Determination of Site Amplification Deep Soil Layers using 1-D Site Response Analysis (Case Study: Jakarta City, Indonesia)

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Abstract. The dynamic response of deep soil layers is used in the development of microzonation maps. The empirical correlation between standard penetratation blow count numbers and S-wave velocity was derived for practical purposes in site characterization based on local data in a case study in Jakarta, Indonesia. For estimating the intensity of potential earthquake shaking at the ground surface as a function of depth to the bedrock surface layer, 1-D site response analysis was carried out in 5745 simulations. The site amplification values were then evaluated by dividing the spectral acceleration (SA) at ground surface by the SA at rock outcrop. Plots of the SA amplification values at interested depth intervals of the bedrock surface layer were assigned. The results showed that the site amplification values estimated by considering the local depth of the bedrock surface layer were generally smaller than the SA amplification values from the Indonesian seismic building code SNI-1726-2012. Also, there appears to exist a tendency of lower levels of mean regression of amplification, in particular for the soft soil site class.

Keywords: *deep soil layer; S-wave velocity; spectral acceleration; site amplification; site response analysis.*

1 Introduction

In seismic building codes, time-averaged S-wave velocity in the upper 30 m of the soil surface (*Vs30*) is a commonly used parameter for grouping soil sites according to their potential to amplify dynamic motion. With this approach problems arise when the depth to the bedrock surface layer does not extend up to 30 m. In such cases, for the extrapolation of the available shear wave velocity (*Vs*), the value that has been proposed by Boore [1] can be adopted to evaluate

Received October 15th, 2018, 1st Revision March 20th, 2019, 2nd Revision October 9th, 2019, Accepted for publication November 25th, 2019.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.6.6

Vs30. In the opposite case, the dynamic response of deep soil layers is used in the development of microzonation maps.

The effect of the depth to the bedrock surface layer on the site amplification is particularly important for sites like Jakarta, where the bedrock surface layer can be found locally up to 750 m, in particular in the northern part of Jakarta, as reported by Ridwan, *et al*. [2] and as shown in Figure 1.

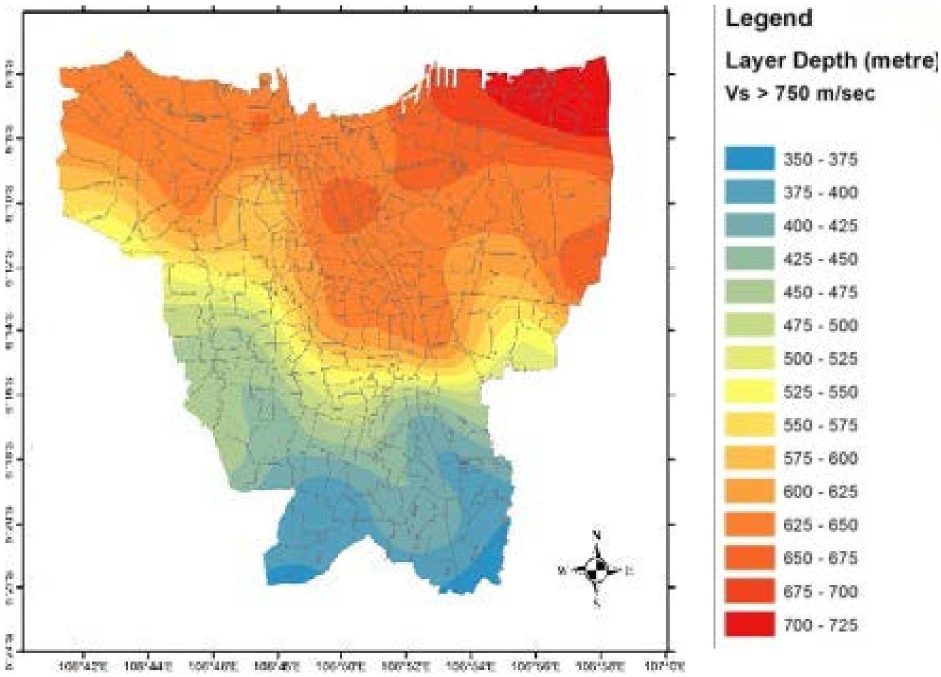


Figure 1 The contour of the depth to the bedrock surface layer beneath Jakarta city (conducted by Ridwan, *et al.* [2]). The contour was generated by interpreting microtremor measurements.

In Indonesian seismic building code SNI-1726-2012 [3], foundation factors for 0.0, 0.2, and 1.0 second periods of amplification are adopted to quantify the amplification potential of the site conditions. The site conditions are grouped into 6 classes based on the average standard penetration blow count numbers (*N*) or the *Vs* in the top 30 m soil layer.

In the present study, amplification of the soil surface motion is defined relative to the motion in the rock surface layer that directly underlies the soil surface layer. The objective of this study was to evaluate the values of the spectral acceleration amplification factor for a typical site in Jakarta city by comparing the results with the values proposed in seismic building code SNI-1726-2012.

2 Methodology

A complete and thorough explanation of the procedures for generating seismic ground motion at ground surface and the methodology to do a site response analysis have been presented by Hutapea, *et al*. [4] and Irsyam, *et al*. [5]. Based on the local soil conditions of Jakarta, the parametric study on site response analysis conducted by Misliniyati, *et al*. [6] evaluated the effect of several input parameters (i.e. the *Vs* at bedrock, the plasticity index of the local site, the amplitude and frequency content of the input motion) on the characteristics of ground surface motion. Zonation maps of Jakarta have been constructed by Delfebriyadi, *et al*. [7].

The maps were produced by applying a relative grouping of the average spectral accelerations (SA) with respect to the frequency distribution in their study area. In our study, a site response analysis was carried out for estimating SA at ground surface in Jakarta,. The site amplification values were determined by dividing the surface response spectra obtained from analysis of the SA of rock outcrop motion. Based on geoseismic and geotechnical measurements collected in the Jakarta area, the relationship between *N* and *Vs* was developed to be used for practical purposes in site characterization.

In seismic microzonation, site characterization is the most important step. In this stage, the average *N* value in the upper 30 m of the soil surface is used as the parameter for grouping the sites. Classification according to SNI-1726-2012 shows that most locations in Jakarta (based on 383 geotechnical boring sites) can be classified as medium soil (SD) and soft soil (SE) sites with an average *N* value in the upper 30 m of the soil surface layer ranging from 15 to 30 blows and ranging from 2 to 15 blows, respectively (Figure 2).

The *Vs* of the soil plays an important role in site response analysis. It can be used for site classification and for determining the small strain stiffness of the soil related to dynamic loading. For developing an empirical *N*-*Vs* correlation, we selected a total of 47 boring sites for which *Vs* and *N* measurements were available in the same borehole.

The *Vs* values were obtained by a downhole seismic survey. A number of pairs of data points of *Vs* and *N* values from each borehole at the same depth were used to derive the empirical correlation.

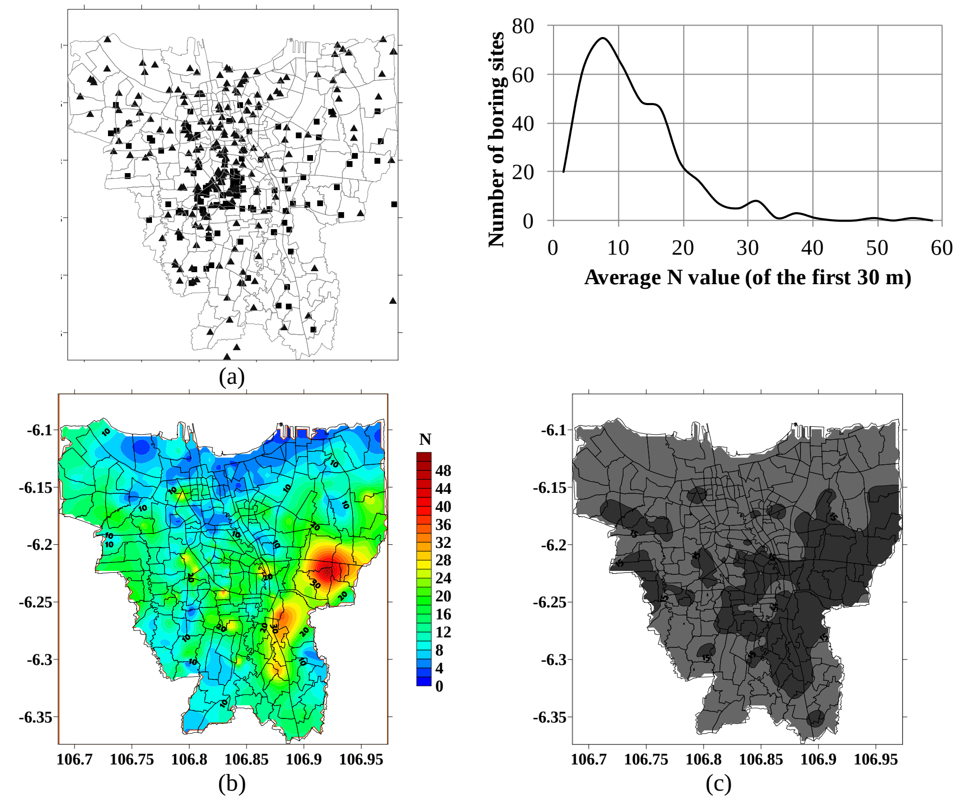


Figure 2 (a) Location of the boring sites in Jakarta, (b) the contour of the average *N* values (of the first 30 m), and (c) site classification map based on the average *N* values (SE site = triangle symbol or grey color; SD site = square symbol or black color).

The data analysis in this study was corroborated by data from the previous study by Yunita [8]. Thus, a total of 650 pairs of data points of *N* and *Vs* values, plotted in Figure 3, were collected to find the regression equation. From these data, the empirical correlation between Vs and N was calculated using Eq. (1):

$$Vs = 103.7\ N^{0.294} \tag{1}$$

N is the uncorrected standard penetratation blow count number. Statistically, the R^2 value is 0.686, which indicates a good enough relationship between *Vs* and *N*.

Several nonlinear relationships between *Vs* and *N* have been be utilized to convert these values, i.e. the correlation proposed by Goto & Ohta [9], Imai & Tonouchi [10], and Prakoso [11] proposed an empirical correlation for cemented soils for the Jakarta area. Among the three of them, the nonlinear relationship between *Vs* and *N* developed in this study had the best fit with the correlations proposed by Goto & Ohta [9] and Imai & Tonouchi [10].

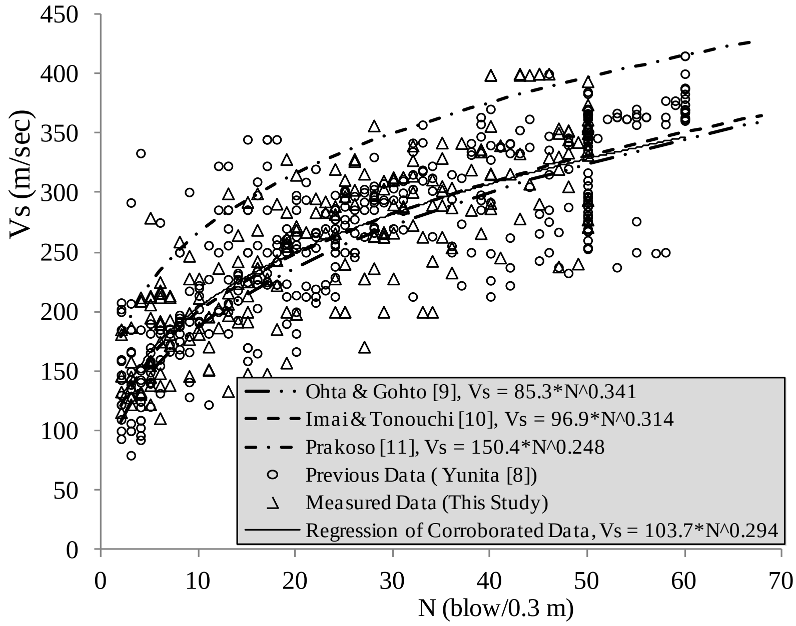


Figure 3 Variation of *Vs* and *N* values in several locations in Jakarta.

The *Vs* soil profiles constructed by utilizing available *N* values for the boreholes were established using three empirical correlations, given by Ohta & Goto, Imai & Tonouchi and Eq. (1), respectively. These empirical correlations were selected since they involve all soil types.

The contour of *Vs30* and the distribution of *Vs* values with depth for all 383 borehole sites are shown in Figure 4. Comparing the site classification map based on the *N* values (Figure 2(c)) with the site classification map based on the *Vs30* values (Figure 4(c)) there was a dominant shift to medium soil (SD) classes.

Site response analyses were carried out at 383 borehole sites. Representative *Vs* profiles along the boreholes were constructed for each layer. Figure 4(b) shows that all of the bases of the boreholes failed to reach the bedrock surface layer (corresponding to a *Vs* of 760 m/sec). Therefore the bedrock surface layer was added to each soil column in the analysis. The bases of the soil columns were constructed between 350 and 725 m depth based on information from the mapped depth to the engineering bedrock beneath Jakarta, as shown in Figure 1.

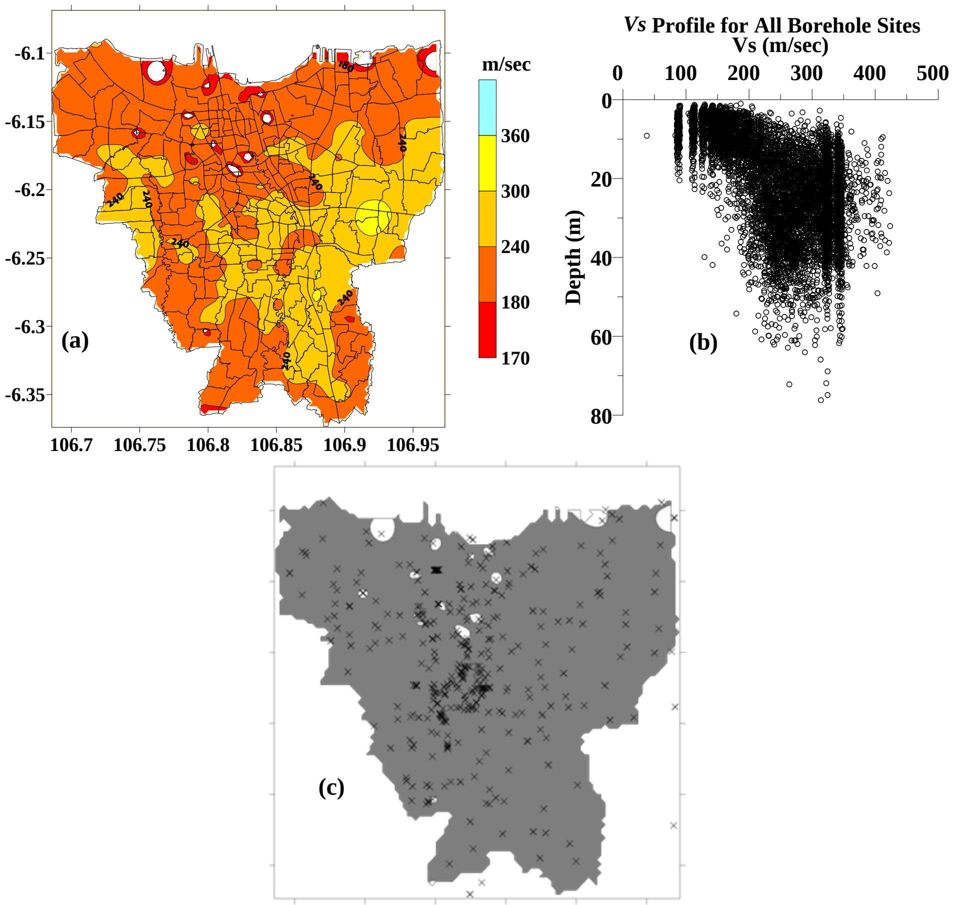


Figure 4 (a) The contour of *Vs30*, (b) shear wave velocity profile across Jakarta from all borehole sites established by utilizing 3 empirical correlations, and (c) site classification map based on *Vs30* (*SE* site = grey color; *SD* site = dark color, cross sign = distribution of borehole points).

The *Vs* profiles from the end of the boreholes to the base of the soil columns were extrapolated with assumption of *Vs* increasing with depth. The soil columns were then modelled by NERA (Bardet & Tobita [12]), a 1-D site response macro script. The input data of the *Vs* intervals as well as the mass density of the soil (ρ) and the soil layer thickness were used for each layer down to the rock half-space.

The soil model used in the site response analysis consisted of small to large values of the shear-strain relationships on material damping ratio and on normalized shear modulus. A shear modulus (G_{max}) correlating with a small value of shear strain is directly associated with Eq. (2).

The shear strain dependent relationships for each soil type, as shown in Figure 5, were used in this study. In the *Vs* profiles, the soil layer was divided into a number of sublayers to meet the fundamental frequency requirement of at least 25 Hz. This is because frequencies above 10 to 25 Hz contain a relatively small amount of energy of dynamic loading (Schnabel *et al.* [14]).

The strong motion was considered to be due to rock outcrop for modeling purposes. Because of a lack of actual ground-motion records for Jakarta, modified earthquake acceleration time histories from previous historical earthquake events were adopted in this study (Figure 7). A method to adjust the spectral values was used to synthesize the existing earthquake waves compatible with the target spectrum for bedrock motion (Abrahamson [17]).

$$G_{\max} = v_s^2 \rho \tag{2}$$

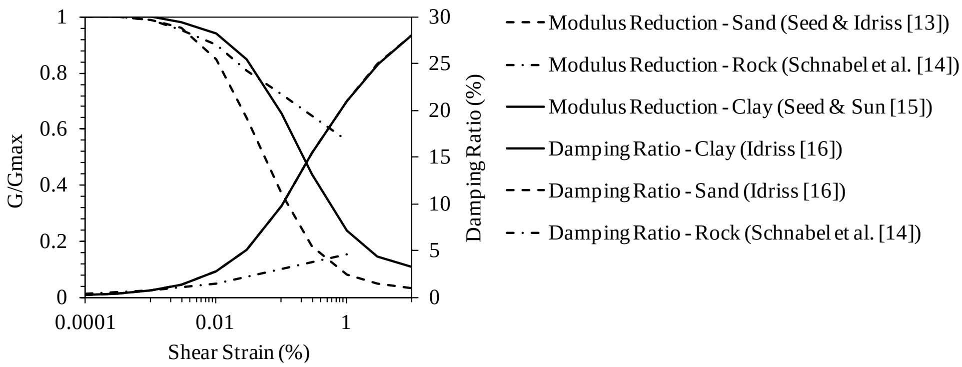


Figure 5 Shear strain dependent relationships adopted in the site response analyses.

The target acceleration response spectrum was scaled at some spectral periods of the uniform hazard spectrum (UHS) of a 2500-year earthquake return period (RP), shown in Figure 6, which was obtained using the probabilistic seismic hazard analysis (PSHA) method (Asrurifak, *et al.* [18]). The fault model and the subduction model were applied by utilizing the available earthquake sources and their parameters issued by the Team for Revision of Seismic Hazard Maps of Indonesia 2010 (Irsyam, *et al.* [19,20]).

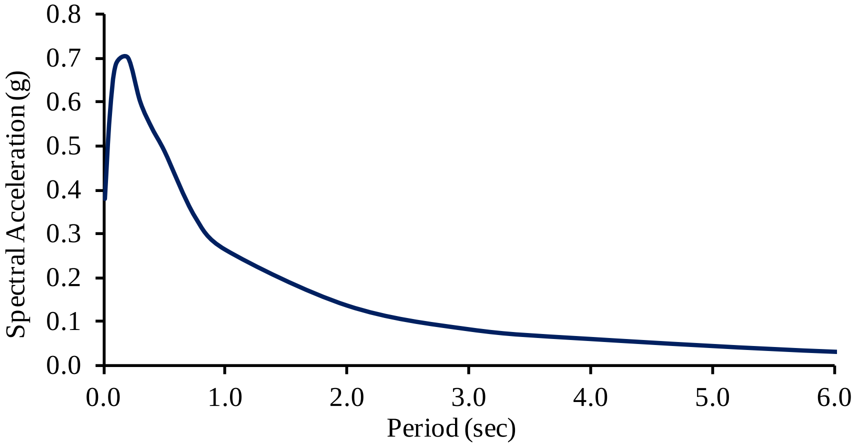
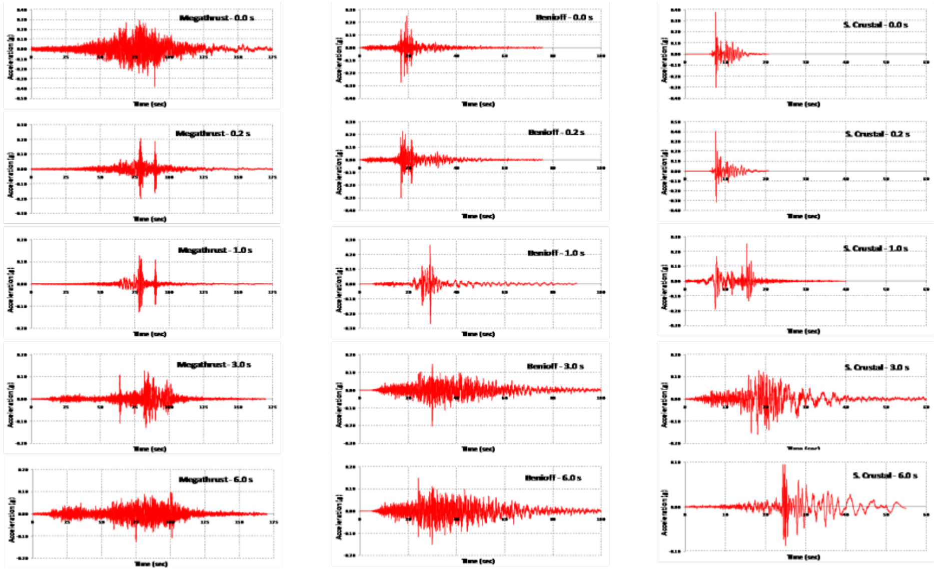


Figure 6 Plot of UHS corresponding to 2500-year earthquake return period.



(a) Megathrust (b) Benioff (c) Shallow crustall

Figure 7 Modified acceleration time histories for bedrock in Jakarta from megathrust, Benioff, and crustal earthquake sources for an RP of 2500-year. The ordinate is the acceleration in *g* scale, and the abscissa is the time in seconds.

The deaggregation of PSHA at five spectral periods was then used to find the historical ground-motion records of earthquake events with similar source-site distances and magnitudes. The tabulation of the deaggregation result is summarized in Table 1.

Table 1 Deaggregation results for Jakarta corresponding to 2500-year Earthquake return period.

Period	Source	*Mw*	R (km)
PGA	Megathrust	8.8	172
	Shallow crustal	5.9	45
	Benioff	7.0	113
SA 0.2sec	Megathrust	8.8	172
	Shallow crustal	6.0	45
	Benioff	7.0	108
SA 1sec	Megathrust	8.7	186
	Shallow crustal	6.3	41
	Benioff	7.2	111
SA 3sec	Megathrust	8.7	193
	Shallow crustal	7.0	79
	Benioff	7.4	122
SA 6sec	Megathrust	8.7	202
	Shallow crustal	7.3	111
	Benioff	7.3	124

3 Result and Discussion

Figures 8 to 10 show the contours of the spectral acceleration values at ground surface obtained from plots of the result of the site response analysis on 383 borehole sites. These contours indicate mean plus one standard deviation. Also, Figures 8 to 10 plot the spectral acceleration amplification values of each soil class, of which the values were determined individually by dividing the SA at ground surface by the SA at rock outcrop for the same spectral period.

The peak ground acceleration (PGA) of the input motion was varied, ranging from 0.1 g to 0.4 g (Figure 7). These plots of the site amplification values versus the SA for rock outcrop were assigned from the results of over 5745 simulations. For comparison of the results, the regression slopes of the amplification factor from SNI-1726-2012 are also attached in the amplification diagrams of each soil site class. The amplification diagrams show that the trend of the site amplification values estimated by considering the mapped depth of the bedrock surface layer were generally smaller than the SA amplification values from SNI-1726-2012.

In Figure 11, the results (the amplification diagrams in Figures 8 to 10) are deaggregated into 5 different interval depths of the bedrock surface layer. The grouping was addressed to find the regression slope of the site amplification corresponding to the depth interval. The defined depth intervals to the bedrock surface layer were 350-400 m, 400-500 m, 500-600 m, 600-700 m and 700-750 m. The results show that the regression lines generally had a decreasing amplitude as the depth of the bedrock surface layer increased. Also, the amplification value decreased with increasing input motion amplitude. After comparison with the slopes of regression of the amplification factor from SNI-1726-2012, a tendency of lower levels of mean plus one standard deviation of the regression line for all spectral periods seems to exist, in particular for the soft soil site class.

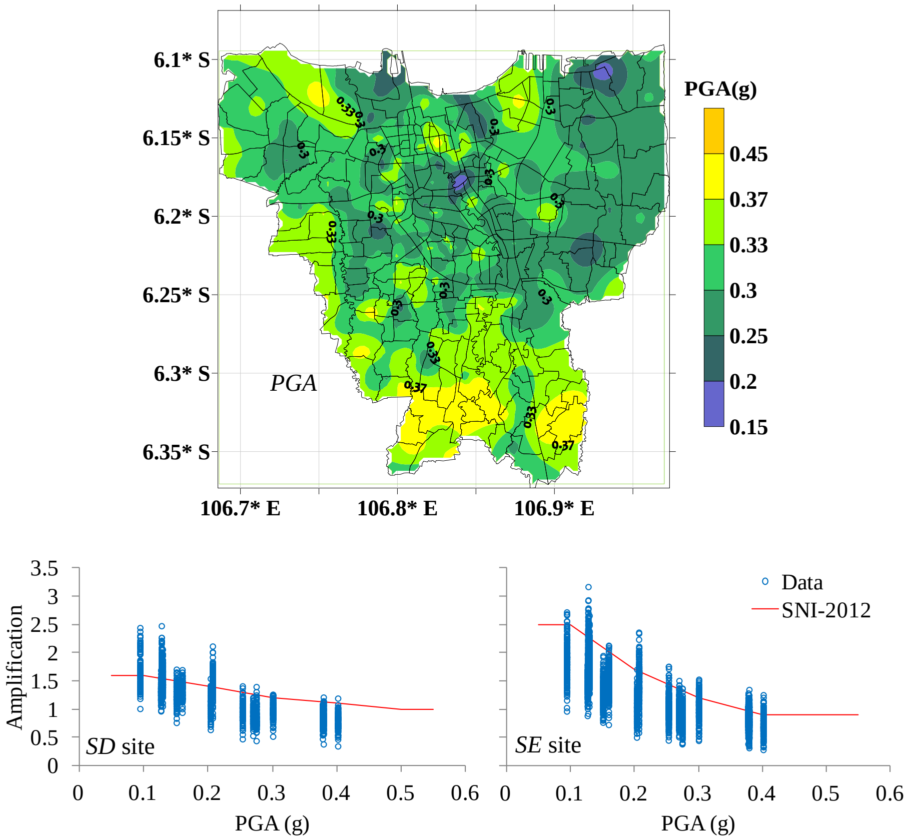


Figure 8 The PGA map at ground surface corresponding to a 2500-year earthquake return period and distribution plots of the site amplification values obtained from the site response analysis evaluated at 350 to 750 m depth intervals to the 'bedrock surface layer' in the Jakarta area. The site amplification values of each soil class were determined individually at each input motion and the contour map indicates mean plus one standard deviation. The regression slopes of the mplification factor from SNI-1726-2012 are also attached in the amplification diagrams.

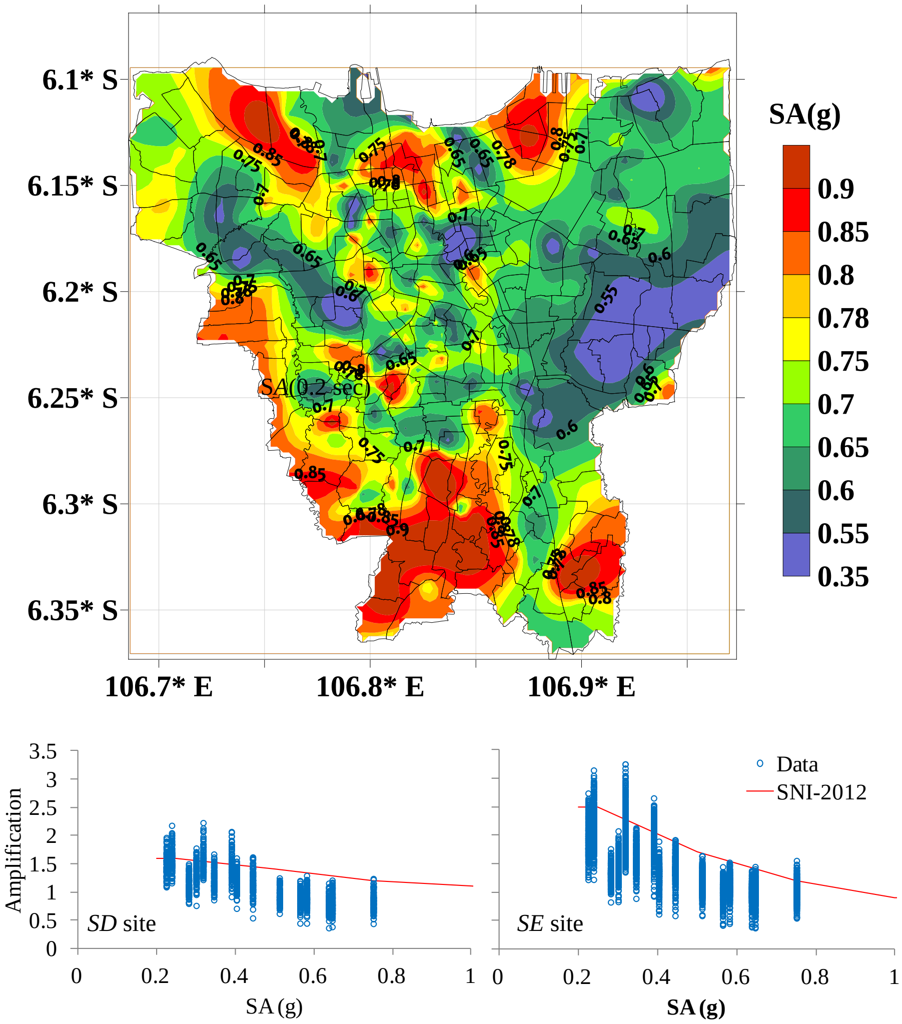


Figure 9 The map for SA (0.2 sec) at ground surface and distribution plots of the site amplification values obtained from the site response analysis evaluated at 350 to 750 m depth intervals to the 'bedrock surface layer' in the Jakarta area. The site amplification values of each soil class were determined individually at each input motion and the contour map indicates mean plus one standard deviation.

At long periods (Figure 11(c)), the regression lines for the soft soil site class obtained from the analysis were relatively low compared to the regression based on the amplification factor from SNI-1726-2012, whereas the regression lines for the medium soil site class were relatively high. The amplitudes of motion characterize the energy and the change in frequency content of motions with distance. When a seismic wave propagates from the bedrock to the ground surface, high frequency waves are absorbed. If soil damping is smaller, the soil will absorb less energy. This allows more energy to propagate and the long-period waves gradually dominate the ground motion.

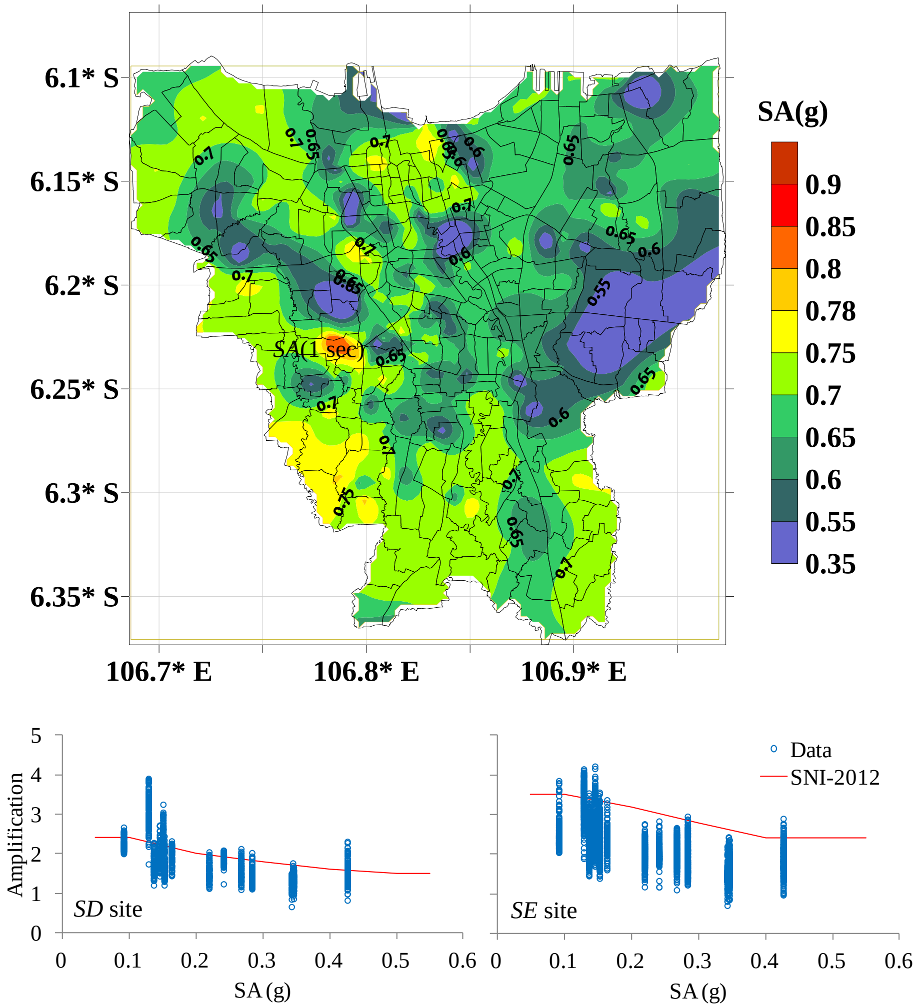
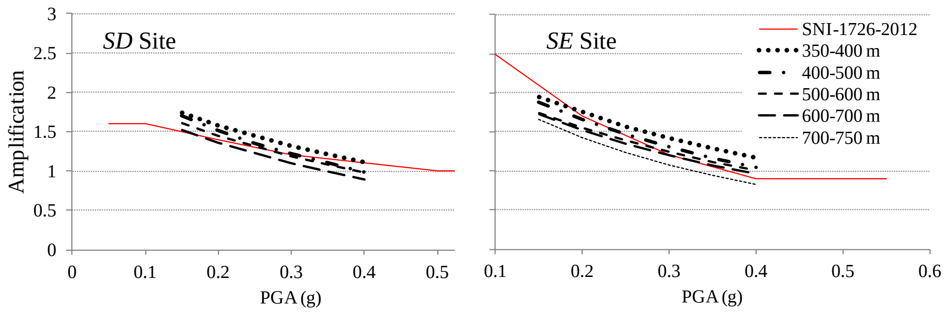
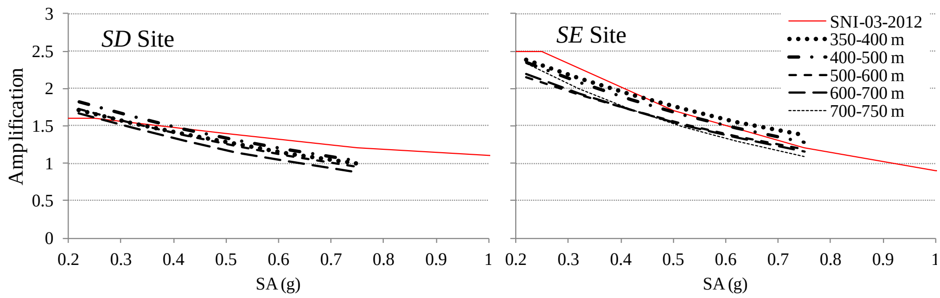


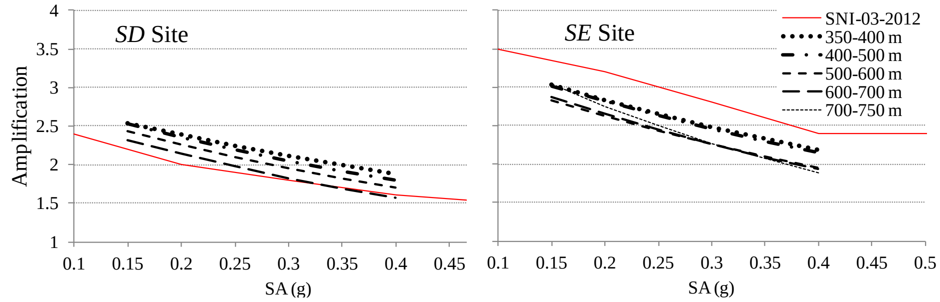
Figure 10 The map of SA (1.0 sec) at the ground surface and distribution plots of the site amplification values obtained from the site response analysis evaluated at 350 to 750 m depth intervals to the 'bedrock surface layer' in the Jakarta area. The site amplification values of each soil class were determined individually at each input motion and the contour map indicates mean plus one standard deviation.



(a) Mean + 1 standard deviation regression curves of site coefficient (at 0 sec period)



(b) Mean + 1 standard deviation regression curves of site coefficient (at 0.2 sec period)



(c) Mean + 1 standard deviation regression curves of site coefficient (at 1 sec period)

Figure 11 The correlation between site amplification factor (mean plus one standard deviation regression curves of site coefficient) and SA for the rock outcrop, evaluated from the mapped depth intervals to the bedrock surface layer in the Jakarta area. The regression slopes of the amplification factor from SNI-1726-2012 are also attached in the amplification diagrams.

4 Conclusion

The empirical correlation between *N* and *Vs* was developed for the Jakarta area and applied to site classification. The best fit of the correlation was with the correlations proposed by Ohta & Goto and Imai & Tonouchi. The correlation seems to shift the site classification map of the Jakarta area into a stiffer site class. For the local site conditions of Jakarta, the result shows that the site amplification values estimated by considering the local depth of the bedrock surface layer were generally smaller compared to those according to the current code. The trend shows the amplification value to decrease as the depth of the bedrock surface layer increases. This study gives a better site response towards dynamic excitation for sites with deep soil surface layers like Jakarta.

Acknowledgements

The authors gratefully acknowledge the government of DKI Jakarta for supplying the data used in this study. Acknowledgments are also addressed to the Team for Revision of Seismic Hazard Maps of Indonesia 2010.

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