Estimation of S-wave Velocity Structures by Using Microtremor Array Measurements for Subsurface Modeling in Jakarta

Mohamad Ridwan[1*], Afnimar[2], Sri Widiyantoro[2,3], Masyhur Irsyam[3,4] & Hiroaki Yamanaka[5]

[1]Graduate Research in Earthquakes and Active Tectonics,
Faculty of Earth Science and Technology, Institut Teknologi Bandung
[2]Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
[3]Research Center for Disaster Mitigation, Institut Teknologi Bandung
[4]Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung
Jalan Ganesa No. 10, Bandung 40132, Indonesia
[5]Department of Environmental Science and Technology, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
*Email: m.ridwan@pu.go.id

Abstract. Jakarta is located on a thick sedimentary layer that potentially has a very high seismic wave amplification. However, the available information concerning the subsurface model and bedrock depth is insufficient for a seismic hazard analysis. In this study, a microtremor array method was applied to estimate the geometry and S-wave velocity of the sedimentary layer. The spatial autocorrelation (SPAC) method was applied to estimate the dispersion curve, while the S-wave velocity was estimated using a genetic algorithm approach. The analysis of the 1D and 2D S-wave velocity profiles shows that along a north-south line, the sedimentary layer is thicker towards the north. It has a positive correlation with a geological cross section derived from a borehole down to a depth of about 300 m. The SPT data from the BMKG site were used to verify the 1D S-wave velocity profile. They show a good agreement. The microtremor analysis reached the engineering bedrock in a range from 359 to 608 m as depicted by a cross section in the north-south direction. The site class was also estimated at each site, based on the average S-wave velocity until 30 m depth. The sites UI to ISTN belong to class D (medium soil), while BMKG and ANCL belong to class E (soft soil).

Keywords: *engineering bedrock; microtremor array; S-wave velocity; site class; Jakarta.*

1 Introduction

Jakarta is one of the major cities of Indonesia for which the government has prioritized the preparation of seismic microzonation maps. This was done under consideration of various aspects, such as seismicity, infrastructure, population, etc., in which Jakarta has a high risk. Site response analysis is part of the

Received December 20th, 2013, Revised October 9th, 2014, Accepted for publication November 3rd, 2014.
 ISSN: 2337-5760, DOI: 10.5614/j.math.fund.sci.2014.46.3.9

microzonation studies that consider the effects of ground shaking. This is to be calculated by using the results of a complete geotechnical investigation. Subsurface information, such as bedrock depths and soil dynamic properties, are important parameters in the dynamic response analysis of the ground related to a hazard analysis for the surface.

Previous studies concerning the subsurface geology of Jakarta have been conducted by Padmosukismo and Yahya [1] and showed the configuration of the Northwest Java basin and the Ciputat sub-basin in which Jakarta is located. Turkandi, *et al.* [2] have conducted a regional geological mapping and Fachri, *et al.* [3] studied the hydrostratigraphy of the groundwater basins. The results of these studies provide very important information, but further studies for earthquake engineering purposes are still required to obtain more physical parameters and the position of bedrock.

In this study, a microtremor array method was applied to investigate the subsurface underneath Jakarta and to construct a stratigraphic model based on S-wave velocity parameters. The advantage of this method is that it simplifies the field operation because it does not require active vibration sources or boreholes. Microtremor array observation was first developed by Aki [4] to obtain the dispersion curve by using a circular array employing the SPAC method. Then Okada [5 and 6] expanded this method for subsurface exploration and modified the array configuration into a triangular shape using only 4 sensors. Furthermore, Morikawa, *et al.* [7] developed 2sSPAC by employing only 2 sensors in an effort to reduce difficulties in the field work.

Microtremor array measurements were conducted in Jakarta at 10 sites along a north-south line, from ANCL to UI (Figure 1), in order to determine bedrock depth and site class. To achieve the objective above, we used small and large arrays for shallow and deep surveys, respectively. Borehole data to a depth of 150 m at the BMKG site were available, so they could be used to verify the 1D S-wave velocity model derived from the analysis of the microtremor data along with the standard penetration test (SPT) data.

2 Geological Setting

Jakarta is located in the Ciputat sub-basin of the Northwest Java basin. The Ciputat sub-basin is filled by Tertiary and Quarter sediments and controlled by geological structures with a dominant north-south direction that form heights and depression zones [1].

Referring to the regional geological maps [2 and 3], the stratigraphy sequence from old to young is as follows: first, the Rengganis formation (Early Miocene), then the Bojongmanik formation in the western part, which is inter-fingered with the Jatiluhur formations in the eastern part lying on top of it (Middle Miocene), while above the two formations there are the Klapanunggal formation (Late Miocene), the Genteng formation (Early Pliocene), and the Serpong formation (Late Pliocene). The Quarter sedimentary rocks covering the whole Jakarta area are: Banten tuff (Plio-Pleistocene), young volcanic rocks (Pleistocene), alluvium fan, coastal sediment and alluvium.

3 Data and Method

3.1 Data Acquisition

Microtremor array measurements were performed at 10 sites in Jakarta along the ANCL-UI line (Figure 1) using triangular arrays with 4 sensors, where one sensor was placed at the center and 3 sensors were deployed on a circular array. (See Figures 2a). Figure 2b shows an example of the array configuration for microtremor measurements carried out at the BMKG site.

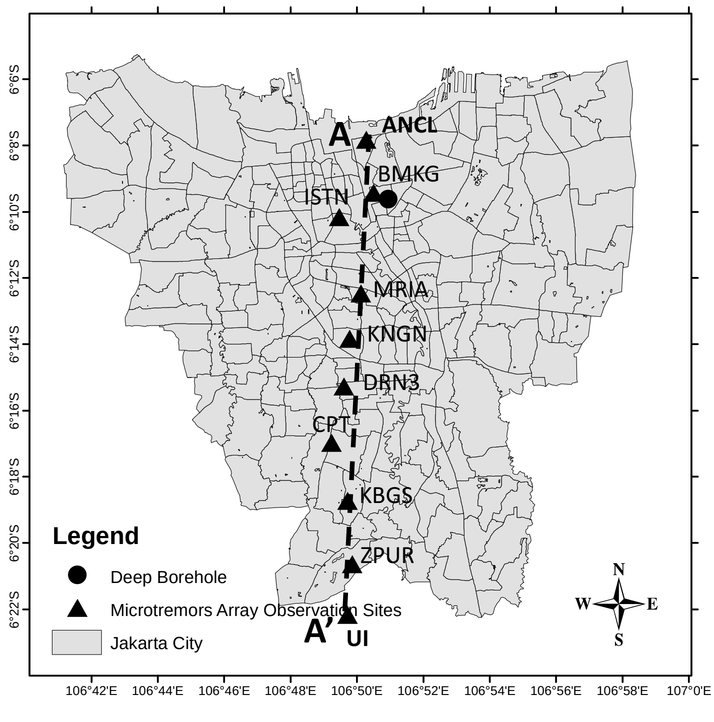

Figure 1 Locations of microtremor array measurements along the UI-ANCL line and deep borehole.

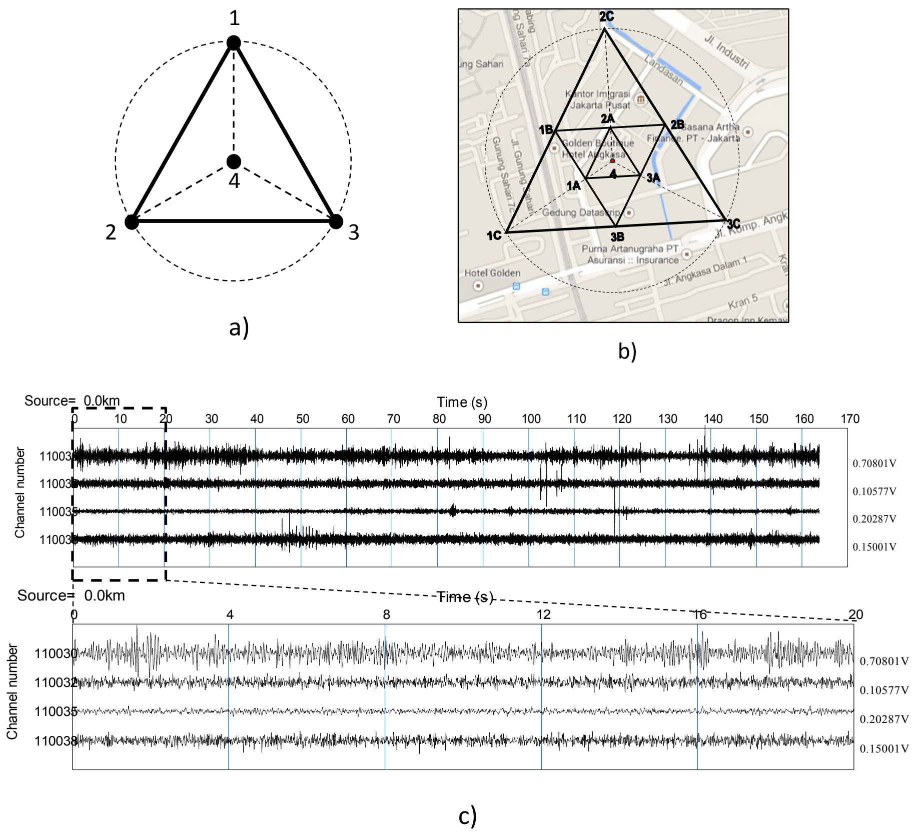

Figure 2 a) Array shape and location of 4 sensors, b) example of microtremor array measurements at the BMKG site, and c) example of microtremor data record.

The array size was designed in consideration of the target layer depth. Array sizes of 600 m, 300 m and 150 m were used for deep layer surveys, while for shallow layers the array sizes were 30 m and 15 m. Microtremor data recording was conducted in 1-1.5 hours for the large arrays, while for the small arrays it was approximately 30-45 minutes [5 and 6]. The data records were digitized with a sampling interval of 0.01 seconds and then divided into several blocks consisting of 16,384 samples for each block to be used in the data processing. Figure 2c shows an example of the data recorded at the BMKG site for a time block with a duration of 163.84 seconds.

The instruments used in the field work were: four units of microtremor equipment (McSEIS Neo-MT) produced by OYO Corporation completed with GPS for time synchronization. For the data processing, SeisImager and Yamanaka software was used.

3.2 SPAC Method

Following, Okada [6] and Morikawa, *et al.* [7], phase velocity calculations were performed using the SPAC method for the vertical component of microtremors. For the triangular array configuration, the coherence function between two stations within a distance r was calculated. SPAC coefficient $\rho(\omega,r)$ is the average of the coherence function for all pairs of stations on the circular array, which can be directly calculated by the following equation:

$$\rho(\omega;r) = \frac{1}{2\pi}\int_0^{2\pi} \frac{\mathrm{Re}\left[S_{CX}(\omega;r,\theta)\right]}{\sqrt{\left[S_C(\omega;0,0)\right]\cdot\left[S_X(\omega;r,\theta)\right]}}\,d\theta \tag{1}$$

where $S_c\ (\omega,0,0)$ and $S_x\ (\omega,r,\theta)$ are the power spectrum of the microtremors at stations C and X, while $S_{cx}\ (\omega,r,\theta)$ is the cross spectrum between stations C and X.

Since the array configuration is circular, the SPAC coefficient can be expressed as a Bessel function with variables r and k, as follows:

$\rho\ (\omega,\ r) = J_0(r,k)$, where $k = \omega/c(\omega)$; $c(\omega)$ = phase velocity, therefore:

$$\rho(\omega;r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \tag{2}$$

J_o = Bessel function of the first kind zero order, $c(\omega)$ = phase velocity as a function of frequency ω, r = distance between two stations.

3.3 Inversion of Dispersion Curves Using Genetic Algorithm

The S-wave velocity structures were estimated from the dispersion curves through an inversion technique using a genetic algorithm. This technique was introduced in seismology by Yamanaka and Ishida [8] as a global optimizing method. The inversion process is conducted on the searched area as the population by minimizing the misfit function (ϕ), which can be defined by the difference between observed phase velocity $U_o(T_i)$ and calculated phase velocity $U_c(T_{i,})$, and can be expressed as follows:

$$\phi_j = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{U_o(T_i)-U_c(T_i)}{\sigma(T_i)}\right)^2 \tag{3}$$

where N is the number of observed data and $\sigma(T_i)$ is the standard deviation of the observed phase velocity over a period of T_i.

A genetic algorithm was applied to the phase velocities of the fundamental modes of the Rayleigh waves, assuming the layer models are horizontal, isotropic, and homogenous. In the inversion, the model parameters of S-wave velocities and thicknesses are the unknown parameters to be estimated, while the density is fixed.

In this study, the inversion was conducted by performing 20 populations with 10 iterations of the genetic algorithm and the parameters of genetic operation following Yamanaka and Ishida [8]. The inversion was conducted on the initial population by all genetic operations, where the model that had the smallest misfit survived in the next generation, while bad models were replaced.

4 Results

4.1 Dispersion Curves

The results of the estimated dispersion curves using the SPAC method for deep layers is shown in Figure 3a. The dispersion curves of microtremors were obtained in a frequency range of 0.2-5.0 Hz and have various phase velocities. Figure 3b shows the dispersion curves for the shallow layers, which have a higher frequency range (3-16 Hz). The variation of phase velocities is due to local geological conditions.

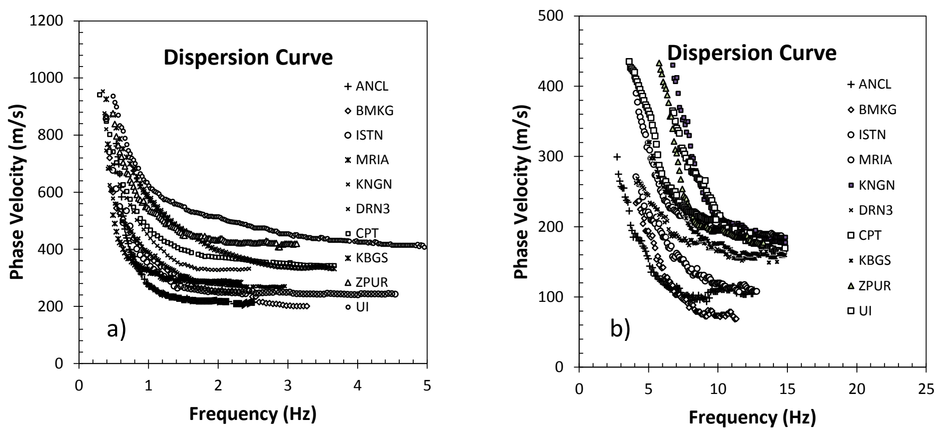

Figure 3 Dispersion curves of microtremors for: a) deep layers, and b) shallow layers.

The inversion technique was performed for specified initial models, considering geological conditions. This study assumed 5 layered models for deep layers and 4 layered models for shallow layers. These initial models were inverted by using a genetic algorithm to generate close fits of dispersion curves between observed and calculated ones, as shown in Figures 4 and 5.

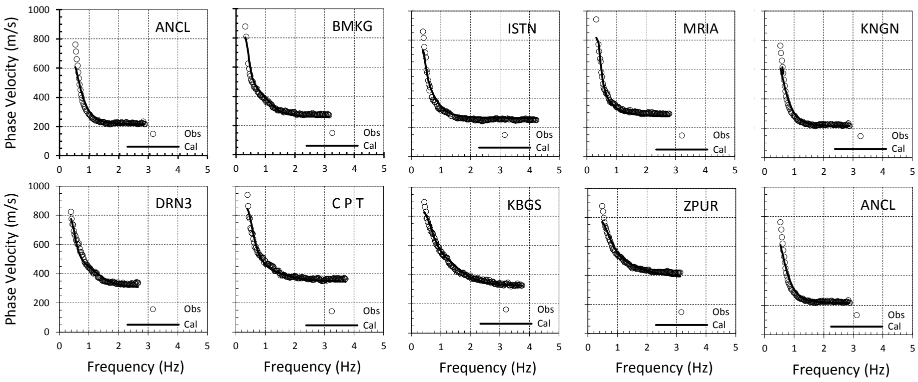

Figure 4 Comparison between observed (circles) and calculated (solid lines) dispersion curves for deep layers.

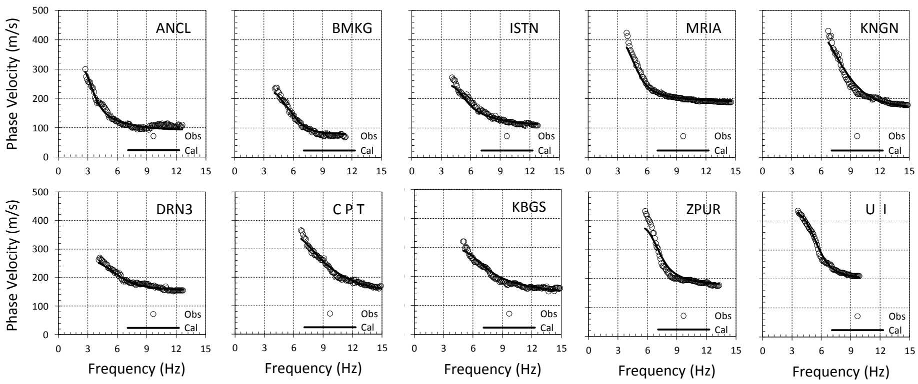

Figure 5 Comparison between observed (circles) and calculated (solid lines) dispersion curves for shallow layers.

4.2 One-dimensional S-Wave Velocity Profiles

The 1D S-wave velocity profiles resulting from the individual inversion of each dispersion curve are illustrated in Figure 6 for deep layers and in Figure 7 for shallow depths. The bedrock depth with S-wave velocity value > 750 ms^{-1} [9] can be estimated from each 1D S-wave velocity profile. Generally, the bedrock depth increases toward northern Jakarta. In southern Jakarta (UI) the bedrock depth is about 378 m for V_s = 875 ms^{-1} and in the north (BMKG) the bedrock depth is about 651 m for V_s = 965 ms^{-1}.

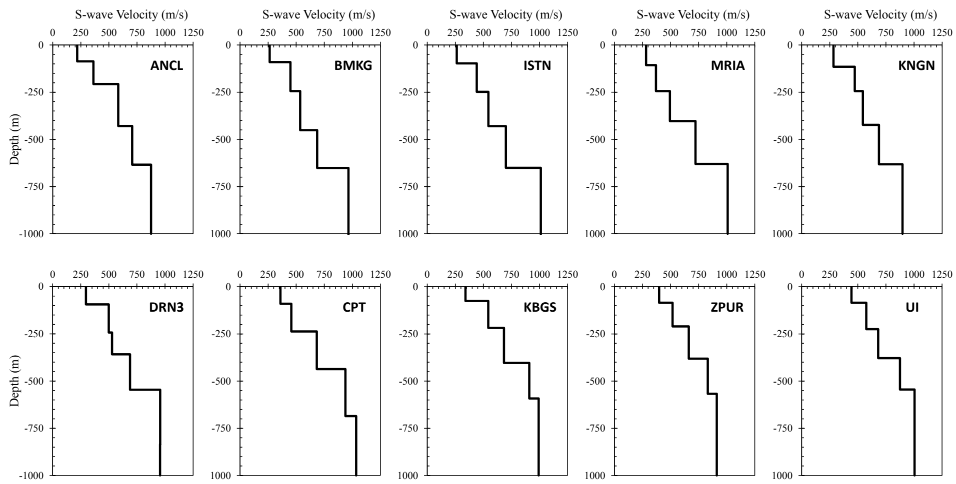

Figure 6 1D S-wave velocity profiles at the 10 surveyed sites for deep layers.

The estimated 1D S-wave velocity profiles for shallow depths were also modeled into four layers down to 40 m depth. The site class determination was based on Vs_{30}, where sites UI to ISTN belong to class D (medium soil), while BMKG and ANCL belong to class E (soft soil).

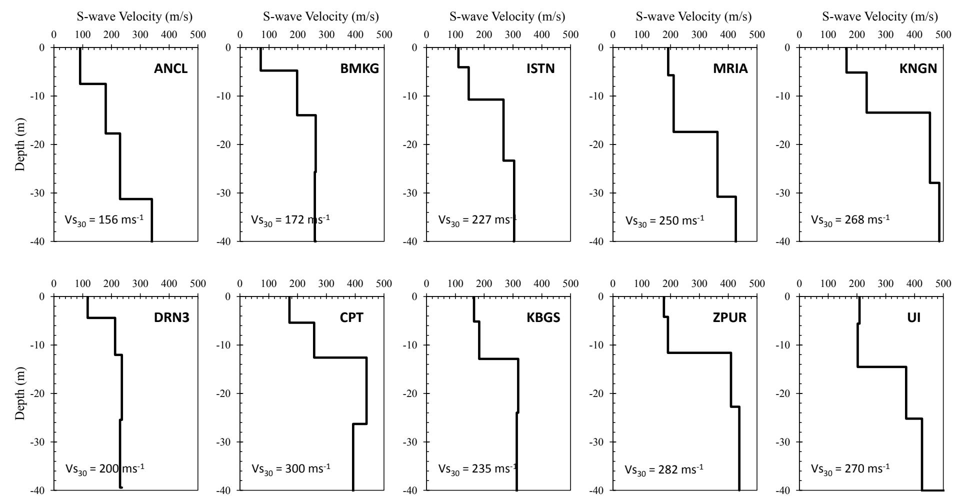

Figure 7 Same as Figure 6, but for shallow depths.

4.3 Comparison with Borehole Data

S-wave velocity parameters can also be calculated from standard penetration test (SPT) data using an empirical formula, as shown in Table 1. All these empirical formulas can be used for Vs calculation by taking the average of the results.

At the BMKG site, SPT was conducted down to a depth of 100 m in a borehole near the microtremor measurement site. Comparison of the S-wave velocity profiles derived from SPT and microtremor array measurements demonstrates a strong similarity (Figure 8) and has a positive correlation with the lithological condition.

Table 1 Empirical correlation between N-SPT and S-wave velocity [10].

References	Vs (m/sec) Correlation	Soil Type
Imai and Tonouchi [11]	$Vs = 96.9\ N^{0.314}$	Clay and sand (Japan)
Imai [12]	$Vs = 91\ N^{0.337}$	Clay and sand (Japan)
Ohta and Goto [13]	$Vs = 85.3\ N^{0.341}$	Clay and sand (Japan)
Sykora and Stokoe [14]	$Vs = 101\ N^{0.29}$	Clay (USA)

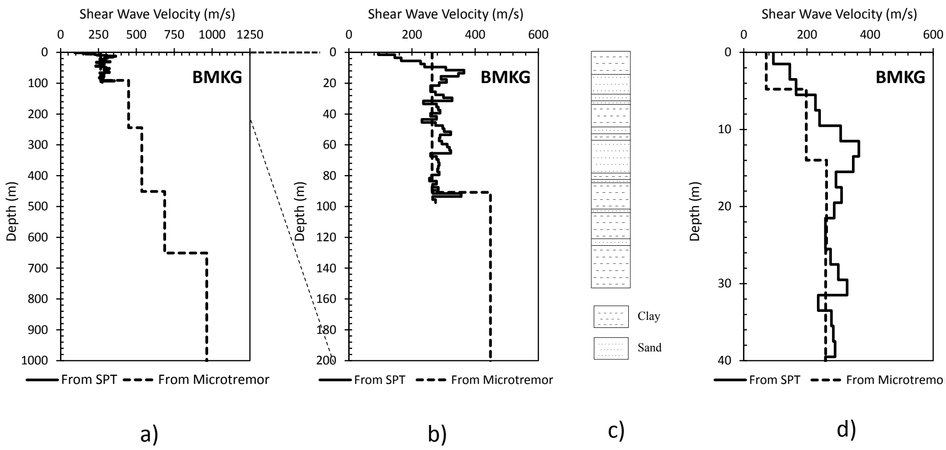

Figure 8 Comparison of 1D S-wave velocity profiles derived from microtremor array measurements (dash lines) and SPT (solid lines) at BMKG. a) and b) are for deep layers, c) lithology, and d) for shallow layers.

4.4 Two-dimensional S-Wave Velocity Profiles

The results of the individual inversions of the dispersion curves for each site show a lateral variation in the S-wave velocity. The 1D S-wave velocity profiles in central and northern Jakarta that resulted from the first inversion indicate a four-layer model over the engineering bedrock, while in the southern part there is a three-layer model. Basically, it is difficult to conduct a stratigraphic correlation based on such S-wave velocity structures. Hence, the second inversion was applied to the dispersion curve with a constant velocity as the initial model (cf. Yamanaka and Yamada [15]).

According to the 1D S-wave velocity profiles (Figure 6), the four-layer model was assumed for the initial model with the S-wave velocity of the second, the third and the fourth layers being 500, 700 and 900 ms^{-1}, respectively, determined by averaging the S-wave velocity of each layer. This initial model was inverted again for each dispersion curve to obtain the depth of each fixed velocity. The results are shown in Figure 9.

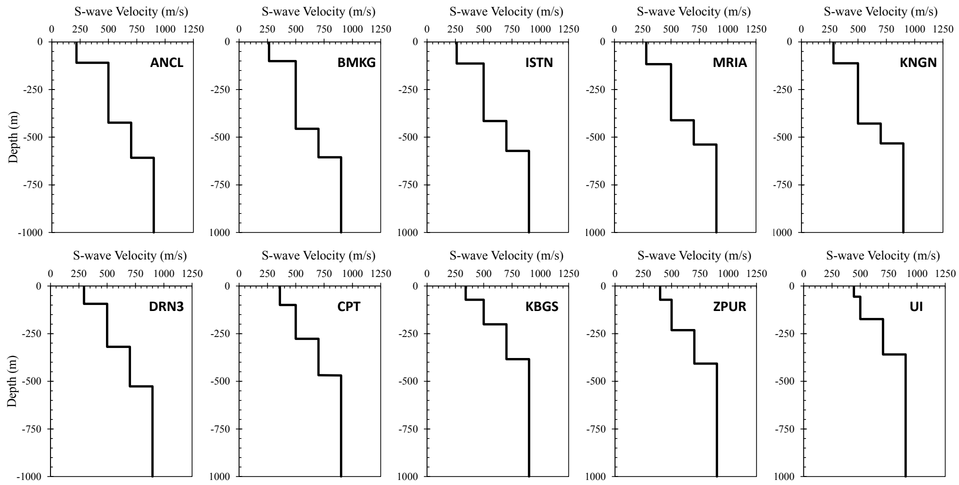

Figure 9 1D S-wave velocity profiles of the 10 surveyed sites derived by second inversion using the initial model, in which the S-wave velocity for each layer is fixed.

The 1D S-wave velocity profiles resulting from the second inversion were then utilized to perform a stratigraphic correlation. The result of S-wave velocity correlation along the ANCL-UI line forms a cross section depicting a subsurface model for Jakarta (Figure 10). This model consists of four layers with the S-wave velocity from the second to the fourth layers being 500, 700, and 900 ms^{-1}, respectively, while the S-wave velocity varies laterally in the first layer. A subsurface model for a similar north-south line derived from borehole data down to 350 m depth was conducted by Fachri, *et al.* [3]. The comparison of the stratigraphic model from the microtremor measurements and their geological cross section derived from the borehole data [3] indicates a good correlation (see Figure 11).

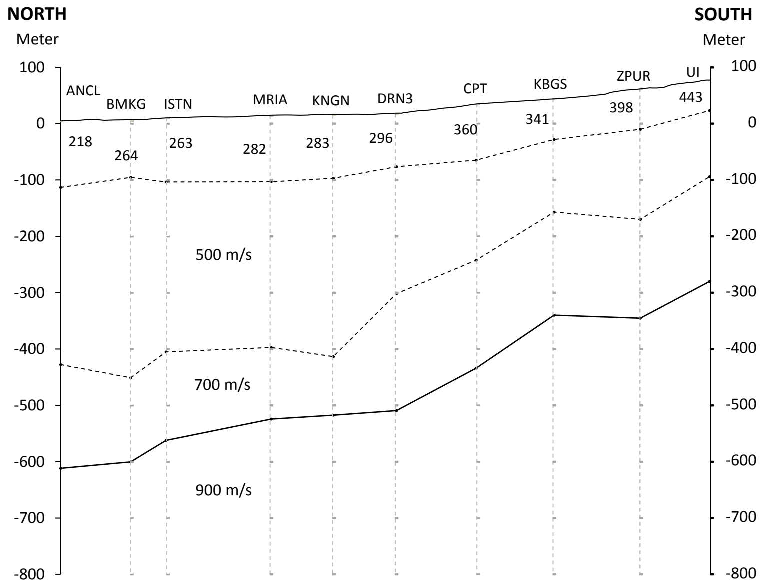

Figure 10 Cross section of the S-wave velocity structure along the ANCL-UI line. The solid line depicts the estimated bedrock depth.

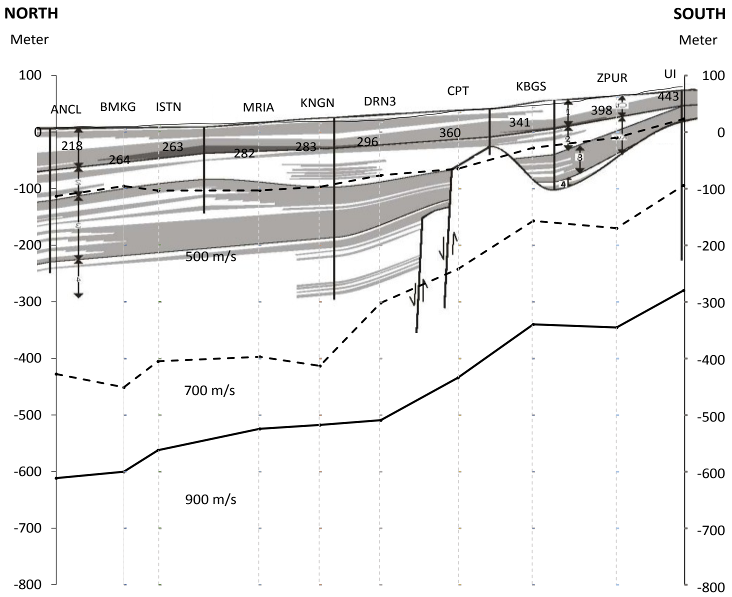

Figure 11 Comparison of microtremor analysis (solid and dash lines) and geological cross section derived from borehole data (modified from Fachri, *et al.* [3]).

Referring to SNI-1726-2012 [9], in which for engineering purposes the bedrock is defined by V_s > 750 ms^{-1}, the top of the fourth layer on the cross section, which has an S-wave velocity of about 900 ms^{-1}, represents the engineering bedrock depth. In most cases, the subsurface model along the north-south line shows a bedrock morphology that is slanting towards the northern part of Jakarta with a depth range of 359-608 m.

5 Discussion

The results of the microtremor array analysis of each site show various dispersion curves that have been influenced by the geological conditions, as expressed by the variation in S-wave velocities. The section along the north-south line across Jakarta (Figure 10) depicts the subsurface model consisting of four layers, in which the first layer has S-wave velocities in the range of 218-443 ms^{-1}, associated with Quarter sediments. The second and third layers have S-wave velocities of about 500 and 700 ms^{-1}, respectively, associated with Tertiary sediments. The fourth layer, which has an S-wave velocity of about 900 ms^{-1}, is estimated as the bedrock for earthquake engineering purposes and has a depth range from 359-608 m.

Comparison with the previous geological cross section from Fachri*, et al.* [3], depicted in Figure 11, shows that the results of the microtremors analysis are in good agreement, whereby the sediment thickness increases northward. Nevertheless, the presence of faults around the Babakan site at a depth of 100-300 m, as suggested by Fachri*, et al.* [3], cannot be identified well by the microtremor data. Therefore, future work is needed to add more measurement data from sites around the envisaged fault area.

In brief, the available limited data derived from other methods cause difficulties in verifying the results of our microtremor data analysis for each site. However, the borehole data down to a depth of 150 m at the BMKG site, which has SPT data until 100 m depth, could be used to verify the microtremor data analysis results. The comparison of the S-wave velocity profiles derived from both microtremor and borehole data shows that these profiles agree well (see Figure 8). All in all we note that more information about subsurface conditions in Jakarta is essential for further studies.

6 Conclusions

This study obtained a subsurface model for Jakarta by using microtremor array measurements. Based on the results of measurements at 10 surveyed sites, the stratigraphic model for Jakarta consists of 4 layers, with S-wave velocity values ranging from 218 ms^{-1} to 443 ms^{-1} in the uppermost layer, and increasing from the second to the forth layers, i.e. 500 ms^{-1}, 700 ms^{-1}, and 900 ms^{-1}, respectively. In general, the thickness of each layer increases northward, particularly the second layer. This result is in good agreement with the geological conditions in Jakarta, where sediments are very thick in the northern part.

From the cross section (Figure 10), this study identifies the bedrock position in the fourth layer. The depth of the bedrock is diverse, within a range of 359-608 m. The deepest position of the bedrock is in the northern Jakarta area (ANCL), which reaches 608 m. Therefore it is expected that seismic wave amplification will be higher in the north than in the south, due to the very thick sediments.

Acknowledgments

The authors gratefully acknowledge the Research Institute for Human Settlement (RIHS), Ministry of Public Works, Republic of Indonesia and the team of microzonation projects for supporting data used in this study. This research is part of the microzonation study for Jakarta that is supported by RIHS and ITB through the “Riset Unggulan” program.

References

[1] Padmosukismo, S. & Yahya, I., *The Basement Configuration of the North West Java Area*, IPA Proceedings of the 3rd Annual Convention, Jakarta, **1**, pp. 129-152, 1974.

[2] Turkandi, T., Sidarto, Agustiyanto, D.A. & Hadiwodjoyo, M.M.P., *Geological Map of Jakarta and Kepulauan Seribu Quadrangles Jawa*, Geological Research and Development Centre, Ministry of Energy and Mineral Resources, 1992.

[3] Fachri, M., Djuhaeni, Hutasoit, L.M. & Ramdhan, A.M., *Stratigraphy and Hydrostratigraphy of Ground Water Basin for Jakarta*, Bulletin Geology, **34**(3), pp. 169-189, 2002. (Text in Indonesian)

[4] Aki, K., *Space and Time Spectra of Stationary Stochastic Waves, with Special Reference to Microtremors*, Bulletin of the Earthquake Research Institute, University of Tokyo, **35**, pp. 415-456, 1957.

[5] Okada, H., *Microtremors as an Exploration Method*, Geoexploration Handbook, **2**, Society of the Exploration Geophysicists of Japan, 1998.

[6] Okada, H., *The Microtremors Survey Method*, Geophysical Monograph Series, **12**, 2003.

[7] Morikawa, H., Sawada, S. & Akamatsu, J., *A Method to Estimate Phase Velocities of Rayleigh Wave Using Microseisms Simultaneously Observed at Two Sites*, Bulletin of the Seismological Society of America, **94**(3), pp. 961-976, 2004.

[8] Yamanaka, H. & Ishida, H., *Application of Genetic Algorithms to an Inversion of Surface Wave Dispersion Data*, Bulletin of the

Seismological Society of America, **86**(2), pp. 436-444, 1996.
[9] SNI3-03-1726-2012, *Guidelines of Earthquake Resistant Design for Building Structures*, The National Standardization Agency of Indonesia, 2012. (Text in Indonesian)
[10] Irsyam, M., Sahadewa, A. & Darjanto, H., *Soil Dynamics and Machine Foundation*, Institut Teknologi Bandung, ISBN 978-979-1344-24-1, 2008. (Text in Indonesian)
[11] Imai, T. & Tonouchi, K., *Correlation of N-value with S-Wave Velocity and Shear Modulus*, Proceedings of the 2nd European Symposium on Penetrating Testing, Amsterdam, Netherlands, pp. 67-72, 1982.
[12] Imai, T., *P- and S-Wave Velocities of the Ground in Japan*, Proc. 9th, Int. Conf. Soil Mechanics and Foundation Eng., Tokyo, pp. 257-260, 1997.
[13] Ohta, Y. & Goto, N., *Empirical Shear Wave Velocity Equation in Terms of Characteristic Soil Indexes*, Earthquake Engineering and Structural Dynamics, **6**, pp. 167-187, 1978.
[14] Sykora, D.W. & Stokoe, K.H., *Correlation of In Situ Measurement in Sands of Shear Wave Velocity, Soil Characteristics, and Site Conditions*, Geotechnical Engineering Report GR83-33, The University of Texas, Austin, 1983.
[15] Yamanaka, H. & Yamada, N., *Estimation of 3D S-wave Velocity Model of Kanto Basin, Japan, Using Rayleigh Wave Phase Velocity*, Bulletin of the Earthquake Research Institute, University of Tokyo, **81**, pp. 295-301, 2006.