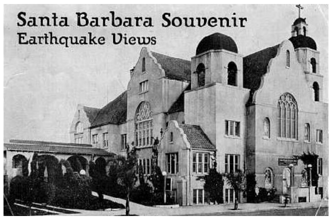

4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

DEEP SEDIMENTARY LAYERS IN METRO MANILA, PHILIPPINES ESTIMATED WITH THE JOINT INVERSION OF RECEIVER FUNCTION AND SURFACE-WAVE DISPERSION

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ABSTRACT

Ten strong motion accelerometers have been operated by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and Tokyo Institute of Technology in Metro Manila, since 1998, to observe the strong ground motions and amplifications at different geological settings. In this study, we performed joint inversion of receiver function (RF) and surface-wave phase velocity to determine the deep sedimentary layers in the metropolis and to evaluate the site effects. Using the conventional receiver function method in the analysis of 12-year earthquake strong motion data, the observed RFs contained seismic phases that are generated from the P-S conversions at velocity discontinuities. Long-period microtremor array measurements were conducted within and near the strong motion stations to be able to perform efficiently the joint analysis with receiver function. For the long period microtremor exploration, we deployed temporary circular arrays consisting of 7 stations to measure surface waves and applied the frequency-wavenumber (F-K) spectral analysis to obtain the phase velocity dispersion curves. We applied the hybrid genetic simulated annealing algorithm (HGSAA) in the joint inversion for the successful determination of S-wave velocity profiles. Amplification characteristics were also evaluated using the inferred S-wave velocity profiles.

INTRODUCTION

Records from strong motion accelerographs contain waves that come from the source, path and local geological setting. The first part of the waveform, usually on the P-wave, can yield abundant information about the subsurface structure directly beneath the strong motion station. One method that can be applied to strong motion records is the receiver function (RF) analysis to identify the shear-wave velocity (Vs) structures underneath the seismic station. RF analysis has been applied extensively to broadband seismic records to estimate the fine scale Vs of the lithosphere by applying an inversion technique (e.g. Owens *et al.* 1984; Ammon *et al.* 1990). Moreover, deeper Vs structures can also be inferred using long period microtremor exploration by exploiting the surface-wave dispersion curves (e.g. Yamanaka *et al.* 1994). Recently, in crust and mantle studies, the joint inversion of RF and surface-wave group velocities is used to bridge the gaps associated with the two separate methods using RFs and surface wave dispersions (e.g. Ozalaybey *et al.* 1997; Du and Foulger 1999; Julia *et al.* 2000). The advantages of the two methods in Vs profiling can be jointly applied to have good estimates of Vs structures. The RFs are sensitive to Vs contrast and vertical travel times while surface wave dispersions are sensitive to vertical shear wave velocity averages (Julia *et al.* 2000).

The importance of identifying the Vs profiles down to the basement is useful to provide better estimates in the simulation of earthquake ground motion and assessment of the site amplifications in the metropolis. Firm rock with Vs of 3 km/s is usually regarded as the basement. In this study, we performed joint inversion method using hybrid heuristic search method to estimate the Vs structure of deep sedimentary layers in Metro Manila. The 12-year records of strong motion were used in the RF analyses and the obtained data from the long period microtremors in the metropolis were utilized for the surface-wave dispersions.

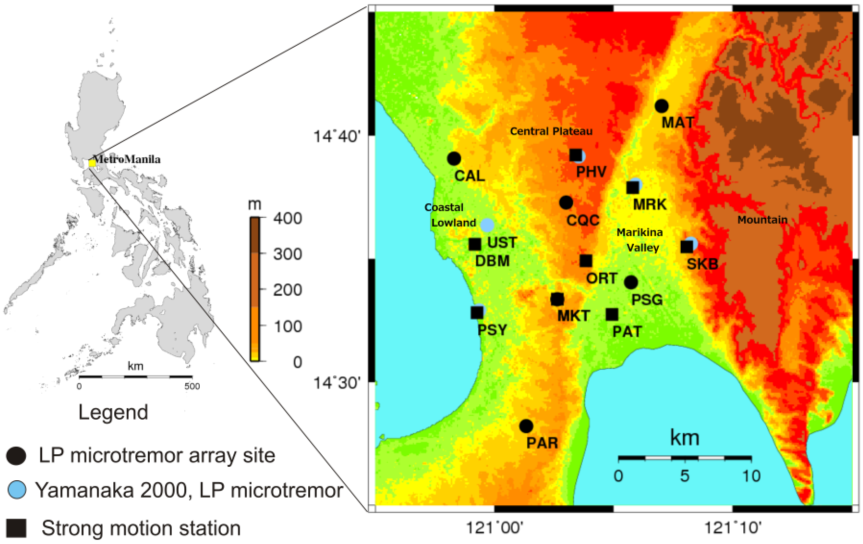


Fig. 1. Digital Elevation Model (DEM) showing locations of strong motions accelerographs and long period microtremor array sites.

STRONG MOTION OBSERVATION

In 1998, ten Strong Motion (SM) accelerometers were installed in different geological setting in Metro Manila. For this study, we used only 8 stations with complete 3-component records, because the two remaining SM stations are operating only with the horizontal components. These SM instruments have been operated by Philippine Institute of Volcanology and Seismology (PHIVOLCS) and Tokyo Institute of Technology to observe the strong ground motions and amplifications from different geological conditions (Yamanaka *et al.* 2002). The geomorphologic feature of Metro Manila is divided into three major districts; the Central Plateau, Coastal Lowland and the Marikina Valley. The SM at DBM and PSY are located in Coastal Lowland, while PHV, ORT and MKT are in Central Plateau area as shown in Figure 1. In the Marikina Valley, MRK and PAT stations are situated. As of December 2010, a total of 147 earthquake events have been recorded by the SM network with magnitudes ranging from 2.3 to 6.8. With these 12-year strong motion records the RF analysis could be performed.

Closely watching the SM records for RF analysis, it was observed that in the P-wave part of strong motion acceleration record there are P converted S waves contained in horizontal component of the waveform, as shown in Figure 2. For the radial component of strong motion P-SV type of waves are contained in the P wave part of the record which represent the conversion from different interfaces below the station. These interfaces are sedimentary layers, basement/sediment interface, crust/upper mantle interface and others. In order to limit the observation to basement and sedimentary layers a certain time window starting from the first impulse of the P wave should be assessed. In this study the first 10 seconds of P waveform was extracted. P-SH type of wave could also be observed in the tangential component of the strong motion record.

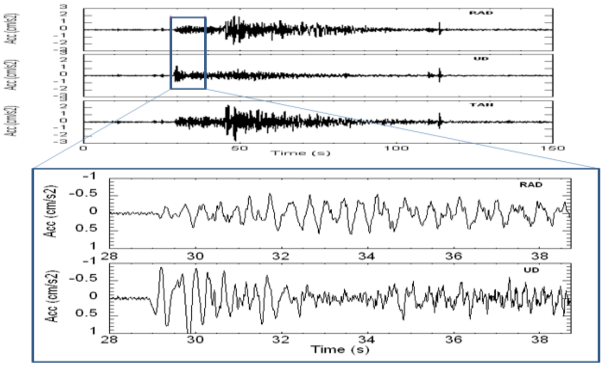


Fig. 2. Strong motion acceleration record at PSY station for the Feb. 9, 2005 earthquake, with a magnitude of 5.4, 89km depth, and epicentral distance of 106km. (Top) whole 3-component waveform record. (Bottom) close-up view of radial and vertical component. The first ten seconds is used in receiver function starting from 0.15 sec before the first arrival.

To obtain the incident angle at each station, we applied a ray tracing formalism in the PHIVOLCS earth model. This PHIVOLCS earth model was based on IASP91 with some modification to be appropriate in the Philippine settings. It has been the model used in the Philippines for locating earthquake hypocenters and it has an interface between crust and upper mantle at the depth of 25 km. The earth model that was used for ray-tracing does not have sedimentary layers and the surface was assumed to be basement rock or an outcropping basement rock. The incident angles calculated for each event at the depths of 1-20 km for a distance of 110-210 km are 48.17° and 51.54°, respectively. These two incident angles represent the critical angle. For earthquake events with depths of 80-95 km for an epicentral distance of 100-150km the corresponding incident angles ranges from 28° to 38°.

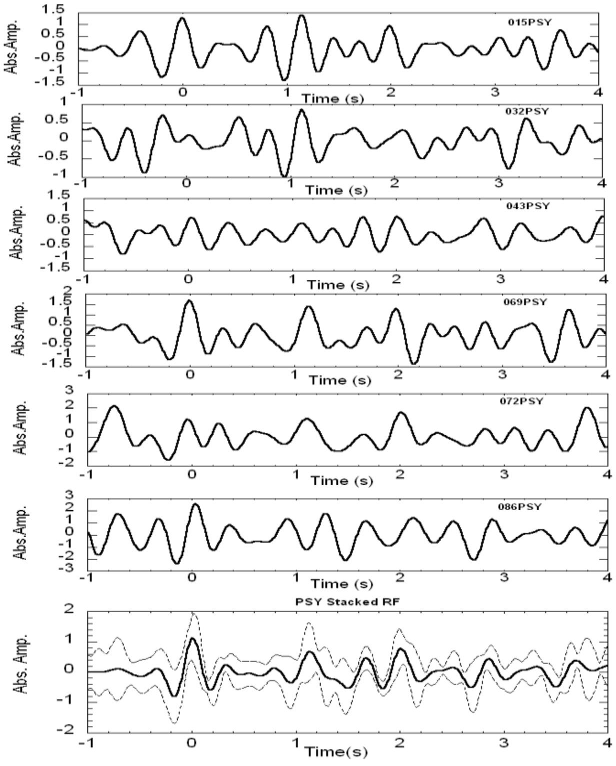


Fig. 3. Receiver functions calculated from earthquake records and stacked receiver function with standard deviation indicated by broken line.

Table 1. List of earthquakes used in the calculation of receiver functions at PSY station

Code	Lat. (deg)	Long. (deg)	Depth (km)	Mag	Epi.Dist. (km)	BAZ (deg)
015PSY	13.707	120.290	66	4.3	119.92	218.78
032PSY	14.748	119.922	72	4.2	116.80	280.89
043PSY	15.420	121.670	5	5	121.57	37.13
069PSY	13.699	120.535	89	5.4	106.16	207.33
072PSY	13.558	120.584	95	5.3	118.25	201.57
086PSY	13.328	120.140	1	4.9	163.44	213.93

The source equalization method of Langston (1979) was applied to the observed strong motion records to isolate the response of basement and sedimentary layers beneath a station and the absolute amplitude of RF was computed by the method of Ammon (1991). Figure 3 displays the observed RFs at PSY station and the details of the analyzed earthquake events are listed in Table 1. The epicentral distances of the events range from 106 to 168 km. In applying the RF method to P waveforms at PSY station, careful selection of earthquake waveforms that exhibit clear records of P wave arrival and with incident angles that satisfy the ray tracing formalism was made. The individual RF was evaluated if it has anomalous troughs and negative polarities before applying the stacking. It was clear in the individual RF (Figure 3) that the arrival of direct P wave at zero lag time and followed by the arrival of P converted S (P-S) phases which consequently yielded significant pulses of P-S waves from the stacked of individual RFs to have dominant pulses at 1.1 and 2.0 seconds. These pulses represent conversions from high velocity contrast at major interfaces below the PSY seismic station. The conversion of P-S wave in sediment/basement and major sedimentary layers interfaces were included in these RF phases. Thus, inversion of whole RF waveform will reveal the major interfaces of substructures at PSY station.

The incident angle of stacked RF at PSY derived from the average of individual receiver functions is 38°. In this study, the conversion of P-S wave in crust/mantle interface was tested if it has an effect in the RF observations. Using theoretical receiver function analysis, the first arrival time of P-S wave for crust/mantle interface were distinguished to be at 3 seconds after the arrival of direct P wave (zero lag time) which means that in the RF waveforms the time window from 0 to 3 seconds is not significantly affected by the mantle/crust interface. The main focus of this study is only within this time window and the RF phases after 3 seconds are considered to be reverberations at the sediments and arrival of P-S wave from crust/mantle interface.

OBSERVED LONG PERIOD MICROTREMORS

We conducted long period array measurements at 6 sites within Metro Manila on July 2010 to be able to know the deep S-wave velocity structures and to analyze jointly with strong motion records. These six long period microtremor sites are combined to the previous work of Yamanaka *et al.*, 2000 that surveyed 5 sites around Metro Manila (Figure 1). The survey set-up for microtremor measurements was composed of a circular array of 7 stations to measure Rayleigh wave type of surface waves. At each station of the individual arrays, we installed a portable vertical accelerometers composed of a highly damped (h~26) moving coil type with natural frequency of 3 Hz and a data recorder equipped with an amplifier. The internal clock of the recorder was calibrated with a timing system using GPS signal. The accuracy of the timing of the records was less than 0.01 second and stored in the memory of the recorder. Configuration of the arrays are triangular in shapes and inscribe in a circle with a radius of 0.1, 0.5, 1.5 and 2.5 km to better estimate the phase velocities at periods from 0.3 to 4 seconds using frequency-wavenumber (F-K) spectral analysis. Moreover, the dispersive features of surface phase velocities from these records exhibit the propagation of Rayleigh waves that will be used in this study for the joint inversion with the RFs.

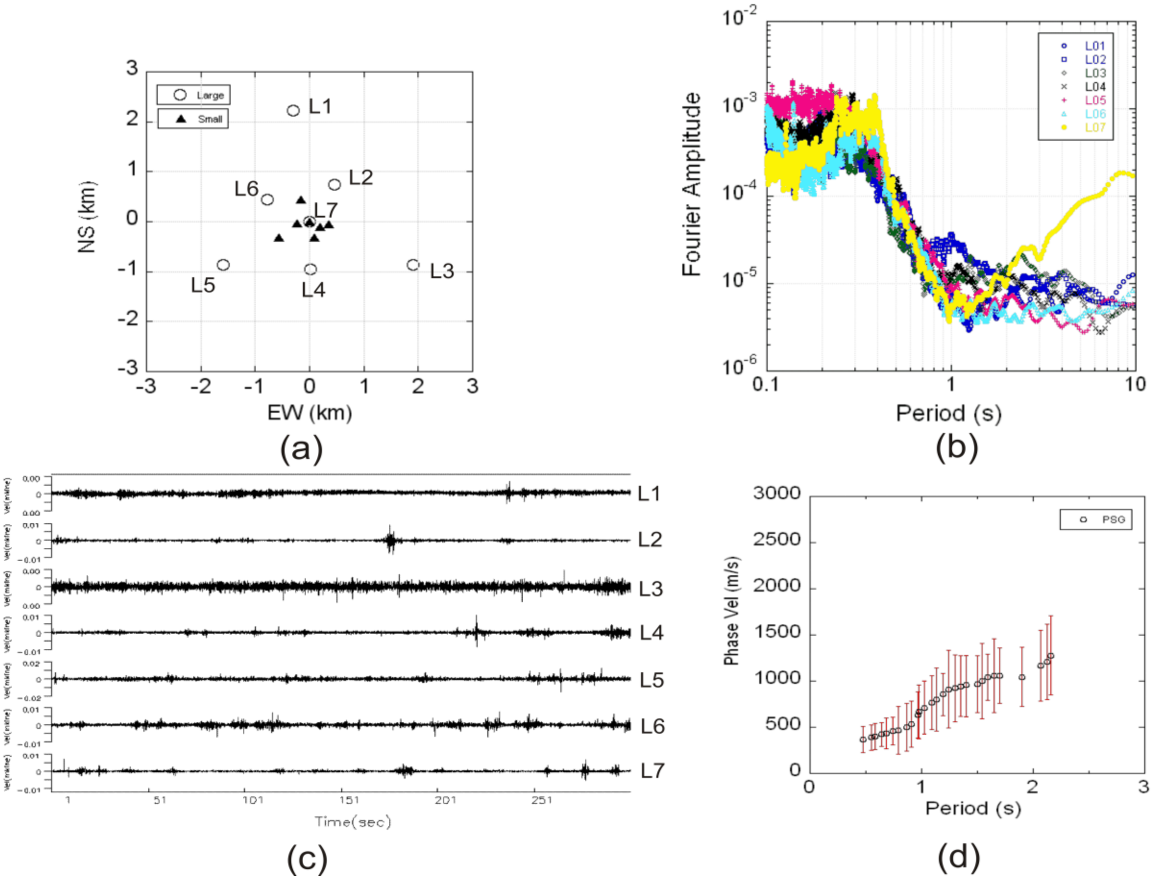


Fig. 4. Long period microtremor array data for PSG. a) array set ups during the survey, b) Fourier spectra of the bigger array composed of 7 vertical sensors, c) waveforms from the microtremor records, d) the obtained phase velocity dispersion curve with standard deviation for PSG from the F-K analysis of both large and small arrays.

Estimation of Phase Velocity from Microtremors

The observed microtremors were processed in order to estimate frequency-dependent phase velocities, as shown in Figure 4. In the Fourier spectra of Figure 4b, we can see coherent waves in the microtremor records and the spectral amplitudes are consistent with each other in the period range from 0.3 to 2 seconds. The microtremor records are divided into data files with duration of 163.84 seconds before applying the F-K spectral analysis based on the method by Capon (1969) to the array records. Once we obtained a frequency dependent F-K spectrum, phase velocity and propagation direction can be determined from the wave number of the maximum peak of the F-K spectrum. Furthermore, we take the average of all the phase velocities at each period to get the final phase velocity dispersion curve of one site and specifying the standard deviation from the averaging, as shown in Figure 4d. Standard deviation will also be used in the inversion procedure.

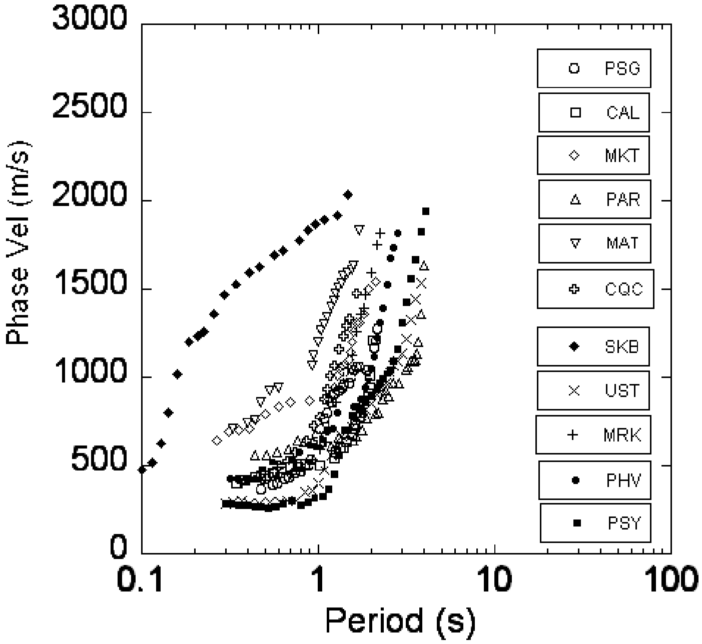


Fig. 5. Phase velocity dispersion curves obtained from long period microtremor array measurements in Metro Manila.

Figure 5 shows all the averaged phase velocity dispersion curves of 11 sites that exhibit normal-dispersive features. Dispersion curves indicate that these phase velocities can be interpreted as phase velocities of Rayleigh waves, because these records are obtained from the vertical motions. The phase velocity dispersion curve of SKB significantly attained steep slope in the period range of 0.1 to 1 second, as compared to the other sites, suggesting that thin sedimentary layers exist underlain by a basement. This basement is found to be outcropping in the mountainous area that is characterized as a basement complex in geology. Consequently, the basement complex gradually goes deeper in the Coastal Lowland forming a basin in the metropolis. For that reason, the site MAT also shows dispersion curve of high velocities and steep gradient around 1 second, showing that the basement that exist in site SKB already had been covered by sedimentary layers into a certain depth. The PSY and UST are located in the Coastal Lowland showing phase velocity dispersion curves reaching 3 to 4 seconds together with PAR indicating that deeper sedimentary layers exist in the area.

JOINT INVERSION

The Hybrid Genetic Simulated Annealing Algorithm (HGSAA) that was implemented here for the joint inversion is similar to that of Takekoshi and Yamanaka (2009), which is a modified Genetic Algorithm (GA) of Yamanaka and Ishida (1996). The method adopted a real number coding and introduced an elite selection and dynamic mutation, except for the definition of misfit, which will be minimized in the inversion.

Joint inversion of two independent data sets, arises questions regarding consistency. However, joint inversion usually means refinement of results to obtain the optimum value. In the case of receiver function the dimensions and number of data are different from that of surface wave phase velocity (Figures 6a and 6b). Thus, the data are reduced to dimensionless form in order to invert them simultaneously. The objective function (goodness of fit) for receiver function ϕ_{RF} and for the phase velocity ϕ_{ph}, are defined as the sum of squared differences between the observations and calculated values, normalized by the standard deviation and divided by the number of data. Kurose and Yamanaka (2006) enumerated this as follows.

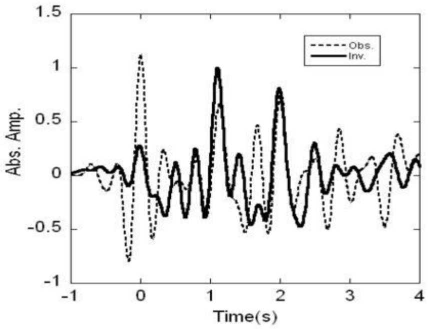
$$\begin{aligned}\phi_{RF} &= (1/N_{RF})\sum_i \left[\{R_{obs}(t_i) - R_{cal}(t_i)\}/\sigma_{RF}(t_i)\right]^2 \\ \phi_{ph} &= (1/N_{ph})\sum_j \left[\{C_{obs}(T_j) - C_{cal}(T_j)\}/\sigma_{ph}(T_j)\right]^2\end{aligned} \tag{1}$$

where N_{RF} and N_{ph} are the number of data while $\sigma_{RF}(t_i)$ and $\sigma_{ph}(T_j)$ are the standard deviations of the observed receiver function $R_{obs}(t_i)$ at time t_i, and the observed phase velocity $C_{obs}(T_j)$ at period T_j, respectively. The objective function ϕ to be minimized in the joint inversion is defined as the average of two misfits ϕ_{RF} and ϕ_{ph}:

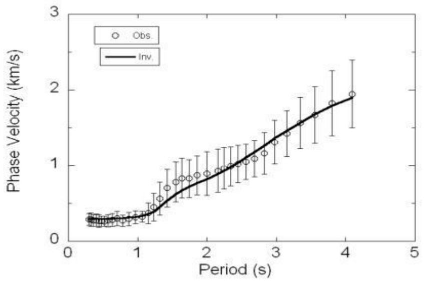
$$\phi = (\phi_{ph} + \phi_{RF}) / 2 \tag{2}$$

Theoretical RF and Rayleigh-wave phase velocity values are calculated using P and S wave velocities, thickness, and density of each layer in a flat-layered model. The theoretical RF $R_{cal}(t_i)$, and the theoretical phase velocity, $C_{cal}(T_j)$, in equation (1) are calculated by the methods of Haskell (1962) and Haskell (1960), respectively. The unknown parameters in the inversion are S-wave velocity and thickness for each layer. The other parameters are treated as follows: P-wave velocity is derived using an empirical relation of S-wave velocity by Kitsunezaki *et al.* (1990), and density is fixed in the inversion.

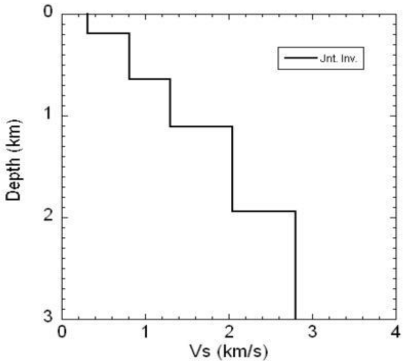
For the HGSAA parameters, the population size and rates of crossover and mutation were set to be 20, 0.7, and 0.01, respectively. Selection was performed according to a roulette rule. The inversion result was evaluated after 10 repetitions of a 100-generation calculation with different seeds of random number generator. During the process the good models with smaller misfit survive more in the next generation while bad models are replaced by newly generated models.



(a) Receiver function



(b) Phase velocity dispersion curve



(c) Inferred shear-wave velocity structure

Fig. 6. Joint inversion results for PSY site: a) comparison of observed and obtained best fitting for receiver function, b) comparison of observed and inverted synthetic phase velocity dispersion curves, c) obtained Vs structure by the joint inversion.

To perform the joint inversion at PSY, the location of strong motion station and the surveyed site for long period microtremor is almost near to each other. Figure 6a shows the best fitting for RF after performing the joint inversion and the comparison shows that the inversion produced an excellent fitting on the major phases in the observed RF. These dominant pulses are coming from interfaces with large velocity contrast. However, the fittings of RF in the period beyond 3 seconds are not the focus of this study because it was known already to be sensitive to conversion of phases at the interface of crust and upper mantle. The inversion for this study only concentrates in the sensitivity of arrival and conversion of phases within the sediments and basement in the RF window span from zero lags time to 3 seconds. Since both RF and phase velocity dispersion shares equally in the influence parameter for the joint inversion, the phase velocity dispersion also searched the best fitting for its curve as shown in Figure 6b.

Figure 6c shows the obtained 1-D Vs structure by performing the joint analysis of RF and phase velocity dispersion curve. We assumed a four layered model over a basement for the inversion. The inferred four layers represent sedimentary layers over a basement with Vs of around 3 km/s. The top layer at PSY area has low velocity corresponding to the Quaternary alluvium of Coastal Lowland. In PSY, the sediment/basement interface is found to be at depth of 2 km. The idea of the deeper sediments in Metro Manila will be significant to amplification of long period earthquakes.

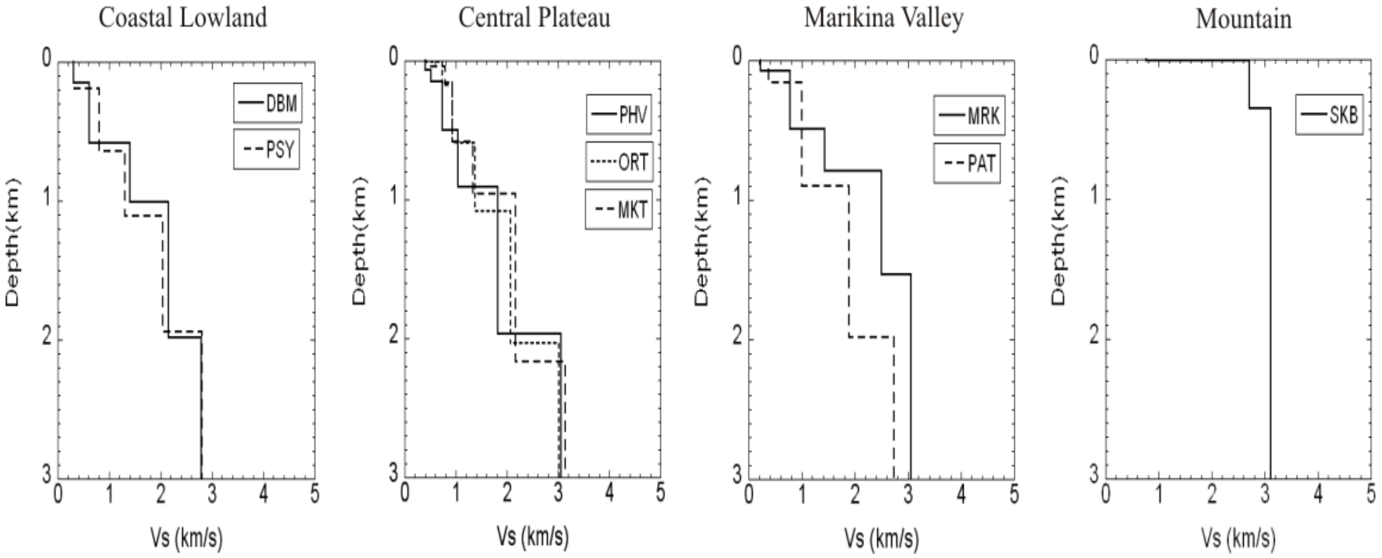


Fig. 7. S-wave velocity profiles from the joint inversion of receiver functions and phase velocity dispersion curves.

In the S-wave velocity profiles, as shown in Figure 7, the joint inversion method inferred 4 to 6-layered Vs structures in Metro Manila. The SKB is represented by a 3-layered model where the basement is shown to be outcropping. The naming of sites for the joint inversion is referred to the strong motion stations. It is significant that the basement having Vs of 3 km/s in the metropolis, inferred at the depth of 2 km, considerably outcropping in MRK and SKB at the depth of 1.5 km and 0.35 km, respectively. The top layer for DBM and PSY sites having Vs of 300 m/s correspond to the deposition of Quaternary alluvium in Coastal Lowland. Stationed in the Central Plateau are PHV, ORT and MKT with corresponding Vs of 500 and two, 700's m/s respectively at the top sedimentary layer which are characterized as tuffaceous sediment and pyroclastic flow deposits that covers about 60 percent of the metropolis. The top layer of the sites MRK and PAT with Vs of 300 m/s correspond to the Quaternary alluvium at the Marikina Valley. Moreover, the layer which has a Vs of 2 km/s that appeared to be at a shallow depth in SKB is distributed at the depth of 1 km in Metro Manila.

DISCUSSIONS

Following the reconnaissance survey of Yamanaka *et al.* (2000), which conducted the first evaluation of deeper sedimentary layers in Metro Manila using long-period microtremor survey, we considered in this study the benefits and advantages of using other method of exploration to be jointly used in the inversion. RF analysis of SM is sensitive to the large velocity contrast of sediment/basement interface and with this approach; the deeper part can be controlled by RF especially if the dispersion curve has insufficient reach at the phase velocity of 3 km/s. Consequently, the sensitivity of RF can be explained by the major peaks in the RF to represent the conversion of P-SV wave in different interfaces that will also be useful in preliminary inputs on how many layers in the medium are appropriate based on the peaks of RF. Individual inversion of RF at PSY inferred a 5-layered model which has a relatively high velocity layers for the top two layers as compared to the results of Yamanaka *et al.* (2000) in the inversion of phase velocity from long period microtremor. RF inversion identified the near surface layer to be directly below the SM site, while long period microtremor array covers a wide area which may compose of different deposits that may have affected the variations of Vs at the top layer of PSY area. However, when we performed the joint inversion, the inferred Vs profiles accommodates the contribution of phase velocity dispersion at the shallow layers, as observed in Figure 8 that the joint inversion has the same profile for the top two layers of Yamanaka *et al.* (2000), which is understandable for the observed phase velocity dispersion at PSY to have a low velocity of 300 m/s (Figure 6b). The results of the individual inversion of surface-wave dispersion had 4 layers as compared to the 5 layers for both the joint inversion and RF inversion. In the 3rd layer of the Yamanaka *et al.* (2000) model, one more layer was inferred by the joint inversion at a depth of 1.1 km with Vs of 2 km/s. This variation in the number of layers happens because of the difference in the search parameters for the inversion of individual data. However, the joint inversion finds the optimum model that suits both methods. Furthermore, the sediments/basement interface depth of 2 km at PSY was identified by the joint inversion.

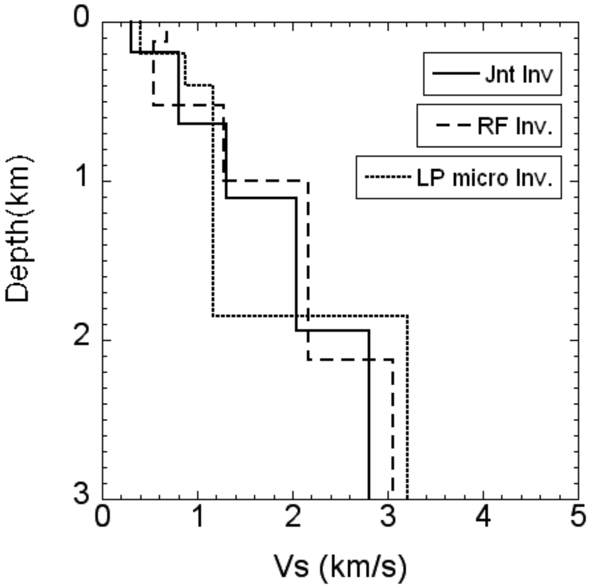


Fig. 8 Comparison between S-wave velocity structures obtained by the joint inversion (solid line), receiver function inversion (dashed line) and inversion of phase velocity dispersion curve from long-period microtremor array of Yamanaka et al. (2000) at PSY.

Site amplifications in the metropolis are shown in Figure 9 to provide an insight on how the entire Metro Manila could respond in different frequency levels in comparison with SKB. The amplification factors are computed using the vertical velocity structures propagating in SH waves and the amplification is defined to be twice of the input motion. The SKB is a stable reference site that has a dominant peak at period of 0.1 second indicating that it has shallower sediments underlain by a basement. As compared to SKB, the other sites implies to have thicker sediments that would respond to a higher periods. The thicker the sediments the longer the period of responses it will have as explained in Figure 8 indicating that these deeper sediments in Metro Manila are influenced by long period waves in the range of 1 to 5 seconds and have amplifications that would reach to a factor of more than 10. The sediments/basement interface at 2 km for the Coastal Lowland corresponds to the amplification peak in the period of 5 seconds. Moreover, the shallow sediments (~100m) are also significant for amplification in the period range of 0.2 to 1 second as detailed in the paper of Grutas and Yamanaka (2011).

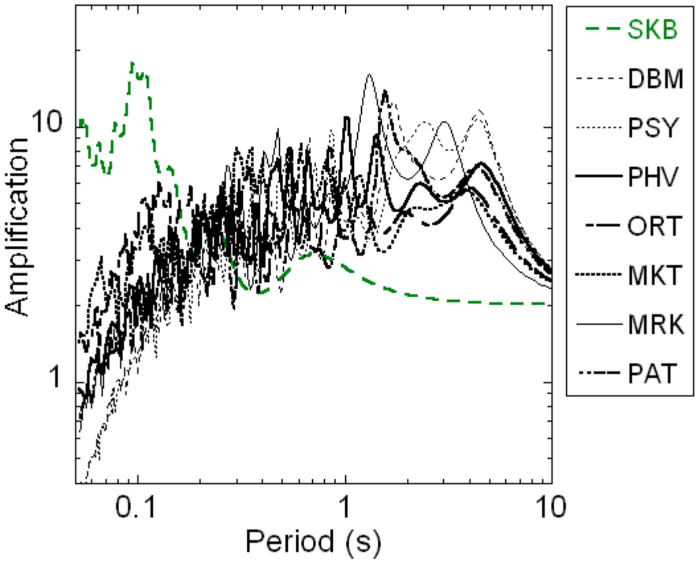


Fig. 9 Amplification factors of vertically incident S-waves with the basement as a half space layer at the bottom.

CONCLUSIONS

This study outlined the implementation of joint inversion of RF and phase velocity dispersion curve. RFs are attained by processing the P-wave part of strong motion and that the phase velocity dispersion curves are obtained by applying the F-K spectral analysis in the observed microtremor array data. Joint inversion provides good estimates of the deeper sediments in the metropolis by exploiting the use of two separate methods namely RFs and surface wave dispersions. We applied the same weight for the misfits of RF (0.5) and phase velocity dispersion (0.5) in order to obtain the objective function in the joint inversion. Application of the method to the data of observed strong motions and microtremors in Metro Manila provided a good insight on how deep the basement is covered by sediments. In the obtained profiles the sediments/basement interface is inferred at the depth of 2 km in the Coastal Lowland and Central Plateau of Metro Manila. From the Metro Manila, the sediment thickness of 2 km became thinner heading the basement to outcrop in the mountainous area of Rizal province where site SKB is located. The significance of this study is that, we inferred the S-wave velocity structures in the metropolis that will be utilized in the assessment of site effects and simulation of earthquake ground motion. The effect of these deep sedimentary layers and surface geology will be significant in the seismic ground motion especially for the longer periods of more than 1 second.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of Center for Urban Earthquake Engineering (CUEE) under G-COE program of Tokyo Institute of Technology. We thank Seismological Observation and Earthquake Prediction Division (SOEPD) of PHIVOLCS-DOST for continued operation and maintenance of Strong Motion Network in Metro Manila. We would like to thank Dr. Renato U. Solidum, Jr., PHIVOLCS Director and Mr. Ishmael Narag for providing major assistance to the team. The authors also acknowledge Torii, D., Sato, Y., Delos Santos A. L., Papiona, K., Legaspi, W., Tabigue, M., Fallarme, J.P., Tiglao, R., Lumbang, R., Salili, R., Havier, R., and Ariola, E. for their help during the long-period microtremor array observations.

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