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Development of Nationwide Surface Spectral Acceleration Maps for Earthquake Resistant Design of Bridges Based on National Hazard Maps of Indonesia 2017

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Abstract. Spectral acceleration at the ground surface, including peak ground acceleration, provides essential information for earthquake resistant design and must be provided to bridge engineers in easily accessible media. Spectra acceleration maps are one way to deliver such information, but unfortunately the most recent Indonesian earthquake resistant design standard for bridges, SNI 2833-2016, only provides maps of earthquake hazard at bedrock. The development of earthquake acceleration maps at the ground surface for Indonesia in this study was based on earthquake hazard maps at bedrock with probability of exceedance (PE) 7% in 75 years, i.e. equal to an earthquake with a return period of 1034 years. Site conditions were adopted from the nationwide Vs_{30} map of Indonesia proposed by Irsyam (2017), which is a modified version of the Vs_{30} map proposed by Imamura & Furuta (2015). Site conditions combined with hazard value were used to determine the amplification factors according to the criteria in SNI 2833-2016 and then multiplied with hazard at bedrock to obtain surface spectra acceleration maps. The resulting maps are very useful for determining earthquake loads for bridge design at the preliminary design stage. Improvements to incorporate more advanced calculation methods and updated data in a future research are recommended and very feasible.

Keywords: *bridge design; earthquake; hazard map; Indonesia; surface acceleration.*

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1 Introduction

1.1 Background

Development of transportation infrastructure is one of the main programs of the current government in Indonesia. Many new roads, railways, bridges, buildings and dams have been constructed in the past few years. Especially the number of new bridges is considerably high, since nearly 90% of Indonesian commodity movement utilizes land transportation [1]. It is expected that many more bridges will be constructed in Indonesia in the near future. Construction of bridges in Indonesia has to comply with the requirements of earthquake resistant design since four major active plates that cause high seismic activity are located in Indonesia.

According to SNI 2833-2016, which partially adopted the *AASHTO LRFD Bridge Design Specification*, 5th Edition, 2012, bridge engineers require earthquake loads with a 1034-year return period obtained from design surface spectra acceleration curves. Design surface spectra acceleration curves describe the envelope of the peak responses of many single degree of freedom (SDoF) systems with different periods, which can be used for obtaining seismic lateral forces to be employed in designing earthquake-resistant structures. In order to develop the design surface spectra acceleration curves, shaking intensity at bedrock from seismic hazard maps and ground amplification factors from local site characteristics studies are required (Figure 1).

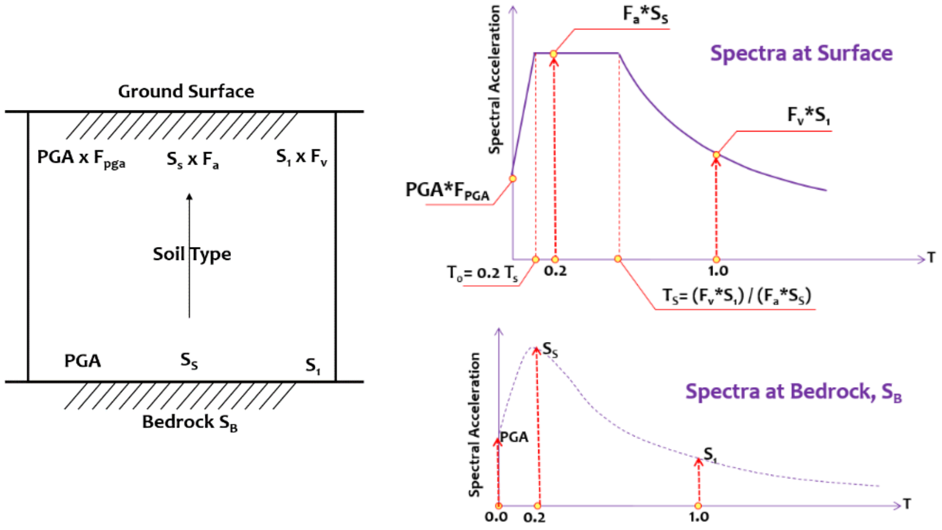

Figure 1 Derivation of surface response spectra.

An earthquake hazard map at bedrock of Indonesia with a probability of exceedance of 7% in 75 years has been published in SNI 2833-2016 [2] and updated in *Earthquake Source and Hazard Maps of Indonesia 2017* [3]. There is no national amplification factor map of Indonesia available yet.

The amplification factors can be obtained individually from soil investigation, including field or laboratory tests. Performing field and laboratory tests to produce amplification factors for the entire country is very costly. A more efficient method to estimate amplification factors is urgently needed.

This paper presents the development of earthquake surface spectra acceleration maps for Indonesia for 3 periods of interest: peak ground acceleration (PGA), T = 0.2 s, and T = 1 s with a probability of exceedance (PE) of 7% in 75 years. The peak earthquake acceleration at bedrock was obtained from Irsyam, *et al.*[3], which is a revision of the *National Hazard Maps* in Research Report, 2010 [4].

The amplification factors were generated based on the Indonesian site classes derived from the nationwide average shear wave velocity down to 30 m depth (Vs30) map proposed by Irsyam, *et al.* in 2017[5]. The value of the amplification factor in relation to acceleration at bedrock, site class, and Vs30 was determined according to SNI 2833-2016 [2]. Acceleration at bedrock multiplied by the amplification factor yielded the acceleration at the ground surface.

The resulting maps can be used immediately to generate response spectra at the ground surface and to estimate earthquake loads in the preliminary design of a bridge. It is thought that these maps will be very useful for bridge engineers in the design process.

1.2 2017 Revision of Indonesia’s National Seismic Hazard Maps

A revision of Indonesia’s national seismic hazard maps has been carried out by the Team for Updating of Seismic Hazard Maps of Indonesia 2017 (TUSHMI 2017). The team was established by the Ministry of Public Works and Housing of Indonesia in 2015. The work by TUSHMI 2017 was released in *Earthquake Source and Hazard Maps of Indonesia 2017*. Based on [6] and [7], TUSHMI 2017 utilized the most recent available data as well as studies and technologies in order to update and enhance the seismic hazard maps of Indonesia.

The basic digital data used for the new seismic hazard maps were taken from SRTM-30, IFSAR DSM (Digital Surface Map) with a grid resolution of 5 m, The General Bathymetric Chart of the Oceans (GEBCO) 2009 bathymetry grid, LiDar, and GPS data for strain analysis.

Hand drillings, trenching, carbon dating, and coring were conducted in several locations in order to thoroughly characterize the structure of active faults. The data for the earthquake catalogue of Indonesia were updated from the following sources: the 1901 to 2014 Preliminary Determination of Epicenters (PDE) data from the National Earthquake Information Center from the United States Geological Survey (USGS), the EHB catalog from the International Seismological Centre (ISC), earthquake data from the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia dating from April 2009 to June 2014, and focal mechanism data from the ISC database.

The preliminary seismicity data were then refined. The refinement was conducted by relocating the hypocenter with the teleseismic double-difference relocation (teletomoDD) method to obtain more precise hypocenter locations. Both probabilistic and deterministic seismic hazard analyses were used in the development of the new seismic hazard maps of Indonesia.

The ground motion prediction equations (GMPE) that were used in the hazard analysis are part of the Next Generation Attenuation (NGA). This means that the development of the equations took new earthquake data such as the 2011 Tohoku earthquake as well as improved 3D tomographic models into account.

Calculation of a-b values based on the relocated hypocenters, which were also declustered by utilizing the moving window observation method, produced more stable a-b values than the values from the 2010 hazard maps. The enhancements mentioned also produced a more accurate and up-to-date seismotectonic model, seismic hazard analysis, and eventually seismic hazard maps.

Figure 2 shows the active faults of Java and Sulawesi in the updated *Hazard Maps of Indonesia 2017*. Many more active faults have been identified and included in the 2017 maps. Figures 3 to 5 present the spectral accelerations at bedrock (SB) for 3 period of interest: $T \approx 0$s (PGA), $T = 0.2$ s (Ss), and $T = 1$ s (S_1) with PE 7% in 75 years [3].

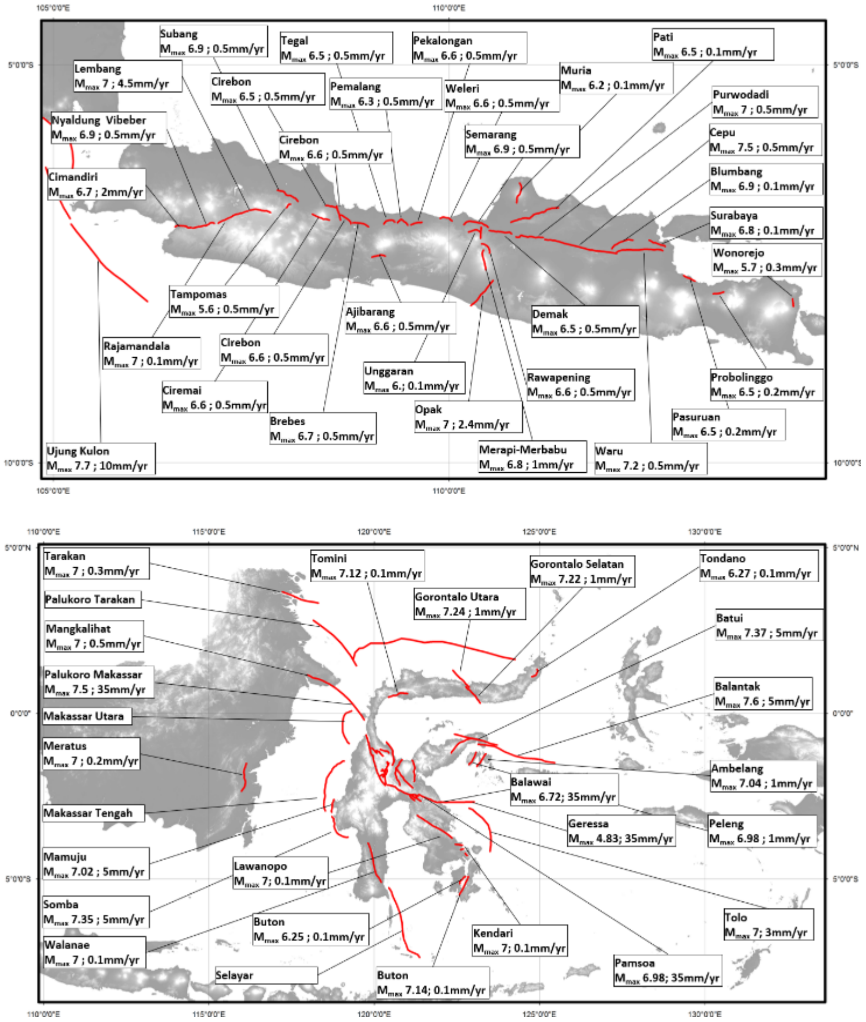

Figure 2 Active faults of Java and Sulawesi in *Indonesian Hazard Maps 2017* (based on [3] and [8]).

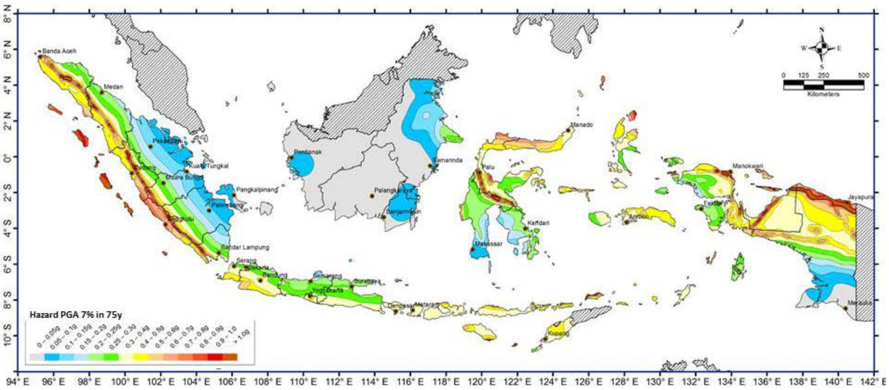

Figure 3 Maximum considered earthquake ground motion of PGA at bedrock with PE 7% in 75 years [3].

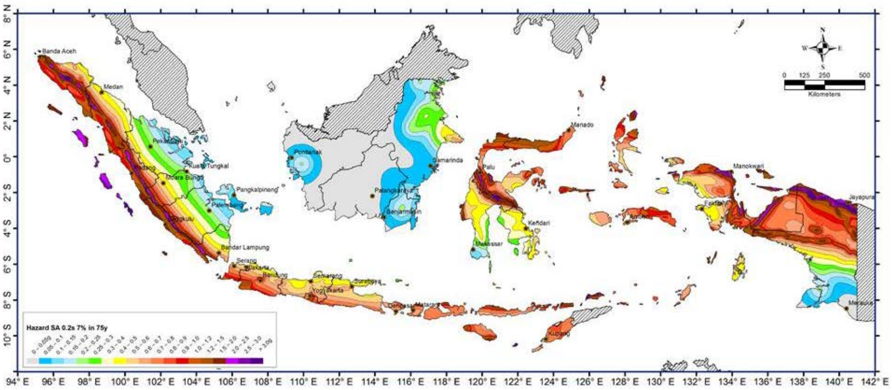

Figure 4 Maximum considered earthquake ground motion of 0.2 s spectral response acceleration at bedrock with a PE of 7% in 75 years [3].

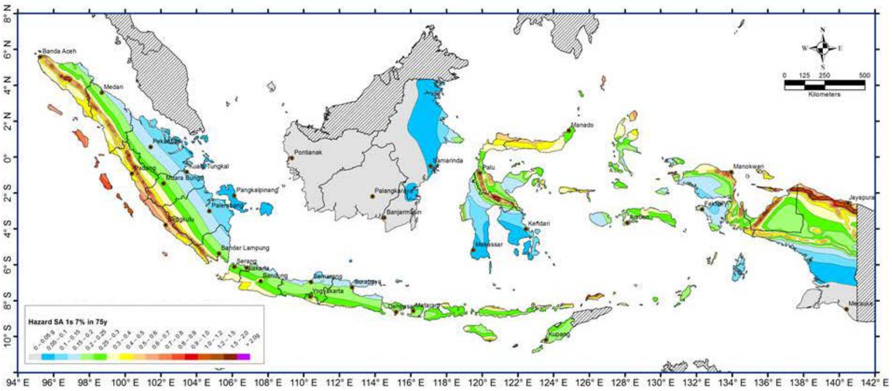

Figure 5 Maximum considered earthquake ground motion of 1.0 s spectral response acceleration at bedrock with a PE of 7% in 75 years [3].

1.3 Site Class Map of Indonesia based on the Correlation between Vs_{30} and Topographic Data

The nationwide Vs30 map for Indonesia was obtained from [5]. It was developed based on the correlation between automated topographic classification by [9] and field Vs measurement by the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG). The topographic classification process utilized three terrain characteristics from the digital elevation model (DEM): slope gradient, local convexity, and surface texture.

Slope gradient is the steepness and flatness of the terrain, while local convexity is the average occurrence of convex terrain within a 3 x 3 cell grid. Similar to local convexity, surface texture is the average occurrence of 'peak' and 'pit' in the DEM within a 10-cell radius. The classification work was conducted by comparing the value of the slope gradient, local convexity, and surface texture to the average value per unit area. The detailed classification method is described in [10] and [11]. Initially, [4] proposed a correlation table and a Vs_{30} map for Indonesia, which was developed from Vs data from Japan and a previous correlation study [12]. Later, [5] conducted an analysis on 136 Vs data by BMKG and modified the correlation table that was previously proposed by [4], which yielded a new correlation and a new Vs_{30} map based on Indonesian data. The Vs_{30} map from [5] can be translated into a site class map in accordance with the criteria from SNI (Figure 6).

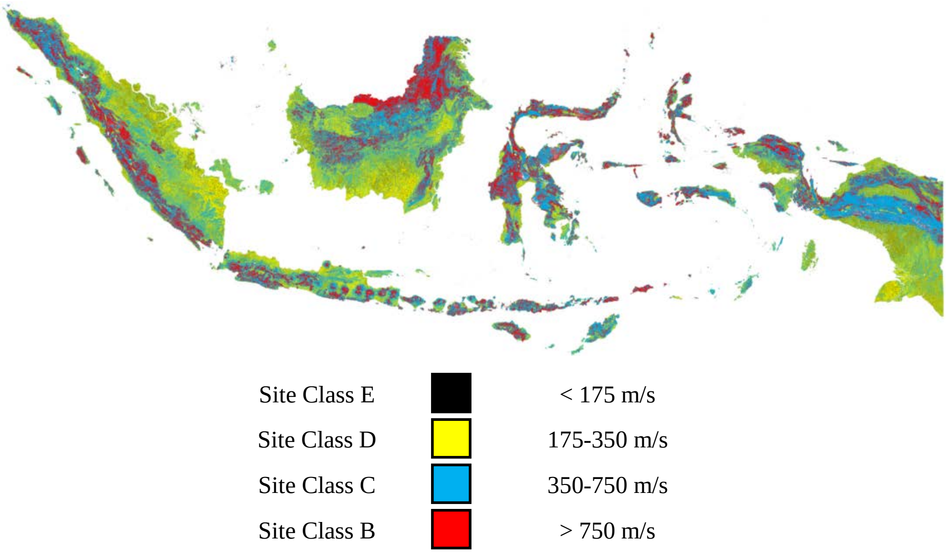

Figure 6 Proposed Vs_{30} map of Indonesia [5].

2 Methodology

2.1 Calculation of Amplification Factor

The earthquake acceleration map at bedrock for PGA, T = 0.2 s (S_s), and T = 1 s (S_1) from *Earthquake Source and Hazard Maps of Indonesia 2017* was digitized by using raster-processing software. The process was intended to obtain image files of Indonesia where every pixel has a value that is mathematically calculable. The proposed Vs_{30} map of Indonesia by [5] in Figure 6 was also prepared in the same way and classified based on the Vs_{30} criteria in [2]. Calculation of the amplification factors was based on Table 1, i.e. the amplification factor criteria from [2].

F_{PGA} (amplification factor for PGA), F_a (amplification factor for Ss), and F_v (amplification factor for S_1) were obtained based on hazard at bedrock and site class. For example, if a certain location has PGA $\leq$ 0.1 g and site class D, then the F_{PGA} for that location is 1.6. If the PGA falls between 0.1 g and 0.2 g with site class D, then the value of F_{PGA} must be interpolated proportionally. The same procedure was applied to the calculation of F_a and F_v. Both hazard at bedrock and site class can be identified at any coordinate in Indonesia since each of the respective maps has been digitized and therefore the amplification factor can also be calculated on a national scale.

Table 1 Amplification factor for PGA, S_s, and S_1 [2].

Site Class	**PGA $\leq$ 0.1 Ss $\leq$ 0.25**	**$S_1 \leq$ 0.1**	**PGA = 0.2 Ss = 0.5**	**S_1 = 0.2**	**PGA = 0.3 Ss = 0.75**	**S_1 = 0.3**	**PGA = 0.4 Ss = 1.0**	**S_1 = 0.4**	**PGA $\geq$ 0.5 Ss $\geq$ 1.25**	**$S_1 \geq$ 0.5**
SA	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
SB	1	1	1	1	1	1	1	1	1	1
SC	1.2	1.7	1.2	1.6	1.1	1.5	1	1.4	1	1.3
SD	1.6	2.4	1.4	2	1.2	1.8	1.1	1.6	1	1.5
SE	2.5	3.5	1.7	3.2	1.2	2.8	0.9	2.4	0.9	2.4

2.2 Procedure for Developing PSA Maps

The three amplification factor maps that were generated in the previous phase were then multiplied with the value of acceleration at bedrock. This multiplication was performed using raster processing software. Both maps were inserted as input in the program: each pixel with a hazard value at bedrock in one map was multiplied with the amplification value from the amplification factor map at the same coordinate. The result of this calculation was the peak earthquake acceleration at ground surface level. A summary of the methodology for development of nationwide ground surface spectral acceleration maps is presented in Figure 7.

3 Results and Discussion

3.1 Nationwide Earthquake Surface Spectral acceleration Maps

Six maps were rendered for three different spectral periods: three amplification factor maps and three surface spectral acceleration maps. The amplification factors for PGA (F_{PGA}) are presented in Figure 8. Figure 9 presents the factors for a short spectral period T = 0.2 s (F_a), which represents constant acceleration zones. The factors for T = 1.0 s (F_v) are presented in Figure 10, which represents constant velocity zones. The amplification factors were then directly multiplied with hazard at bedrock levels.

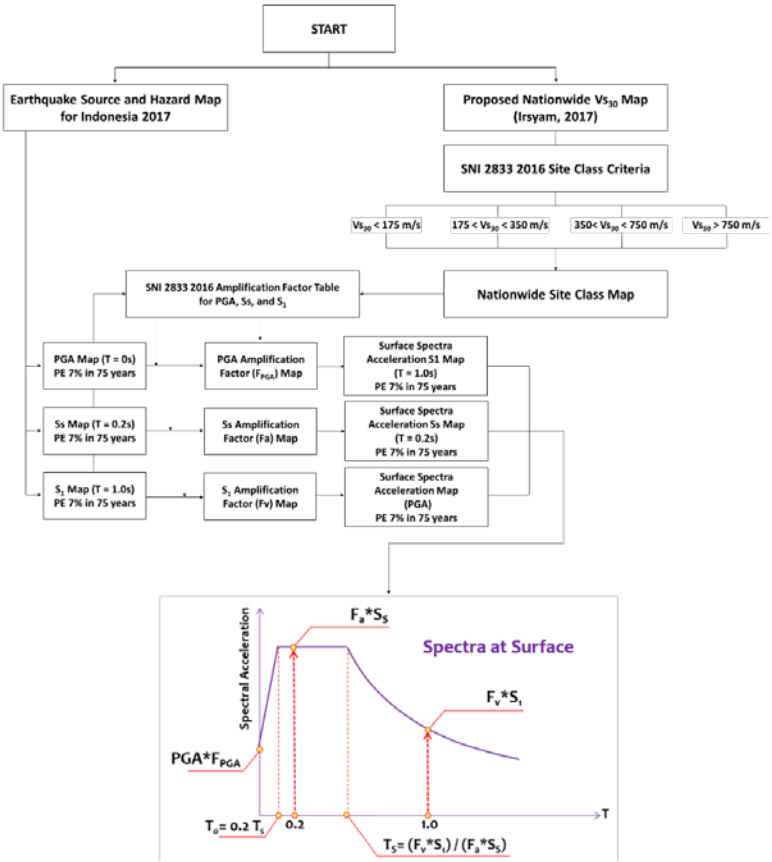

Figure 7 Flowchart of methodology.

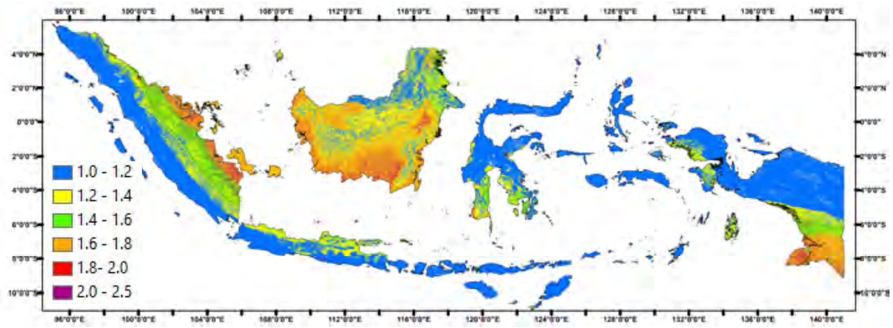

Figure 8 Amplification factors for PGA PE 7% in 75 years.

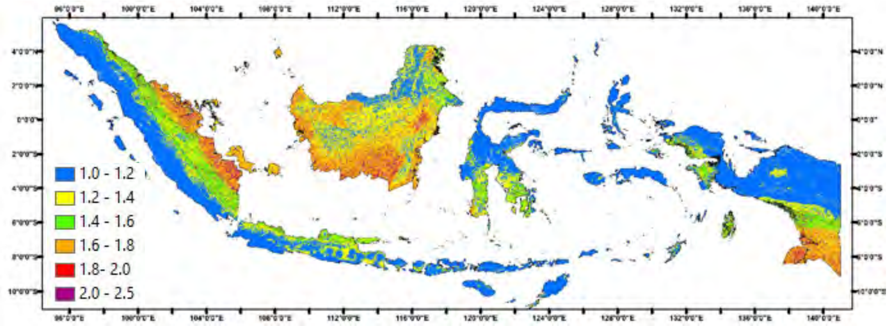

Figure 9 Amplification factors for spectral acceleration T = 0.2s (Fa) PE 7% in 75 years.

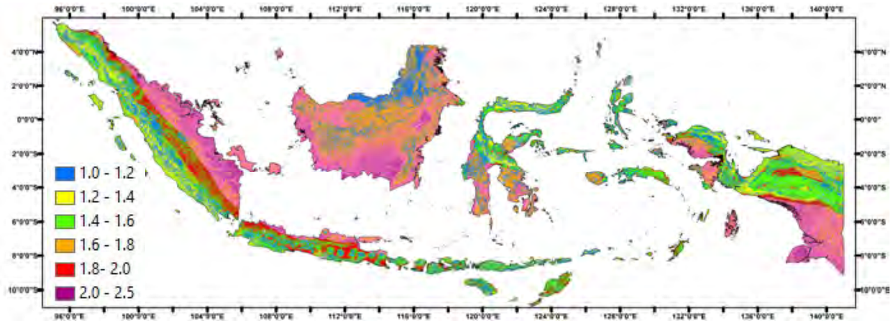

Figure 10 Amplification factors for spectral acceleration T = 1.0s (Fv) PE 7% in 75 years.

Figures 11 to 13 present the surface spectral acceleration values for each spectral period for the whole Indonesian region.

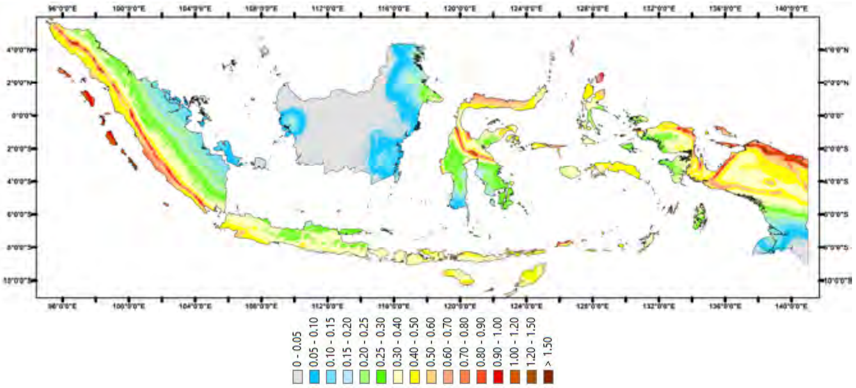

Figure 11 Surface spectral acceleration map for PGA PE 7% in 75 years.

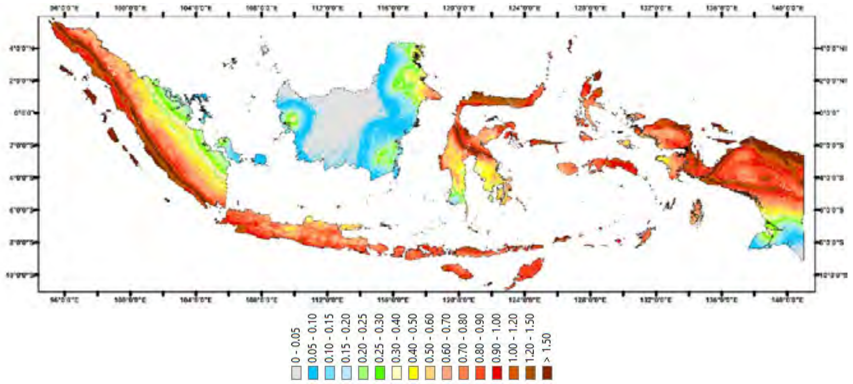

Figure 12 Surface spectral acceleration map for T = 0.2s PE 7% in 75 years.

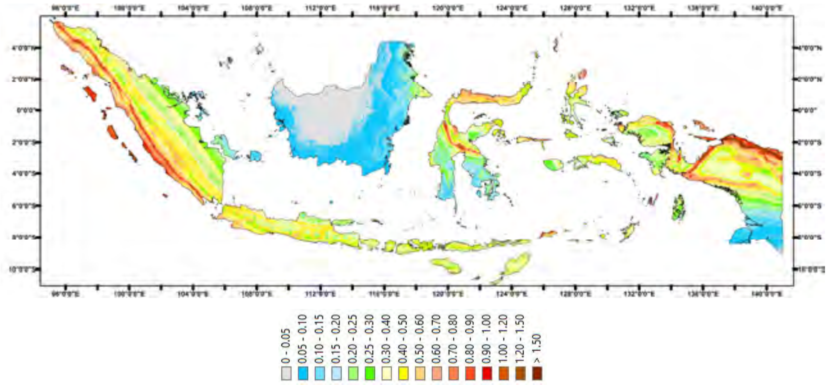

Figure 13 Surface spectral acceleration map for T = 1.0s PE 7% in 75 years.

3.2 Design Spectra at Ground Surface for Big Cities in Indonesia

Surface spectral acceleration curves were constructed for several big cities in Indonesia. The spectra were constructed based on the surface acceleration values at three points of interest: PGA, T = 0.2 s, and T = 1.0 s. The coordinates of the 5 big cities are presented in Table 2. The hazard values at bedrock for each coordinate as well as the amplification factors taken directly from Figures 8 to 13 were compiled as presented in Table 3. The response spectra at surface for each city are presented in Figure 14.

Table 1 Coordinates of big cities in Indonesia.

City	Longitude	Latitude
DKI Jakarta	106.865	-6.175
Bandung	107.619	-6.917
Surabaya	112.752	-7.257
Denpasar	115.213	-8.670
Aceh	95.324	5.548

Table 2 Hazard at bedrock values and amplification factors.

City	PGA (g)	Ss (g)	S1 (g)	F_{PGA}	Fa	Fv
Jakarta	0.28	0.55	0.23	1.30	1.59	3.08
Bandung	0.37	0.81	0.29	1.13	1.18	1.81
Surabaya	0.24	0.49	0.19	1.32	1.41	2.06
Denpasar	0.32	0.66	0.24	1.18	1.27	1.93
Aceh	0.53	1.22	0.48	1.00	1.00	1.51

Figures 8 to 10 are amplification factor maps based on different variables: the site class maps from [5], the amplification factor table from [2], and the hazard at bedrock obtained from [3]. The expected output are maps with distinctive differences between one another, even though the F_{PGA} map in Figure 8 and the Fa map in Figure 9 have similar visual profiles. The similarity actually can be seen from Table 1, where the minimum and maximum value as well as the hazard criteria for F_{PGA} and Fa are similar.

The amplification factor for soft soil tends to be higher than for stiffer soil for the same hazard at bedrock level. On the other hand, the amplification factor for the same site class becomes smaller with increasing hazard at bedrock. This trend can be observed in Figures 5 to 7, where the highest amplification factors are found in areas that correspond to site class D and site class E in Figure 3. In contrast, the lowest amplification factor tends to be found in mountainous locations or around locations with site class B and site class C. This confirms that the amplification factor maps are in line with Table 1.

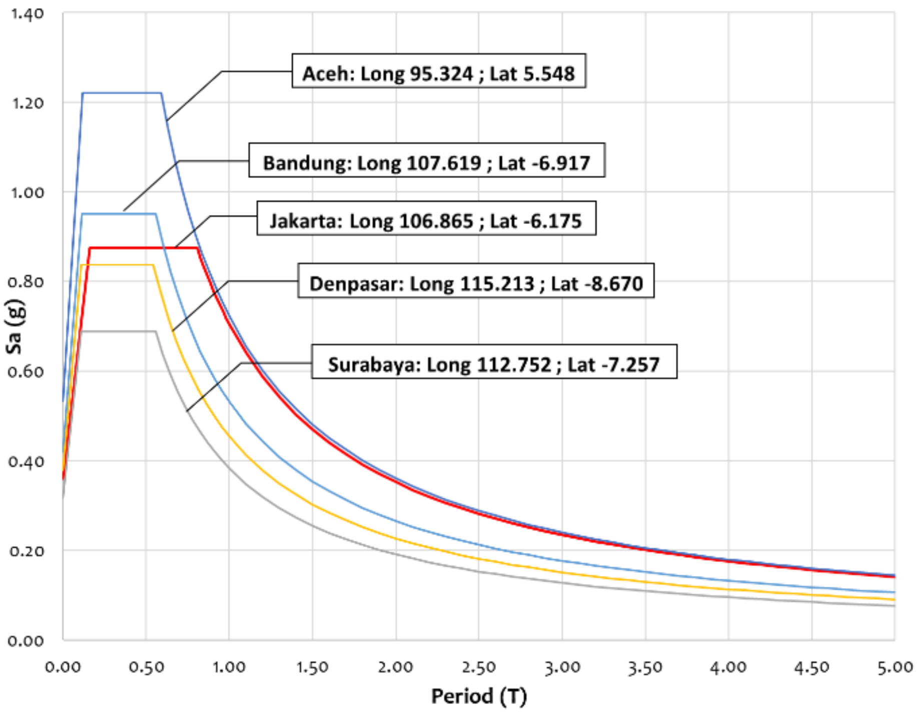

Figure 14 Design spectra at ground surface for big cities in Indonesia with a return period of 1034 years.

The surface spectral acceleration maps in Figures 10 to 13 were directly generated from multiplication of the maps of hazard at bedrock and the amplification factor maps. The results were as expected. The areas with the highest surface acceleration are those that are near active faults. This can be easily seen in Sumatra, Sulawesi, and Papua.

The surface spectra used for design in big cities, as shown in Figure 14, were pinpointed to the exact coordinates as shown in Table 2, which means that the site class was predetermined. The presented response spectra cannot be generalized for the entire cities but could give an indication regarding the seismicity. For example, Aceh in Figure 14 has the highest acceleration value due to its close proximity to active faults and the subduction zone in the west of Sumatra.

The acceleration values in the generated maps are still hazard values. Future development to include a fragility factor is very possible to obtain probability of collapse in a certain bridge lifetime period. Another possible improvement is updating the site class map that was utilized in this study to further enhance the accuracy of the surface acceleration maps as well as the design spectra. The basin effect as well as other advanced calculation methods are also very feasible to be incorporated in future research.

4 Conclusion

Nationwide earthquake peak surface spectral acceleration maps with a return period of 1034 years for 3 different spectral periods (PGA, 0.2 s, and 1.0 s) were generated based on nationwide amplification factor maps and proposed site class maps were put forward. The resulting surface acceleration maps are capable of immediately providing the surface spectra for designated coordinates. This is thought to be very useful for earthquake resistant bridge design at the preliminary design stage. Improvements to incorporate more advanced calculation methods and updated data in future researches are recommended and very feasible.

Acknowledgements

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