).

at 6Hz. As the dispersion curves for SPAC (0Hz to 5Hz) and MASW (5 Hz to 20 Hz) showed a similar trend and were in better agreement with each other compared to CCA results, their combined dispersion curve was used to determine shear wave (Vs) velocity structure (Figure 4 (c)). Dispersion curves for 2D MASW were again combined with 1D SPAC results to show lateral variation of Vs at the site (Figure 4. (c and d)). Figure 4 (d) shows a well layered subsurface structure.

5. ESTIMATION OF LIQUEFACTION POTENTIAL USING FS-METHOD AND EXPLORATION RESULTS

The method of Andrus et al. (2003, 2004) is applied for the estimation of liquefaction potential. The factor of safety (Fs) is defined by the ratio of Cyclic Resistance Ratio (CRR) to Cyclic Stress Ratio (CSR),

$$F_s = \frac{\mathrm{CRR}}{\mathrm{CSR}} \quad . \tag{4}$$

Liquefaction is predicted to occur when Fs is less than or equal to 1.0, whereas when Fs is bigger than 1.0, liquefaction is predicted not to occur. The method chosen for estimation of liquefaction potential is the Factor of Safety method (Fs-method). The shear wave velocity results obtained in this study along with acceleration data from KIK-Net station IBRH10 (NIED) are used. The probability of liquefaction P_L is required for making risk-based design decision. Juang et al. (2002) proposed an approximated Fs-PL relation as follows,

$$P_L = \frac{1}{1+\left(\frac{F_S}{0.73}\right)^{3.4}} . \tag{5}$$

Using a model constructed with 1m layers and the calculated boundary layers from V_s structure to a depth of 10 meters, Fs and P_L were determined for each layer. Figure 5 shows a summary of these results. From surface to 10 meters depth, our results show consistently low values for CRR (0.062-0.099), whereas CSR values are consistently higher (0.194-0.380). This results in very low values for Fs ranging from 0.32 to 0.077. Since liquefaction is predicted to occur at F_s less than 1, these low F_s values categorizes Yoshino Park as a high risk liquefaction site. The probability of liquefaction (P_L) is found to be in the range 0.943 (layer 1) to 1.0 (layer 6) which makes Yoshino Park a site where liquefaction is most likely to occur.

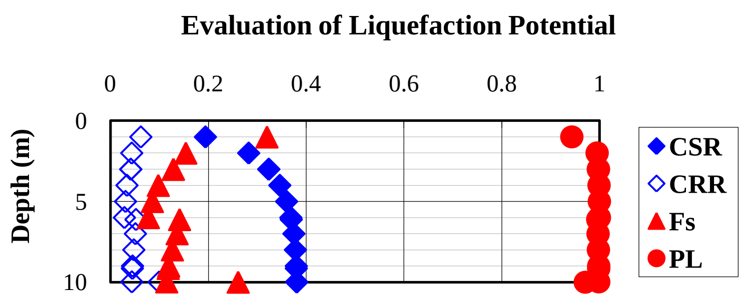

Figure 5. Calculated CSR, CRR, Fs and P_L values for each 1m layer to a depth of 10m. P_L is always close to 1, indicating a high probability for liquefaction occurrence.

6. CONCLUSION

SPAC and MASW are shown to give good estimates of Rayleigh wave dispersion and show a similar dispersion trend across their overlap frequency (circa 5Hz). Thus, their dispersion curves can easily be combined to find Vs structure, with MASW having the advantage of showing lateral variation. CCA is also a possible candidate for determining shallow structure, but further study is necessary. The non-invasiveness and relative low cost for deployment make these survey methods suitable candidates for geotechnical exploration in developing countries such as Jamaica. Fs-method using V_s, can be a reliable tool for liquefaction potential estimation provided the velocity structure is sound and there exists good data on soil properties and lithology to create a reasonable subsurface layer model.

In the final assessment, these exploration methods would be affordable in Jamaica as the greatest cost would be the initial capital outlay for acquiring equipment. Further, many of the sensors needed have already being acquired. As, all equipment can fit into the trunk of a car there is also no additional transportation cost. Although not all existing borehole data went to basement, there is enough data to create reasonable soil layer models. Thus, Fs-method using V_s to estimate liquefaction potential would be affordable as no further equipment or tests would be required.

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